Master Thesis

Launch of an Ecolabel for Passenger Aircraft

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Abstract

Purpose – Introducing an ecolabel for aircraft according to the ISO 14025 standard allowing to compare the environmental impact of different air travel options based on the combination of aircraft type, engine type, and seating configuration.

Methodology – The ecolabel considers resource depletion (fuel consumption), global warming (equivalent CO_2 emission, including altitude-dependent NO_X and aviation induced cloudiness), local air quality (NO_X), and finally, noise pollution. The emissions of each impact category are normalized against a group of reference aircraft that account for over 95% of the passenger aircraft flying today. Based on the results from a life cycle assessment (LCA), the impact categories are weighted 20%, 40%, 20%, and 20%, respectively. The four impact categories are combined into one overall rating using the information from the LCA. Seating arrangements in different travel classes are considered based on the cabin floor area occupied by each passenger. Data sources are the aircraft manufacturer's documents for airport planning, the aviation emission calculator from EMEP/EEA air pollutant emission inventory guidebook 2019, the ICAO Aircraft Engine Emissions Databank, the EASA Certification Noise Levels Database, and the SeatGuru seat map database.

Findings – Over 140 ecolabels were calculated and showed the usefulness of the concept. General conclusions were drawn about the parameters that yield environmentally friendly air travel. When combining the ecolabels of all the aircraft in an airline's fleet, even the comparison between airlines is possible.

Research Limitations – The ecolabel cannot compare travel options that include one or more stopovers at different airports. However, different methods are proposed on how booking systems could be extended to offer a comparison based on the ecolabel approach.

Practical Implications – Passengers understand that they should select a flight on the shortest possible route and select the best combination of aircraft and airline based on the ecolabel. Airlines that operate a modern fleet, have tight seating in a single (economy) class, and are known for their high load factor, are better for the environment. Obviously, a ticket in the economy class should be booked if the cabin features more than one class.

Social Implications – The ecolabel gives a foundation for a general discussion about different travel options based on neutral scientific methods and data. The impact categories are defined such that a comparison between different modes of transportation is also possible.

Originality – So far, an ecolabel has not been defined and applied to this level of detail and scientific rigor.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Launch of an Ecolabel for Passenger Aircraft

Task for a Master thesis according to university regulations

Background

New commercial aircraft are often advertised with many claims about their environmental advantages over reference and competitor models. These advertisement claims are often not verifiable, not based on any reporting standards (often due to a lack of such standards), and generally not backed up by reviewed scientific publications. This published PR information does not help the traveling public to choose the least environmentally damaging flight. Therefore, the concept of the Ecolabel for Passenger Aircraft was introduced as part of previous theses. It was found that aviation affects the environment most with the impact categories resource depletion and global warming (both due to fuel consumption), local air pollution (due to the nitrogen oxides emission in the vicinity of airports), and noise pollution. A calculation method was developed for each impact category based solely on official, certified, and publicly available data. To ensure that every parameter is evaluated independent of aircraft size, which allows comparison between different aircraft, normalizing factors such as the number of seats, rated thrust, and noise level limits were used.

Task

The existing Ecolabel for Passenger Aircraft should be updated and launched based on the latest available data and design considerations. ISO standards for ecolabels have to be followed. The overall environmental impact is determined by the weighted contribution of considered impact categories. For each category, a rating scale from A to G has to be updated based on the performance of the aircraft in service today. The scientific and environmental information has to be presented in an easily understandable way on the label, in a flyer, and in complete documentation. The ecolabel itself compares real aircraft in service and as such direct flights. Other tools should compare the environmental footprint when traveling between city pairs in more than one leg. It should be linked to information about the environmental footprint of other modes of transportation.

The detailed tasks are:

- Perform a brief literature study on existing and future aircraft labeling schemes.
- Discuss the ISO standards for environmental labeling and how they are applied to the "Ecolabel for Passenger Aircraft".
- Discuss and improve the existing calculation methods and calculate the environmental impact for each category (resource depletion, climate impact, ...) based on the latest available data.
- Present the environmental information in a meaningful and visually attractive Ecolabel for Passenger Aircraft, based on the EU Energy Label.
- Update and improve the existing Ecolabel Calculator. Additionally, find a way to present the environmental impact of a flight when one or more stopovers have to be made.
- Develop a comprehensible document to explain the ecolabel for Passenger Aircraft to the traveling public.

The report should be written in English based on international standards on report writing.

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List of Symbols

a	Speed of sound
B	Breguet factor
C	Fuel consumption
c	Specific fuel consumption
E	Aerodynamic efficiency
f_{km}	Fuel consumption per kilometer
g	Gravitational acceleration
h	Altitude
k	Travel class-specific weighting factor
k_H	Humidity correction factor
k_T	Temperature correction factor
L	Stage length
m	Mass
M_{cr}	Cruise Mach number
M_{ff}	Fuel fraction
m_{MZF}	Maximum zero fuel mass
m_{OE}	Operating empty mass
m_{TO}	Takeoff mass
n	Number of seats
$n_{flights}$	Number of flights
p_0	Reference pressure at sea level
p_{amb}	Ambient pressure
p_v	Saturation vapor pressure
R	Range
r	Boeing's correction factors
$\mathrm{R}_{\mathrm{air}}$	Specific gas constant for dry air
S	Seat area
s	Forcing factor
s_{LFL}	Landing field length
T_0	Reference temperature at sea level
T	Rated thrust
T_{amb}	Ambient temperature
V	Velocity
V_{TAS}	True airspeed
W_f	Total airplane fuel flow

Greek Symbols

β	Coefficient for saturation vapor pressure
γ	Adiabatic gas constant
δ	Pressure ratio (ambient to sea-level)
θ	Temperature ratio (ambient to sea level)

List of Abbreviations

AEED	Aircraft engine emissions databank
AEM	Advanced emission model
AIC	Aviation-induced cloudiness
APU	Auxiliary power unit
ATM	Air traffic management
BADA	Base of aircraft data
BC	Business class
BFFM2	Boeing fuel flow method 2
CAEP	Committee on Aviation Environmental Protection
CCD	Climb, cruise, descent
CF	Characterization factor
DGAC	Direction Générale de l'Aviation Civile française
EASA	European Union Aviation Safety Agency
EC	Economy class
EEA	European Environment Agency
EF	Emission factor
EFL	Effective floor loading
EI	Emission index
EPD	Environmental product declarations
EPNdB	Effective perceived noise in decibels
EPNL	Effective perceived noise level
EU	European Union
FAA	Federal Aviation Administration
FAR	Federal aviation regulations
FC	First class
FEIS	Fuel burn and emissions inventory system
FOI	Swedish Defence Research Agency
FP	Fuel performance
GHG	Greenhouse gas
GWP	Global warming potential
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industries Associations
IPCC	Intergovernmental Panel on Climate Change
ISA	International standard atmosphere
ISO	International Organization for Standardization
LAP	Local air pollution
LAQ	Local air quality
LAT	Latitude
LCA	Life cycle assessment

LCIA	Life cycle impact assessment
LNL	Local noise level
LON	Longitude
LTO	Landing and takeoff cycle
MLW	Maximum landing weight
MTOW	Maximum takeoff weight
MV	Metric value
MZFW	Maximum zero fuel weight
NGO	Non-governmental organization
NIV	Noise index value
NMVOC	Non-methane volatile organic compound
OEM	Original equipment manufacturer
OEW	Operating empty weight
OPR	Overall pressure ratio
OR	Overall rating
PCR	Product category rules
PDCA	Plan-do-check-act
PEC	Premium economy class
PM	Particulate matter
PNL	Perceived noise level
PURL	Persistent URL
RF	Radiative forcing
RGF	Reference geometric factor
SAF	Sustainable aviation fuel
SAR	Specific air range
SARP	Standard and recommended practice
SGTP	Sustained global temperature potential
TAS	True airspeed
TCDSN	Type certificate data sheet for noise
TEE	Trip emission ecolabel
TOW	Takeoff weight
UHC	Unburned hydrocarbons
UN	United Nations
VOC	Volatile organic compounds
WHO	World Health Organization

List of Definitions

Airway

A control area or portion thereof established in the form of a corridor. (ICAO 2007)

Aviation induced cloudiness

Aviation-induced cloudiness (AIC) is defined to be the sumx of all changes in cloudiness associated with aviation operations. (Solomon 2007)

Bathtub curve

The Bathtub Curve is a visualization of fuel consumption per passenger and 100 km flight distance over the flown distance. With this diagram, the range on which an aircraft can be operated most efficiently can be shown. The course of this curve conforms figurative to the profile of a bathtub, where the name originates. (Burzlaff 2017)

Cruise flight

Portion of a flight from the point where the aircraft has leveled off following a climb to its initial cruising altitude until the point where it commences its descent. (Young 2017)

Emission index

The mass of species emitted per kilogram of fuel burned. (Van Endert 2017)

Landing field length

The landing distance of an aircraft multiplied by a safety factor. (Scholz 2015)

Life cycle assessment

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise. (Rebitzer 2007)

Radiative forcing

Radiative forcing (RF) is the difference between the energy the earth absorbs from the sun and the energy radiated back into space and is expressed in units of Watts per square meter. (Caers 2019)

Specific air range

The still air distance traveled per unit of fuel mass consumed. (Young 2017)

1 Introduction

1.1 Motivation

The last couple of years were characterized by the ever-growing environmental awareness of humankind. With the growing focus on environmental change, there has never been this much attention on our carbon footprint. Environmental activists have changed our attitude towards flying. In Sweden, the home country of Greta Thunberg, flight shame - Flygskam in Swedish - caused the passenger numbers at the ten busiest airports to drop by more than 5% in 2019. In Germany, the number of people flying domestically even dropped by 12% in November 2019 compared to November 2018 (Farmbrough 2019).

The COVID-19 pandemic has a massive impact on global air travel. On March 22, 2020, airline capacity in Europe was down by almost 88% compared to the same day in 2019. In the first half of 2020, global air passengers declined by approximately 1.2 billion passengers (Mazareanu 2021). The drop in passenger numbers might be temporary, although many companies are changing their travel policies now that online meetings have become the standard. The question that now arises is if the "normal" situation will return and if we still want to go back to this situation of flying all over the globe for the slightest reason.

Nevertheless, aviation is still essential. Not only does it link up families, friends, and employment, but very often, flying demonstrates a time when people are happy and share time with their loved ones on hard-earned holidays. Furthermore, travel can be the best education many of us can have. Learning about different religions, countries, and history. Learning about ourselves, tolerating others, and celebrating differences (Asquith 2020).

Therefore, the main objective in aircraft development is to reduce environmental burden through more efficient and sustainable methods, planning, regulations, and new technology. The aviation sector is a growing market and is likely to expand even further. However, not only environmental protection itself is an issue. Airlines try to save fuel as it accounts for a significant part of operating costs. Moreover, there is much competition, which means that every airline is trying to find a compromise in terms of environmental impact, fuel consumption, and passenger comfort while at the same time complying with regulations and high safety standards.

For many consumer goods and services, so-called ecolabels have been established. These labels provide information about the environmental impact and the energy efficiency of specific products. An ecolabel informs consumers about how and to what extent the environment is affected by the fabrication and use of the product and allows for comparison with similar products.

In aviation, such labels are practically non-existent. Aircraft, especially the latest generation of modern commercial airliners, are often advertised with claims about their environmental advantages. However, most of these claims cannot be verified due to a lack of standards or scientific backup. In this context, the phenomenon of 'greenwashing' is observed. Greenwashing was defined by Delmas (2011) as "the intersection of two firm behaviors: poor environmental performance and positive communication about environmental performance". In order to counter this trend of greenwashing, it is time to introduce an ecolabel for aircraft. This label aims to provide a single source of easily accessible, easy-to-understand data and enable the traveling passengers to make an educated choice among different airline offers (a specific aircraft with a particular seating arrangement) such that the flight is the least environmentally damaging.

The Hamburg University of Applied Sciences started developing an ecolabel for passenger aircraft back in 2015, based on an ecolabel designed by the airline Flybe (Massy-Beresford 2007). Different students already worked on the subject, with new improvements being introduced with every new project or thesis. At this point, even EASA received a mandate to develop an environmental labeling system for aviation (EASA 2019b). In a tender, the public contract for the development of "Environmental Labelling for Aviation (aircraft, airlines, flight)" is said to be awarded. This contract will support the implementation of the project's pilot phase, focusing on refining existing metrics and developing an approach towards life cycle assessments to underpin the labels for aircraft, airlines, and flights (EASA 2021c).

1.2 Title Terminology

"Launch of an Ecolabel for Passenger Aircraft"

Launch
The Cambridge Dictionary defines the word *launch* as:

> *To begin something such as a plan or introduce something new such as a product.*

This thesis aims to present and introduce the Ecolabel for Passenger Aircraft to the general public, allowing them to make an educated choice among different airline offers when looking for a flight.

Ecolabel
The word *ecolabel* is defined by the Cambridge Dictionary as:

> *An official symbol that shows that a product has been designed to do less harm to the environment than similar products.*

This dictionary definition will, however, be slightly adjusted.

Energy Label

The European Commission designed its own EU *Energy Label*, which is defined as:

> *The energy label has been a key driver for helping consumers choose products which are more energy efficient. At the same time, it also encourages manufacturers to drive innovation by using more energy efficient technologies (European Commission 2020).*

The concept of the Energy Label as a well-established and well-known label is closest to the purpose of this thesis. However, the term ecolabel will be used to refer to the concept of the energy label as it is a shorter word and an equally well-established term.

Aircraft

The International Civil Aviation Organization (ICAO) definition (ICAO 2005) of *aircraft* is:

> *Any machine that can derive support in the atmosphere from the reaction of the air.*

Aircraft category

Additionally, ICAO (ICAO 2020b) defines the *aircraft category* as:

> *Classification of aircraft according to specified basic characteristics, e.g., airplane, glider, rotorcraft, free balloon.*

The aircraft category is defined by the rules applied for its certification, shown in the type certificate. This thesis deals with aircraft certified by FAR Part 25, Transport Category Airplanes (USA) or EASA CS-25, Large Airplanes (Europe). As such, the title of the thesis is meant more precisely as: "Launch of an Ecolabel for Passenger Transport Category Airplanes" (USA) or "Launch of an Ecolabel for Large Passenger Airplanes" (Europe). Instead, the title was kept simple, while a clarification is given here.

1.3 Objectives

A crucial objective of this thesis is to deliver an overview of the most significant environmental impacts of aviation and investigate how they can be assessed and rated using measured aircraft emission data from publicly available databases. Based on these results, the Ecolabel for Passenger Aircraft shall be finalized, taking into account ISO 14025 (2006): Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures. The required documentation related to the launch of this new type of ecolabel must be drawn up according to the principles and procedures described in the standard.

The indicators included in the label are the fuel performance, the local air pollution, the CO_2 equivalent emission, and the local noise level. Based on previous work, metrics for the different indicators have to be developed or adjusted to reflect the environmental impact of the aircraft in service today.

Additionally, the Excel tool that was introduced to calculate the ecolabel must be updated. This includes updating the pollutant emission and noise emission data using the latest available data from EASA, ICAO, and EMEP/EEA databases and updating the list of reference aircraft with the latest data on the size of the global air fleet. Finally, the database of the available aircraft-engine-airline combinations must be extended to be able to calculate as many ecolabels as possible.

The chosen environmental impact indicators should be implemented in a visually attractive label, which is easy to understand. The goal should be to provide the passenger access to the ecolabel when booking a flight. Therefore, a way has to be found to introduce the ecolabel as an extra tool in a booking engine. Additionally, the ecolabel and its components should be explained in a comprehensible way in the form of a flyer or an article in an inflight magazine.

In the end, the main objective is to help the passengers to understand that they should select a flight on the shortest possible route and select the best combination of aircraft and airline based on the ecolabel. Going even further, the ecolabel should give a foundation for a general discussion about different travel options based on neutral scientific methods and data.

1.4 Previous Research

This thesis is mainly based on previous work by Tim Haß (2015), Lynn Van Endert (2017), Sophie Sokour and Tobias Bähr (2018), and Alejandro Ridao Velasco (2020).

The ecolabel for aircraft was first defined in the bachelor thesis of Tim Haß (2015). Haß established the basis for future work on the topic. Lynn Van Endert (2017) continued the work in her master thesis by reviewing the ecolabel defined by Haß and optimizing the metrics and the design of the ecolabel. The updated label consisted of more environmental impact categories, and the design was derived from the European Union energy label, which is visually more appealing than the previous label by Haß. Finally, Sophie Sokour and Tobias Bähr (2018) improved the Excel tool to create the ecolabel that Van Endert developed by automating the transfer of the necessary data into a comprehensible label. The automation allowed for the simplified creation of ecolabels, making a more straightforward comparison between different aircraft possible.

In his bachelor thesis, Alejandro Ridao Velasco (2020) summarized all the work that had already been done. Additionally, the environmental pollution of different vehicles was discussed, including airplanes, trains, ships, and cars.

1.5 Structure of the Work

This work consists of 7 main chapters. The structure of the thesis is as follows:

Chapter 2 The starting points for the label are discussed.

Chapter 3 This chapter studies the ISO standards for environmental labels. It will clarify the requirements of the ecolabel which have to be met.

Chapter 4 The General Program Instructions are discussed as part of the required documentation for the ecolabel according to ISO 14025.

Chapter 5 A short introduction to the life cycle assessment of aircraft and the resulting environmental impact categories, as well as the development of the metric systems, formulas, and definitions, and the rating scales of each impact category are presented in this chapter.

Chapter 6 An insight is given into the design of the Ecolabel for Passenger Aircraft.

Chapter 7 This chapter explains different ecolabel tools, including the Excel tool developed to automatically create ecolabels when the correct input parameters are given and the tool to calculate the environmental impact of a complete trip (including stopovers).

Chapter 8 Different documents are introduced to help the traveling public understand the ecolabel and its purpose.

2 Starting Points

2.1 EASA Environmental Label

In an online passenger survey performed by the European Union Aviation Safety Agency (EASA) in 2019 and updated in 2020, it was found that passengers are not aware of the environmental impact of an aircraft. For example, only 5% of the more than 9500 respondents from 18 European countries know the share of aviation in the global CO_2 emissions. However, 80% of the respondents are ready to receive environmental information on the aircraft and the airline, preferably in the form of a label available during the booking process or on the boarding pass (Bauer 2020).

Today, passengers receive very little information on the actual environmental impact of aviation. As many different measures and calculation methods exist, the limited amount of information that is given is often inconsistent and contradictory (EASA 2019b).

Therefore, EASA stated that: “passengers, the general public, and people around airports should be provided with visual, relevant, consistent, and up-to-date information on aviation environmental performance as it will help to increase transparency and help passengers make more informed and more sustainable choices when they choose to fly” (EASA 2019b). To reinforce this statement, EASA is designing a grading system to grade the environmental performance of aircraft. The idea is to provide a single source of easily accessible, easy-to-understand data showing how an airlines' fleet ranks on fuel efficiency and noise (Reals 2019).

EASA aims to use data generated by the certification process for the ICAO noise and emissions standards, including the new CO_2 standard, as the basis for its grading system. Additionally, the labeling system is intended as a voluntary scheme (Reals 2019).

In a technical workshop organized by EASA in 2019, the Environmental Label Program was first introduced. The workshop provided information about the rationale, metrics, graphical concepts, and communication elements around environmental labeling for aviation (EASA 2019b). Additionally, the first concept of an environmental label for aviation was presented. This concept is also shown in Figure 2.1.

In a tender, EASA awards the public contract for the development of "Environmental Labelling for Aviation (aircraft, airlines, flight)". This contract will support the implementation of the project's pilot phase, focusing on refining existing metrics and developing an approach towards life cycle assessments to underpin the labels for aircraft, airlines, and flights (EASA 2021c). The tender is subdivided into two tasks: "Aircraft technology environmental performance and labeling" and "Airline and flight environmental performance and labeling". A task overview can be found in part II of the EASA Procurement Documents (EASA 2021c).

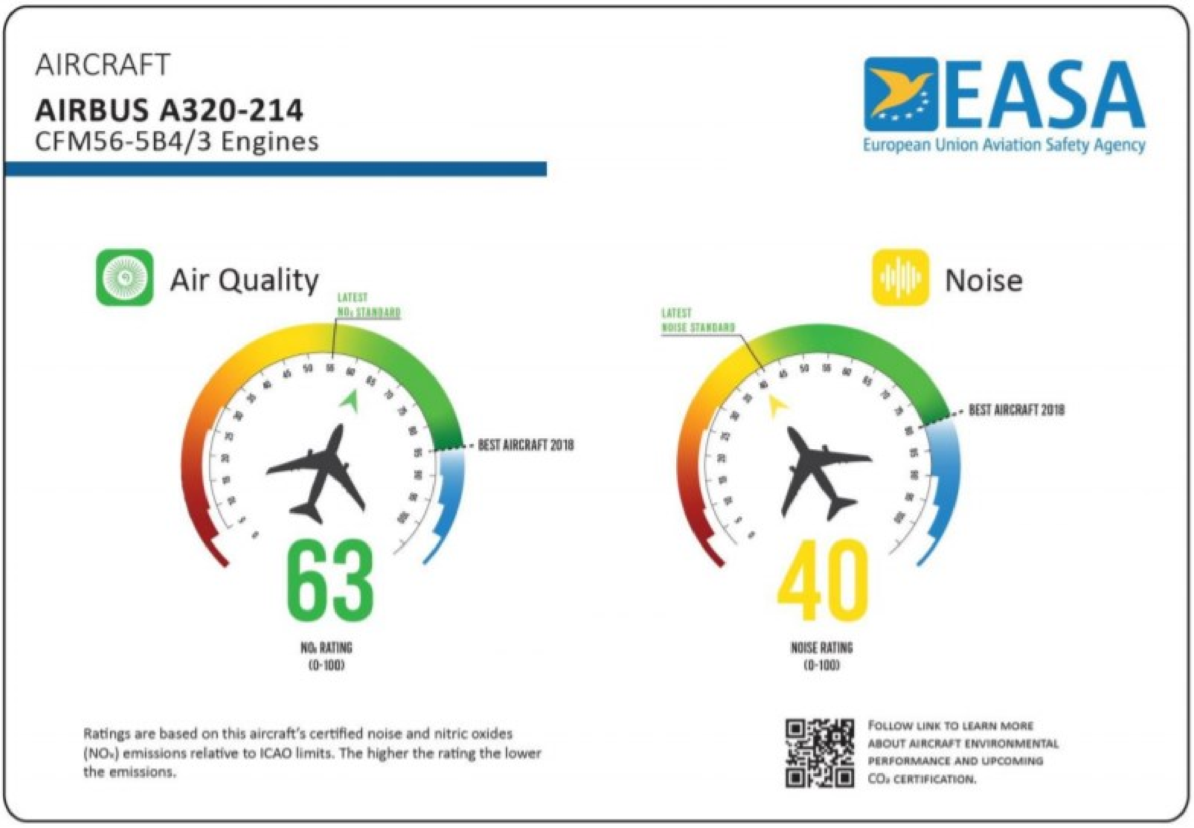

Figure 2.1 First concept of an environmental label for aviation (Bauer 2019)

2.2 Flybe Aircraft Ecolabel

The airline that first came up with an ecolabel scheme for their fleet was Flybe. In 2007, the airline introduced an ecolabel for their aircraft, which was modeled after established energy labels used on household appliances. The label was displayed on Flybe's aircraft, in the inflight magazine, in the company's advertising campaigns, and during the online ticket booking process. Other airlines were encouraged to adopt this labeling scheme; however, no other carrier adopted it (Haß 2015).

The label provides information on noise, CO_2 emissions, NO_X emission, fuel consumption, and seat pitch (legroom) and uses a rating system where emissions are related to parameters such as the number of seats in an airplane. The values are then given a score between A and F based on self-defined rating scales (Haß 2015).

The environment data included in Flybe's ecolabel is evaluated by the independent assurance company Deloitte & Touche LLP. In their assurance statement, it is mentioned that the following aspects were subject to a review of collation, aggregation, validation, and reporting (Van Endert 2017):

- Journey fuel consumption (kg) for domestic, near EU, and short-haul flights;
- CO_2 emissions during the landing and takeoff cycle (LTO) and CO_2 emissions per seat during LTO;
- CO_2-emissions kg/seat for domestic, near EU, and short-haul flights;
- NO_X emissions during the LTO cycle (kg);
- Noise rating produced by aircraft; and
- Seat pitch (inches) and number of seats onboard the aircraft.

Deloitte assures the correctness of the environmental data:

> *Based on the assurance work we performed, nothing has come to our attention that causes us to believe that the environmental performance data within Flybe's Environment Labels is materially misstated. (Van Endert 2017)*

Two examples of Flybe's ecolabel are shown in Figure 2.2.

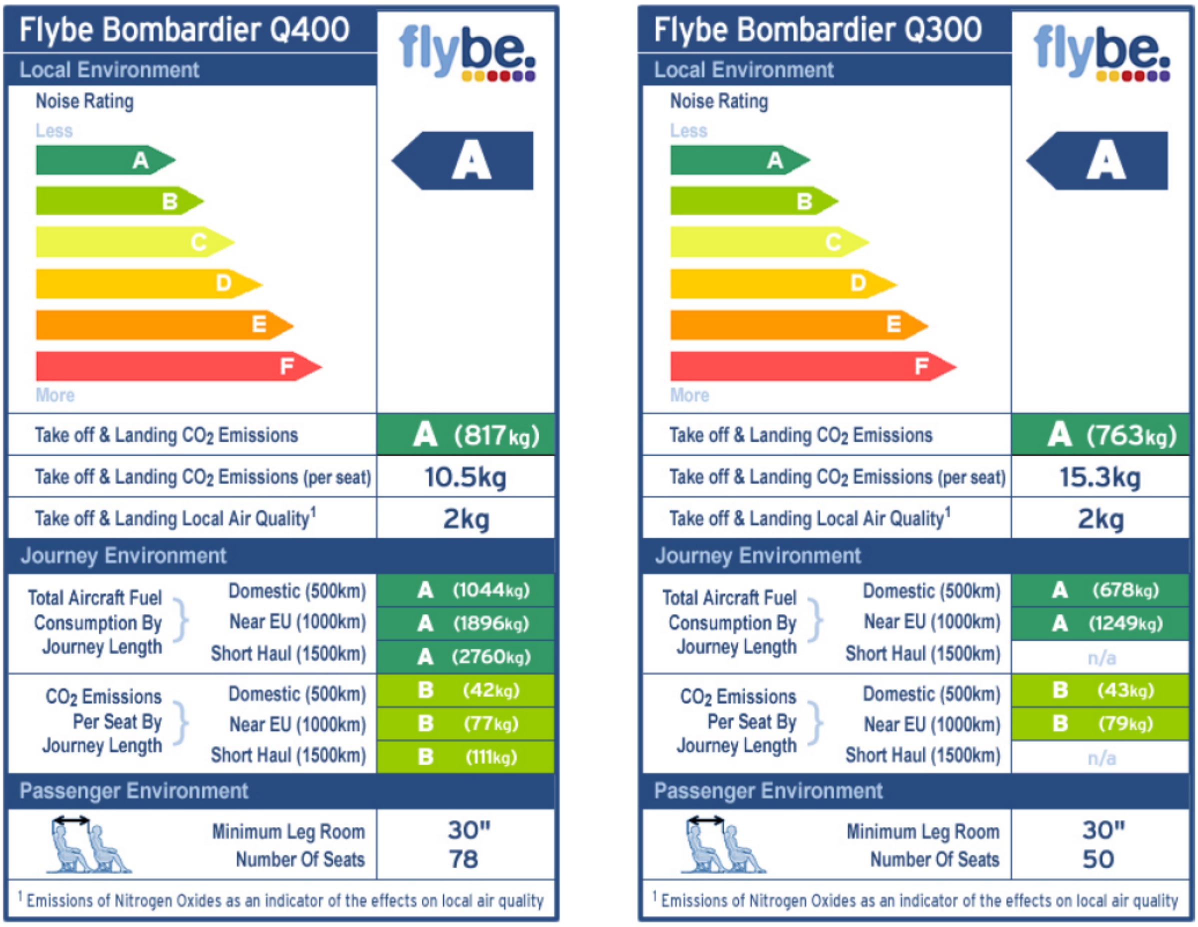

Figure 2.2 Flybe's Aircraft Ecolabel (Haß 2015)

3 ISO Standards for Environmental Management

3.1 General Overview

The International Organization for Standardization (ISO) established guiding principles for the development and use of environmental labels and declarations. These guiding principles were assembled in the ISO 14000 family of standards. The ISO 14000 family – Environmental Management is designed to be implemented according to the plan-do-check-act (PDCA) cycle (ISO Central Secretariat 2009). Within the ISO 14000 standards, a subdivision can be made into specific and more detailed standards. In the framework of this thesis, the focus will be on the ISO 14020 series of standards.

The ISO 14020 standards are aimed at the use and communication of environmental statements and claims (ISO 14020:1998). This means that ISO 14020 falls under the "Act" part of the PDCA cycle (ISO Central Secretariat 2009). More specifically, the ISO 14020 family of standards describes three types of environmental labels that are all voluntary.

The **type I** environmental labeling program was defined in ISO 14024 (1999) as:

> *Voluntary, multiple-criteria-based third-party program that awards a license that authorizes the use of environmental labels on products indicating overall environmental preferability of a product within a particular product category based on life cycle considerations.*

This standard establishes the principles and procedures for developing Type I environmental labeling programs, like selecting product categories and product environmental criteria and assessing and demonstrating compliance. ISO 14024 also establishes the certification procedures for awarding the label (ISO 14024:1999).

The objective of Type I environmental labeling programs is to contribute to a reduction in the environmental impacts associated with products by identifying products that meet specific criteria for overall environmental preferability (ISO 14024:1999).

Type II environmental labels are based on self-declared environmental claims. According to ISO 14021 (1999), the applicant may declare the environmental quality of a product without any fixed criteria, benchmarks, or quality controls. However, this declaration must be verifiable and not misleading (Suttie 2017).

The top priority of a type II label is the assurance of reliability. Verification of environmental claims must be conducted properly to avoid adverse effects, such as unfair competition, on the market. A self-declared claim should be clear, transparent, scientifically sound, and well documented. A type II label can be presented in several forms, including symbols, package labels, and official statements (ISO 14021:1999).

Finally, the **type III** environmental declarations, intended primarily for business-to-business communication, are described in ISO 14025 (2006). Type III environmental declarations provide quantified and independently verified environmental information that is not misleading, for assessing the environmental impacts of products over their life cycle. This type of environmental label is methodologically based on life cycle assessment (LCA) and developed according to a set of predefined product category rules (PCR). Type III environmental declarations should assist purchasers and users in making informed comparisons between products, fulfilling the same function (Minkov 2015).

The objective of Type III environmental declarations discussed in ISO 14025 (2006) are as follows:

- To provide LCA-based information and additional information on the environmental aspects of products;
- To assist purchasers and users to make informed comparisons between products;
- To encourage improvements in environmental performance; and
- To provide information for assessing the environmental impacts of products over their life cycle.

3.2 Findings

The type I environmental label does not meet the requirements of the ecolabel that will be discussed in this work. The ecolabel for aircraft aims to compare different airline offers with different types of aircraft and seating arrangements using metrics for different impact categories. However, a type I label is binary: either a product meets the requirements and is labeled as environmentally preferable, or it does not meet the requirements, and it is not awarded the label.

The main concern with type II labels is the fact that they are based on self-declared environmental claims. Therefore, it was chosen not to use a type II label as the self-declared environmental claims could affect the credibility of the aircraft ecolabel as an independent and reliable source of information.

Eventually, it was chosen to define the ecolabel for aircraft as a type III environmental declaration according to ISO 14025 (2006): Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures. A type III label is non-binary, nor is it self-declared. In addition, this type of label is verified by several independent parties, which adds to the credibility of the ecolabel for aircraft as an independent and reliable source of information.

3.3 Type III Environmental Declarations

The ISO 14025 (2006) standard describes several essential principles and requirements that must be met:

- The label must be entirely voluntary;
- The label must take into account all relevant environmental aspects of the product through its life cycle;
- The environmental information used for the label must be verifiable through PCR review and independent verification of the environmental declaration;
- The label must be open for interested parties; the interested parties may include manufacturers, trade associations, purchasers, consumers, non-governmental organizations (NGOs), public agencies, etc.;
- The label must be transparent to make sure the information can be understood and correctly interpreted by any person interested;
- The label must be flexible;
- The label allows comparing the environmental performance of products on a life cycle basis; and
- Anyone should be able to calculate the label.

Additionally, the principles set out in ISO 14020 (1998) shall apply.

To conduct a Type III environmental declaration program, a program operator must be selected. According to ISO 14025 (2006), the program operator can be "a company or a group of companies, an industrial sector or trade association, public authorities or agencies, or an independent scientific body". The program operator is responsible for the administration of a Type III environmental declaration program. This administration includes, but is not limited to, the following tasks (ISO 14025:2006):

- Preparing, maintaining, and communicating general program instructions guiding the administration and operation of the program (see Chapter 4);
- Ensuring that the Type III environmental declaration requirements are followed;
- Publish PCR documents and Type III environmental declarations within the program;
- Monitoring changes in procedures and documents of related Type III environmental declaration programs and revising procedures and documents when necessary; and
- Ensuring the selection of competent, independent verifiers and PCR review panel members.

The abovementioned product category rules are described in ISO 14025 (2006).

> *The PCR shall identify and document the goal and scope of the LCA-based information for the product category and the rules for producing the additional environmental information for the product category. The PCR shall also determine the life cycle stages to be included, the parameters to be included and the way in which the parameters shall be collated and reported.*

The program operator should consider the adoption of readily available PCR documents in the same product category. It was found that a PCR document for "passenger commercial airplanes" was prepared by Bombardier Aerospace (2015). This document, however, poses two problems. Firstly, this PCR is only applicable to single-aisle airplanes and does not cover twin-aisle and super large airplane categories. Secondly, the document was only valid until June of 2020. However, the PCR is being updated, but the new version was not yet published at the moment of writing. In order to avoid unnecessary work, it was decided to wait until the updated version of the PCR was published. If this updated version does not meet the requirements of this program, a new PCR document should be prepared.

The program operator must establish the verification procedure of the type III label. Because the ecolabel for aircraft is used for business-to-consumer communication, the verification must be carried out by a third party which is defined in ISO 14025 (2006) as:

> *A person or body that is recognized as being independent of the parties involved, as concerns the issues in question.*

Additionally, ISO 14025 (2006) specifies supplementary requirements for developing type III environmental declarations for business-to-consumer communication. The most essential requirements are highlighted.

- Although type III declarations are complex and require considerable documentation, no part of the required content shall be omitted or simplified.
- The environmental declaration must be available to the consumer at the point of purchase.
- The interested parties should also include representatives of both consumer interests and environmental interests.
- A third party shall carry out the required verification. The declaration shall clearly state that a third party performed the verification.

4 General Program Instructions

The general program instructions are used in the operation of the Ecolabel for Passenger Aircraft, a Type III environmental product declaration (EPD) program developed by students at the Hamburg University of Applied Sciences (HAW Hamburg). The program instructions meet the requirements of ISO 14025:2006 Environmental Labels and Declarations — Type III Environmental Declarations — Principles and Procedures."

4.1 Program Scope

The scope of the Ecolabel for Passenger Aircraft Program is to facilitate the development, verification, and publishing of Type III EPDs for different aircraft with specific engines and certain seating configurations and operated by a particular airline. The primary data used in the development of the ecolabel were extracted from European databases. Therefore, the region of interest is Europe; however, other global regions may be considered because the data can be extrapolated to include the whole world.

4.2 Program Goals and Objectives

This program aims to help the traveling public make more sustainable choices when they choose to fly by disseminating accurate and verifiable information to customers relating to the environmental impacts of the chosen products over their life cycle. The goal is to provide a single source of easily accessible, easy-to-understand data and enable the traveling passengers to make an educated choice among different airline offers (a specific aircraft with a particular seating arrangement) such that the selected flight is the least environmentally damaging. In addition, the label seeks to encourage airlines and aircraft manufacturers to supply more environmentally friendly products and to innovate.

4.3 Program Operator

The Hamburg University of Applied Sciences is the Environmental Product Declaration Program Operator. HAW Hamburg is a higher education and applied research institution located in Hamburg, Germany.

As program operator, HAW Hamburg is responsible for:

- Preparing, maintaining, and public communication of the general program instructions;
- Developing, maintaining, and public communication of the program's PCR;
- Reviewing and approving of the PCR following the requirements of ISO 14025;
- Developing, maintaining, and communicating procedures for the verification of EPD; and
- Ensuring the involvement of interested parties in the program.

4.4 Intended Audience

EPDs registered in the program are intended for business-to-consumer communication.

4.5 Interested Parties

The PCR development process shall be open to all parties interested in or affected by quantifying and/or lessening the potential environmental impacts of commercial air travel, including but not limited to material and equipment suppliers, aircraft manufacturers, airlines, customers (the flying public), educational institutions, and research facilities. Interested parties may participate by applying to serve on the PCR Committee or by submitting comments during the open consultation process. However, only those with adequate knowledge to determine environmental stresses via LCA are considered. The names of those organizations will be published.

4.6 Procedures for Definition of Product Categories

The PCR is applicable for the CPC product category: "49623- Airplanes and other powered aircraft of an unladen weight exceeding 2000 kg." This category can be divided into subgroups:

- Military airplane;
- Commercial air transport: any airplane operation involving the transport of passengers, cargo, or mail for remuneration;
- Aerial work airplane: any airplane operation used for specialized services such as agriculture, construction, and photography; and
- General aviation: any flight activity not involving commercial air transport or aerial work such as corporate aviation, business aviation, personal aviation, and recreational aviation.

The PCR will only focus on the commercial air transport category, more specifically on the transport of passengers by airplanes.

4.7 Procedure for Development and Maintenance of PCR

The PCR document will have to be developed in future work. The document shall contain:

- The intended application of the product;
- The product category definition and description;
- The goal and scope definition for the LCA of the product;
- Details of the life cycle stages (information modules) that are included;
- The procedure for inventory analysis, including the calculation rules and allocation;
- The indicators for reporting of the LCA data;
- The method by which the indicators are collated and reported in the EPD;
- The instructions for producing additional environmental information;
- The instructions on the content and format of the EPD; and
- The period of validity.

The PCR developed under the program will be valid for no longer than five years. Any interested party may submit information regarding changes that may affect the PCR at any time. The Program Operator may revise the PCR before its expiration.

4.8 Procedure for Independent Verification

A third-party panel shall review the PCR. The review panel consists of at minimum two members and a chairperson. The panel consists of an appropriate mix of students and professors of HAW Hamburg. Interested parties can join the review panel if sufficient expertise can be demonstrated.

The review panel will ensure that:

- The PCR has been developed in accordance with the ISO 14040 Series of standards, and specifically in accordance with ISO 14025, Clause 6.7.1;
- The PCR fulfills the General Program Instructions; and
- LCA-based data, together with any additional environmental information prescribed by the PCR, describe the significant environmental aspects of the products.

4.9 Periodic Review of the General Program Instructions

The Program Operator shall review the General Program Instructions at least every five years and within one year of any updates to the relevant ISO standards.

5 Defining an Ecolabel for Aircraft

In Chapter 2, the EASA Environmental Label and the Flybe Aircraft Ecolabel were discussed. These two labels are the starting points for this work. However, Hamburg University of Applied Sciences student Tim Haß (2015) already introduced a first version of the Ecolabel for Passenger Aircraft, based on the simplified LCA described by Johanning (2016), back in 2015. Lynn Van Endert (2017) continued the work in her master thesis by reviewing the ecolabel defined by Haß and optimizing the metrics and the design of the ecolabel. Therefore, the ecolabel for aircraft will assess the environmental impact of aircraft through the rating of different impact categories that will be discussed in this chapter, based on the previous work of Tim Haß (2015), Andreas Johanning (2016), and Lynn Van Endert (2017).

5.1 Life Cycle Assessment

The environmental impact of an aircraft starts with the production of the first component and continues until the final disposal of the last part of the aircraft (Johanning 2013). Therefore, to get an idea of the total environmental impact of an airplane during its life, LCA should be used. The core philosophy of LCA is that all environmental burdens associated with a product or service should be assessed, from the extraction of raw materials to waste disposal (Klöpffer 1997). LCA principles are presented in Environmental management — Life cycle assessment — Principles and framework (ISO 14040:2006).

According to ISO 14040 (2006), LCA studies can be subdivided into 4 phases:

- **Goal and scope definition**: defining the purpose and scope of an LCA study;
- **Inventory analysis**: identifying and quantifying all resources used to manufacture a particular product and all substances, whether harmful or not, released into the environment;
- **Impact assessment**: defined by ISO 14040 (2006) as:

> *a phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.*

- **Interpretation**: evaluating the findings of the inventory analysis and the impact assessment, taking into account the goal and scope of the study.

Since the environmental impact is of particular interest in the context of this work, Haß (2015) proposed the use of a Life Cycle Impact Assessment (LCIA) method called ReCiPe. The main objective of this method is to translate a long list of results from the Life Cycle Inventory analysis into a limited list of scores on impact categories that represent environmental issues of concern (PRé Sustainability 2016). These indicators are distinguished on two levels: 18 midpoint indicators and three endpoint indicators. Midpoint indicators focus on particular environmental problems, for example, climate change, terrestrial ecotoxicity, ozone formation, particulate matter formation, human toxicity, and fossil resource depletion. Endpoint indicators provide a picture of the environmental damage at a higher aggregation level, namely the impact on human health, biodiversity, and resource scarcity (RIVM 2016). An illustration of the ReCiPe method is shown in Figure 5.1.

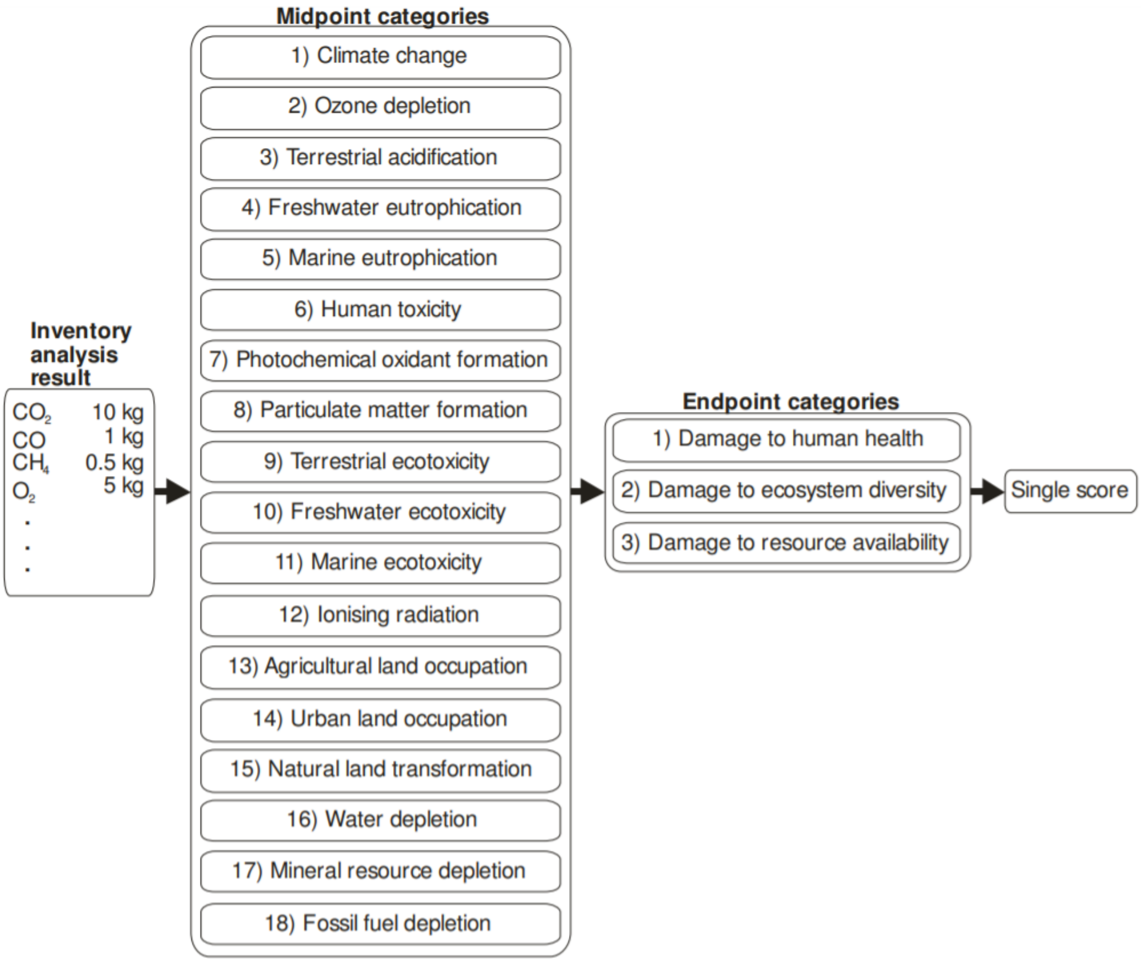

Figure 5.1 Illustration of the ReCePi method (Johanning 2014)

In determining the relevant environmental indicators for an aircraft, an important point of consideration is that commercial aircraft are usually designed to be operated intensively for several decades. Therefore, the emissions associated with airplane use are likely to account for most of the environmental impact. It was shown by Johanning (2014) that production, as well as design and development, have a negligible environmental impact during the lifetime of a commercial aircraft. Figure 5.2 gives as an example the share in the environmental impact for the different stages in the life cycle of an Airbus A320-200.

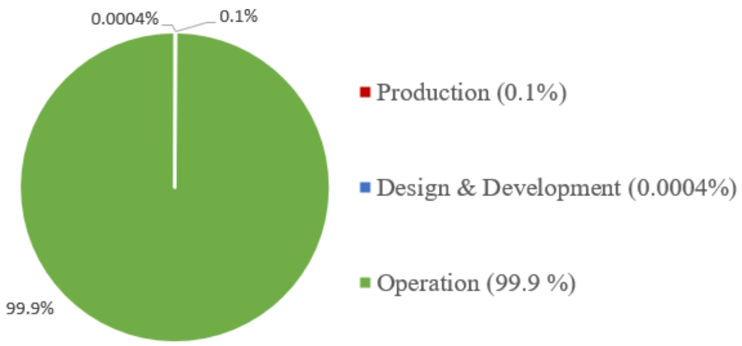

Figure 5.2 Environmental impact of life cycle phases of an Airbus A320-200 adapted from (Johanning 2014)

When calculating the total environmental impact of a flight, it is important not only to consider the cruise flight and to keep in mind additional effects like the emission of ground vehicles and the auxiliary power unit (APU). However, their impact is negligible compared to the impact of the cruise flight. Figure 5.3 summarizes the different processes and their share in the environmental impact of a flight executed with an Airbus A320-200.

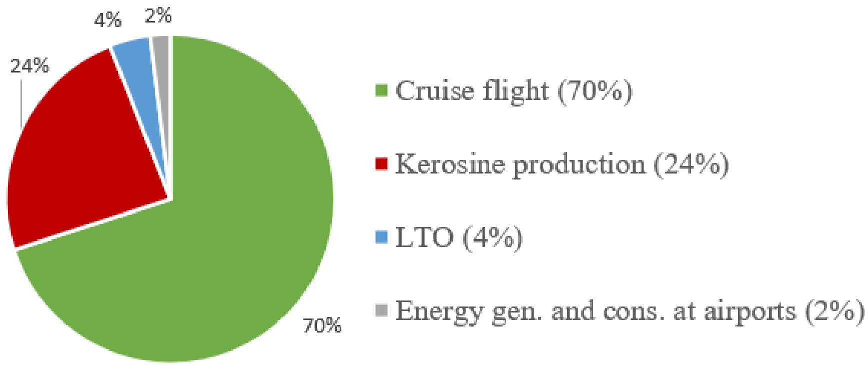

Figure 5.3 Percentage of different processes on the environmental impact of an Airbus A320-200 adapted from (Johanning 2014)

Due to fossil fuel depletion, which was considered an impact category by ReCiPe (Figure 5.1), the production of kerosine accounts for a relatively large share of the environmental impact. This can be seen in Figure 5.4, which also shows the other important impact categories: climate change and particulate matter formation (affects air quality).

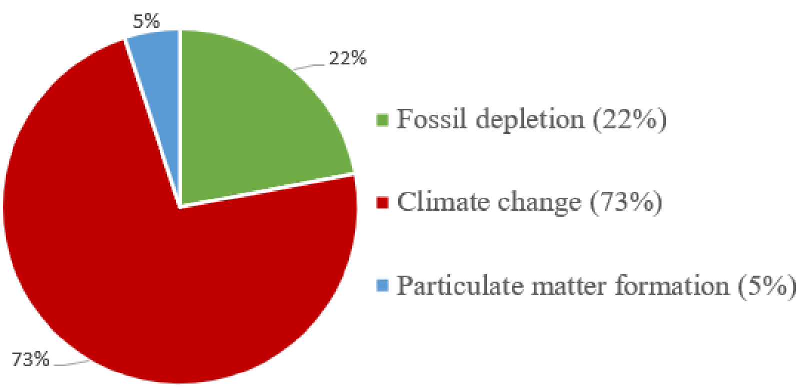

Figure 5.4 Environmental impact by impact category of an Airbus A320-200 adapted from (Johanning 2014)

LCAs generally do not take the altitude at which the emission of pollutants occurs into account. However, as most of the aircraft emissions occur during the cruise phase of a flight, the altitude should be considered. Therefore, it should be noted that the abovementioned diagrams, adopted from Johanning (2014), are based on a modified ReCiPe method, which considers the altitude-related effects of emissions (Johanning 2014). These effects will be discussed in more detail in Section 5.4.4.

The impact categories mentioned in Figure 5.4 are assumed to be relevant for all commercial airliners. This assumption is also encouraged by the publication of relevant environmental reports and articles in the aviation sector (Air Travel – Greener by Design 2005).

Transportation noise, arising from road, rail, and air traffic, can adversely affect health, quality of life, and well-being. Several effects have been associated with human exposure to noise. According to Cucurachi (2012), these effects include but are not limited to "auditory effects but also non-auditory physiological ones such as hypertension and ischemic heart disease, or psychological ones such as annoyance, depression, sleep disturbance, limited performance of cognitive tasks, or inadequate cognitive development". Although noise can have adverse effects on health, quality of life, and well-being, it is not considered an impact category by ReCiPe (Lawton 2016). Due to the high importance of noise pollution, it will be included in the ecolabel. Accordingly, the environmental impact factors that will be examined in this work are:

- Resource depletion;
- Air quality;
- Climate impact; and
- Noise Pollution.

5.2 Resource Depletion

Resource depletion was defined by Resource Center (2021) as:

> *Resource Depletion occurs when the renewable and non-renewable natural resources become scarce because they are consumed faster than they can recover. The term resource depletion is commonly associated with water usage, fossil fuel consumption, trees, and fishing.*

When talking about resource depletion in an aviation context, the shortage of oil is the main issue. A simple indicator for the contribution of aviation to oil depletion can be found in the fuel consumption of an aircraft. There may be differences in fuel consumption due to the type of fuel used, but most commercial aircraft use Jet A-1 fuel.

Although fuel consumption is a good measure for analyzing resource depletion, aircraft manufacturers rarely disclose this information. Because of this secrecy, a new standard for the fuel performance of an aircraft had to be developed.

5.2.1 Specific Air Range

A point performance metric based on the specific air range (SAR) is proposed to calculate the aircraft fuel consumption. While full mission metrics capture the total fuel burn over all phases of a flight, point performance metrics depend only on instantaneous conditions at the measurement point (Bonnefoy 2010). Therefore, the point parameters do not explicitly reflect the fuel consumed during an entire flight. However, the inherent simplicity of a point performance metric makes it attractive for this research (Bonnefoy 2010).

SAR exhibits several advantages over other methods. Firstly, it is a widely used metric for aircraft fuel efficiency. Another advantage of SAR is its independence from a specific mission. SAR measurements only require speed, altitude, weight, and atmospheric conditions, unlike full mission metrics that require many more assumptions (Bonnefoy 2010).

The Multilingual Aeronautical dictionary (AGARD 1980) defines SAR as:

> *the distance flown in still air per unit mass of fuel consumed at the instantaneous weight of the aircraft.*

SAR can also be defined as the ratio of true airspeed (TAS) and gross fuel consumption. These parameters could be measured during a test flight as part of the certification of a new aircraft, but this information is again not made publicly available. Fortunately, the so-called Breguet factor allows calculating SAR, using only publicly available data. Table 5.1 summarizes the necessary parameters and equations to determine SAR according to the mentioned methods.

Table 5.1 Determination of the Specific Air Range

Method	Specific Air Range
Measurement	$SAR = -\frac{dR}{dm} = \frac{V_{TAS}}{C_{gross}}$
Breguet factor	$SAR = -\frac{dR}{dm} = \frac{V \cdot E}{c \cdot g} \cdot \frac{1}{m_{average}}$

As shown in Table 5.1, the Breguet factor depends on the aerodynamic efficiency (*E*) and the specific fuel consumption (*c*). Because these parameters are complicated to determine, an alternative is proposed in the form of the payload-range diagram.

> *The payload-range diagram provides an envelope showing how payload capacity varies with flight range (Baxter 2018).*

These diagrams can be used according to the definition of SAR.

$$SAR = -\frac{dR}{dm} \tag{5.1}$$

$$SAR = \frac{R_2 - R_1}{m_1 - m_2} \tag{5.2}$$

Following Equation (5.2), it can be found that only four parameters are needed to calculate SAR. These parameters can easily be extracted from the payload-range diagram, which can be found in the manufacturer's airport planning document. Figure 5.5 shows an illustrative example of such a diagram where R_1 is the range at maximum payload (also called the harmonic range), m_1 is called the maximum payload, R_2 is the maximum range, and m_2 is the payload at maximum range.

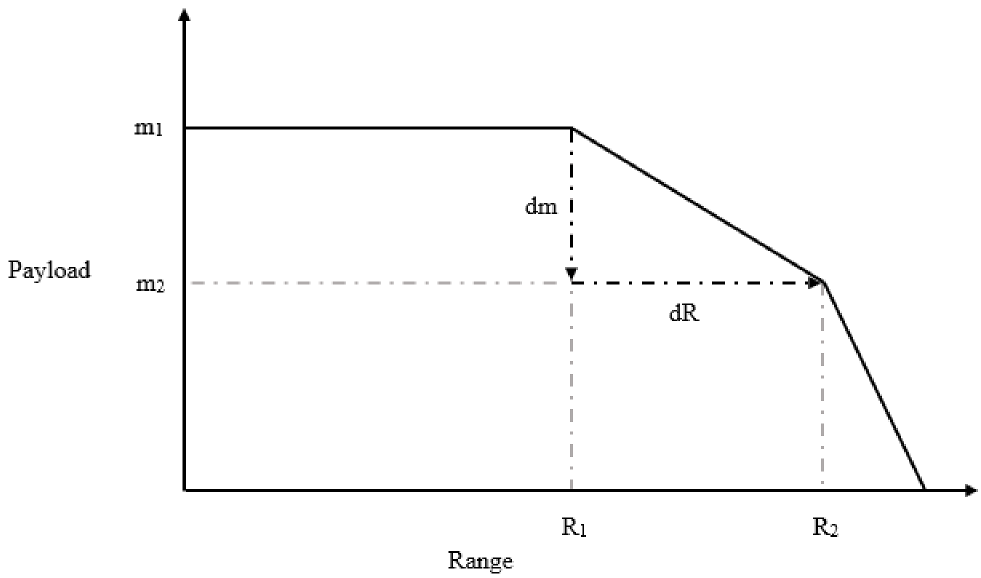

Figure 5.5 Example of a payload-range diagram (Van Endert 2017)

For every aircraft type, the aircraft manufacturer has to develop a specific document that provides helpful information about this aircraft type's characteristics. These documents are called airport planning documents and are essential for airport and maintenance planners to dimension airport infrastructure correctly. For most aircraft in service today, the airport planning document is publicly available on the manufacturer's website. The following information can usually be found in airport planning documents:

- **Aircraft description:** general characteristics, dimensions, clearances, interior arrangements, position of doors, cargo compartments;
- **Airplane performance:** payload-range diagrams, takeoff and landing conditions, runway length and requirements;
- **Ground maneuvering:** turning radii, visibility from cockpit, runway, and taxiway paths;
- **Terminal servicing:** servicing arrangements ground servicing connections, turnaround times, grounding, towing, airflow requirements, de-icing, aircraft systems;
- **Operating conditions:** jet engine exhaust velocities, temperatures and contours, and noise data; and
- **Pavement data:** landing gear footprint and loads, maximum pavement loads, pavement requirements.

The payload-range diagrams can be retrieved from the "Aircraft performance" chapter of the airport planning document. Other interesting data that will be useful in the scope of this work are also included in the document:

- Maximum takeoff weight (MTOW);
- Maximum landing weight (MLW);
- Maximum zero fuel weight (MZFW);
- Maximum and standard seat layout; and
- Landing field length (s_{LFL}).

5.2.2 Aircraft Fuel Consumption – SAR

In Section 5.2.1, the specific air range was introduced as a direct indicator of the fuel consumption of an aircraft. SAR is expressed in kilometers per kilogram, but this is not a typical unit. Therefore, taking the inverse of SAR results in the fuel consumption (reduction of the aircraft mass) per traveled kilometer, which is comparable with the units for a car's fuel consumption (l/100 km). This ratio is called fuel consumption (*C*) and is given by

$$C = \frac{1}{SAR} = \frac{m_1 - m_2}{R_2 - R_1} \quad [\text{kg/km}] \quad . \tag{5.3}$$

The previous result only gives an idea of the average fuel consumption of an aircraft. Larger and thus heavier aircraft carrying more passengers will have a higher total fuel consumption. However, the fuel consumption per passenger might be lower than in smaller aircraft. To allow for a comparison between different aircraft types, the aircraft's seating capacity should be introduced into the calculation.

A rating scale to compare the fuel consumption of different aircraft is developed. Operator-specific modifications like cabin layout may not influence the rating scale. Therefore, the fuel consumption of the different aircraft will be normalized with the default configuration of the original equipment manufacturer (OEM). This means that the inverse specific air range will be divided by the standard number of seats (n) as defined by the aircraft manufacturer.

$$C_{OEM} = \frac{1}{SAR \cdot n_{OEM}} \quad \text{[kg/km/seat]]} \tag{5.4}$$

The typical seating arrangement of an aircraft can often be found in the airport planning document. However, some airport planning documents do not mention the standard number of seats. Nevertheless, the maximum seating capacity is always included. Using the maximum seating capacity to normalize fuel consumption would cause the rating scale to be overly strict because most airliners are fitted with a number of seats that is lower than the maximum number. To overcome this issue, the typical seating of a reference group of 75 aircraft was plotted against the maximum seating capacity of these aircraft. The resulting plot is shown in Figure 5.6.

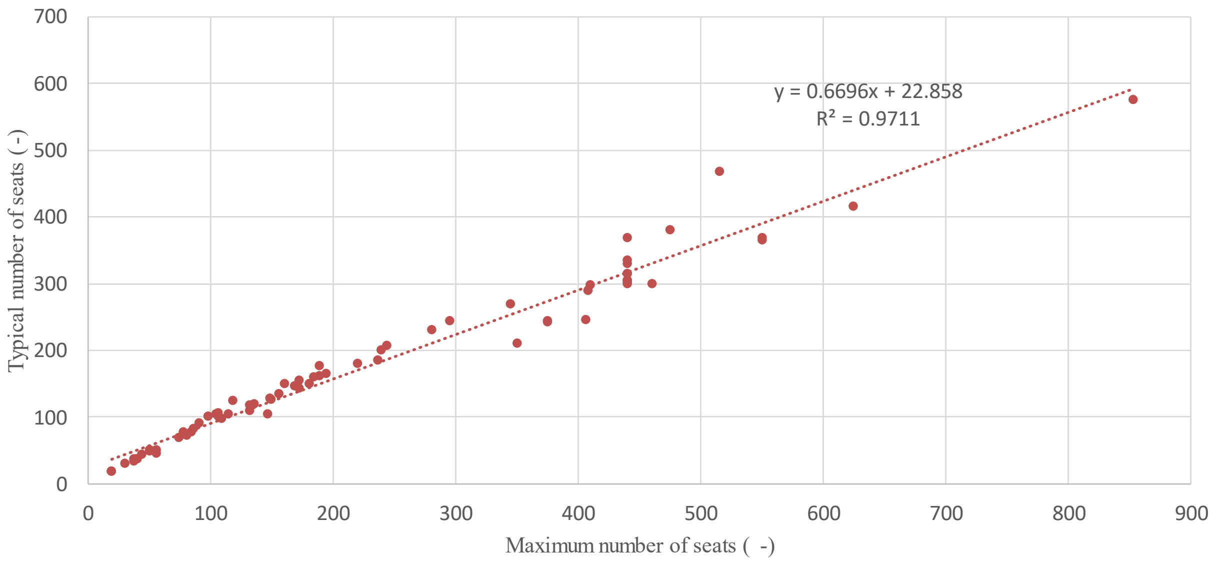

Figure 5.6 Statistic to predict the typical number of seats from the maximum seating capacity

Using linear regression, an equation can be found to estimate the typical number of seats for aircraft for which the standard seating capacity is unknown. Equation (5.5) allows estimating the typical seating capacity with a correctness of around 97%.

$$n_{OEM} = 0.6696 \cdot n_{max} + 22.858 \tag{5.5}$$

As SAR is a point performance metric, it can only be used to determine the fuel consumption at one specific point during the cruise flight (certain altitude, latitude, and speed). Therefore, Equation (5.4) does not give exact information about the amount of fuel consumed during an entire flight. However, the inherent simplicity of a point performance metric makes it attractive for this research (Bonnefoy 2010). Additionally, the main goal of an ecolabel for aircraft is to compare the environmental impact of different aircraft. As the fuel consumption for every aircraft is calculated similarly, it allows for easy comparison between aircraft. The proposed equation can thus be used as a reliable and standardized indicator for the average fuel performance.

5.2.3 Aircraft Fuel Consumption – Extended Payload-Range Diagram

The payload-range diagram discussed in Figure 5.5 can be extended by noting the following two relationships, which link the operating empty weight (OEW), MZFW, and takeoff weight (TOW) (Young 2017):

$$m_{MZF} = m_{OE} + m_{MPL} \tag{5.6}$$

$$m_{TO} = m_{ZFW} + Fuel \tag{5.7}$$

This relationship is shown graphically in Figure 5.7, which illustrates the payload–range diagram (shaded), the range as the abscissa, and the aircraft's weight as the ordinate. From point A to point B, the payload is constant, but the TOW increases as additional fuel is required for the increasing range. From point B to point C, payload is traded for fuel (TOW equals MTOW). This progressive increase in range, resulting from the increase in fuel, is possible until the maximum fuel tank capacity is reached. From point C to point D, the fuel is limited by the size of the fuel tanks, but the payload (and hence the TOW) reduces as the range increases (Young 2017).

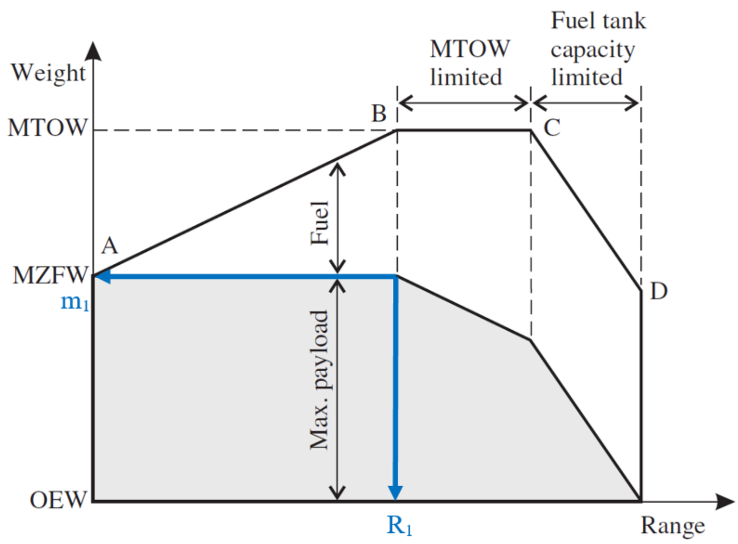

Figure 5.7 Example of an extended payload-range diagram adapted from (Young 2017)

A second point performance metric, based on the extended payload-range diagram, is proposed to calculate the aircraft fuel consumption. As previously discussed, point performance metrics do not explicitly reflect the fuel consumed during an entire flight. However, the inherent simplicity of a point performance metric makes it attractive for this research (Bonnefoy 2010).

It was chosen to determine the fuel consumption for an aircraft of mass m_I and flying a distance of R_I (also see Figure 5.5). This point in the payload-range diagram is called the design point of the aircraft. From Equation (5.7) and Figure 5.7, the consumed fuel per flown kilometer can easily be determined as:

$$C = \frac{m_{MTO} - m_{MZF}}{R_1} = m_{MTO} \cdot \left(1 - \frac{m_{MZF}}{m_{MTO}}\right) \cdot \frac{1}{R_1} \quad \text{[kg/km]} \quad . \tag{5.8}$$

The fuel consumption defined as such assumes also the reserve fuel to be used. For this reason, the fuel consumption calculated from Equation (5.8) for R_I is a little higher than the actual value. This is further discussed in Chapter 5.2.5.

A rating scale to compare the fuel consumption of different aircraft is developed. The fuel consumption of the different aircraft will again be normalized with the default configuration of the original equipment manufacturer. If the typical seating is not known, Equation (5.5) can be used to estimate the typical seating capacity. The calculated fuel consumption C will be divided by the standard number of seats as defined by the aircraft manufacturer.

$$C_{OEM} = \frac{1}{n_{OEM}} \cdot m_{MTO} \cdot \left(1 - \frac{m_{MZF}}{m_{MTO}}\right) \cdot \frac{1}{R_1} \quad \text{[kg/km/seat]} \tag{5.9}$$

Equation (5.8) represents the fuel consumption of an aircraft as a point performance metric. Therefore, it can only be used to determine the fuel consumption at one specific point during the cruise flight. However, the main goal of an ecolabel for aircraft is to compare the environmental impact of different aircraft. As the fuel consumption for every aircraft can be calculated in the same way, it allows for easy comparison between aircraft.

The main advantage of the extended payload-range diagram method over the SAR method is that the extended payload-range diagram only needs three parameters in order to calculate the fuel consumption: MTOW, MZFW, and the design range R_I. The required masses are part of the certification process of an aircraft and are therefore always available. The range R_I can be found in the standard payload-range diagram. The extended payload-range diagram method eliminates the need to study every payload range diagram in depth, and therefore any inaccuracies in reading the diagram are also avoided. In conclusion, the proposed equation can be used as a reliable and standardized indicator for the average fuel performance and as a simplified alternative to the SAR-based fuel consumption.

5.2.4 Aircraft Fuel Consumption – Bathtub Curve

The fuel consumption calculation using SAR or the extended payload-range diagram is only applicable for an airplane in the cruise condition. Calculating the fuel consumption for an entire flight, including all the stages of that flight, requires an adaptation of the Breguet factor (MacDonald 2012). The complete derivation of the formula to determine fuel consumption using this adapted Breguet factor is omitted here. Instead, only an example of a so-called bathtub curve (Burzlaff 2017) is presented, as can be seen in Figure 5.8.

The bathtub curve is a graphical representation of the aircraft fuel consumption per 100 kilometers and per seat. The curve allows determining the range for which the fuel consumption per 100 kilometers and per seat will be the lowest.

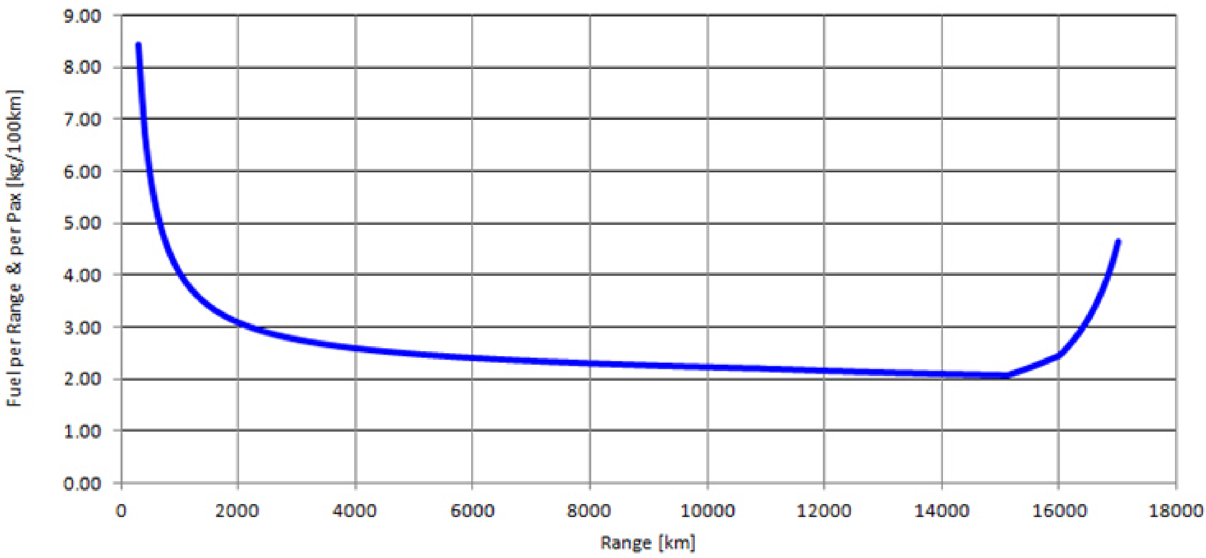

Figure 5.8 Bathtub curve for an Airbus A350-900 (Burzlaff 2017)

As previously stated, this work aims to compare the fuel consumption of different aircraft. Using the bathtub curve allows to calculate the fuel consumption, but this fuel consumption depends on the mission. In the first place, this thesis aims to obtain an ecolabel allowing to compare different aircraft, independent of the mission. An ecolabel for a flight between two airports (with or without stopover) will be discussed in Section 7.2.

Knowing that the bathtub curve allows for a more accurate determination of the fuel consumption of an entire flight, it was nevertheless decided to use the extended payload-range diagram method. However, as previously mentioned, the fuel consumption calculated using this method does not consider the fuel reserves also consumed. For this reason it is only correct for two flight distances and cannot represent the entire curve. Despite these disadvantages, the main objective, comparing different aircraft, can be achieved without the added complexity of using the bathtub curve.

5.2.5 EEA Master Emissions Calculator

For the sake of completeness, one final method for calculating fuel consumption is discussed. The European Environmental Agency (EEA) maintains a database that allows users to input a specific aircraft type and a certain stage length and returns the fuel consumption and the amount of emitted pollutants for the flight. This information is based on Eurocontrol's Fuel Burn and Emissions Inventory System (FEIS). FEIS is described by (EEA 2019) as:

> *FEIS estimates the total masses of jet fuel burnt by all the aircraft that, during the year before, made relevant flights that departed from, or arrived at, or both, an airport (or aerodrome) that is located in a relevant part of the territory of one of the 28 EU Member States.*

FEIS uses Eurocontrol's advanced emission model (AEM) to process large amounts of data in a reasonable time. The AEM processes flight movements to estimate the fuel consumption and then estimates the emissions that result from the combustion of this fuel (EEA 2019).

Below 3000 feet, the fuel consumption is calculated according to the ICAO LTO cycle methodology, which is defined by the ICAO Engine Certification specifications. The ICAO LTO cycle covers four modes of engine operation. Below this altitude, the AEM models flight movements as a series of predefined thrust levels for a defined time associated with each flight phase of the LTO cycle (Eurocontrol 2016); this is discussed in more detail in Appendix E. The fuel burn is calculated thanks to the ICAO Aircraft Engine Emissions Databank (AEED), which provides emission indices and fuel flow for many aircraft engines. As Eurocontrol has developed a table that lists an extensive range of aircraft models and the engines with which they are generally equipped, the AEM can link each flight movement to a specific engine as listed in the ICAO AEED (EEA 2019).

Above 3000 ft, the aircraft is in the climb, cruise, descent (CCD) phase of the flight. The CCD profile is described as "a sequence of straight-line segments retrieved from the updated flight plan data managed by the Eurocontrol Network Manager Operations Centre" (EEA 2019). The fuel burn calculation for each segment is based on the aircraft performance information provided by Eurocontrol's Base of aircraft data (BADA). This database provides altitude- and attitude-dependent performance and fuel burn data for more than 200 aircraft types (EEA 2019). Once the fuel consumption is calculated for each segment, the Boeing Fuel Flow Method 2 (BFFM2) is used to correct the amount of burnt fuel to the atmospheric conditions at altitude before multiplying by the emission factors (EFs). BFFM2 will be discussed in detail in Section 5.4.6.

Using the discussed method, the EEA Master Emission Calculator estimates the fuel consumption for a particular stage length. The stage length can also be defined as the length of the cruise phase of the flight. The payload-range diagram helps to determine a reference stage length that is a realistic representation of the average flight of the aircraft. Each payload-range combination demonstrates the possible missions that can be flown by a specific aircraft. To cater for network flexibility, most of the routes in an airline's network have a mission range that is considerably below the maximum mission range (Linke 2020). Figure 5.9 presents a payload-range diagram for an Airbus A320-200 and a Boeing 737-800 combined with the number of flights the airplanes executed with a specific payload-range combination.

It can be observed that almost no flight was operated with maximum payload or rather the maximum number of passengers. In addition, most of the time, the aircraft are used for relatively short routes of about 1000 NM, which deviates massively from the design range (Husemann 2018). After studying Figure 5.9, it was chosen to define the reference stage length for an aircraft as half of the harmonic range.

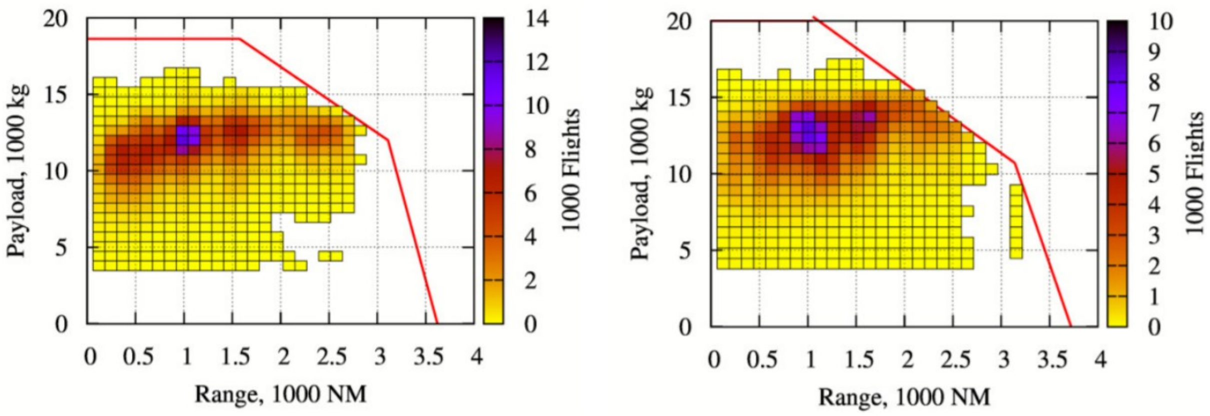

Figure 5.9 Annual number of flights and payload-range diagram of an Airbus A320-200 (left) and a Boeing 737-800 (right) (Linke 2020)

The selected stage length was used to calculate the fuel consumption for a reference group of aircraft with the EEA Master Emissions Calculator. The calculated fuel consumptions were compared to the fuel consumption determined with the extended payload-range diagram method. It was found that the fuel consumption for an entire flight is equal to the fuel consumption calculated with the extended payload-range diagram method multiplied by a factor of 0.84 with a standard deviation of 0.09. This factor is the average of all the multiplication factors for all aircraft on the list. The complete list of aircraft, including the fuel consumptions for these aircraft, is presented in Appendix A. The factor 0.84 tells us that the actual and average fuel consumption at a range R_1 is smaller than the fuel consumption calculated with Equation (5.8). The reason for that is that Equation (5.8) assumes the reserve fuel as used, and on average the range R_1 is flown with less than maximum payload.

The obtained factor can easily be used to estimate the total fuel consumption of a particular aircraft. However, it will not be used in the ecolabel in order not to overcomplicate the label. As discussed previously, this multiplication factor could be used to calculate the total fuel consumption for a specific route with a possible stopover. In this case, the potential customers can get an idea of the extra fuel consumed when traveling between two airports and making a stopover compared to a direct flight.

5.2.6 Fuel Performance Rating Scale

To be able to score fuel consumption, a rating scale should be introduced. The ultimate aim is that the fuel consumption per seat of a particular aircraft with specific engines and seating configuration will be assessed with a score from A to G. An A score is excellent, while a G score is relatively weak. Every class, from A to G, corresponds to a specific range of fuel consumptions per kilometer and per passenger.

To establish the rating scale, first, a reference group of aircraft was determined. This reference group should be a good representation of all commercial airliners in service. Therefore, the World Airliner Census 2020 was used to establish the list of reference aircraft (Cirium 2020). The World Airliner Census covers all commercial aircraft, both jet-powered and turboprop-powered, with a capacity of more than 14 passengers, that were in service in August 2020. The complete list can be found in Appendix B.

Due to the declining demand for air travel because of the COVID-19 pandemic, many aircraft were stored when the World Airliner Census 2020 was published. Therefore, the numbers in the list give a distorted picture of the actual number of aircraft in service. This is why the reference group of aircraft used in this work consists of all aircraft in service plus all aircraft in storage in August 2020. In order to keep the ecolabel up-to-date, a regular update of the group of reference aircraft is recommended.

Figure 5.10 presents the percentage of the total number of aircraft in service as a function of the total number of aircraft types included in the World Airliner Census 2020. Based on the plot, a reference group consisting of the 60 most used aircraft would represent over 95% of all commercial aircraft in service. However, it is impossible to determine the fuel consumption for every plane on the list due to a lack of available data. Therefore, the reference group was increased to 61 aircraft, for which the fuel consumption can be calculated, representing approximately 95 percent of the global commercial aircraft fleet. The entire reference group is given in Appendix C.

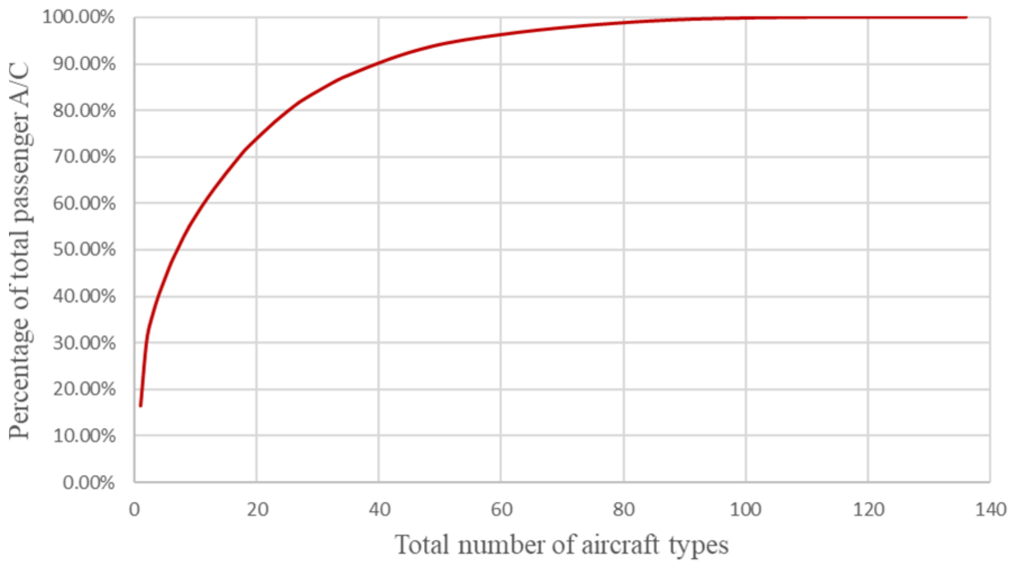

Figure 5.10 Determination of the number of aircraft in the reference group

The aircraft fuel consumption rating scale can subsequently be determined by calculating the fuel consumption for every aircraft in the reference group according to Equation (5.9). It must be noted that this fuel consumption is the amount of burnt fuel per traveled kilometer and per seat (OEM layout). The results of the fuel consumption calculations are shown in Figure 5.11. In addition, an overview of the fuel consumption for all the aircraft in the reference group is given in Appendix D.

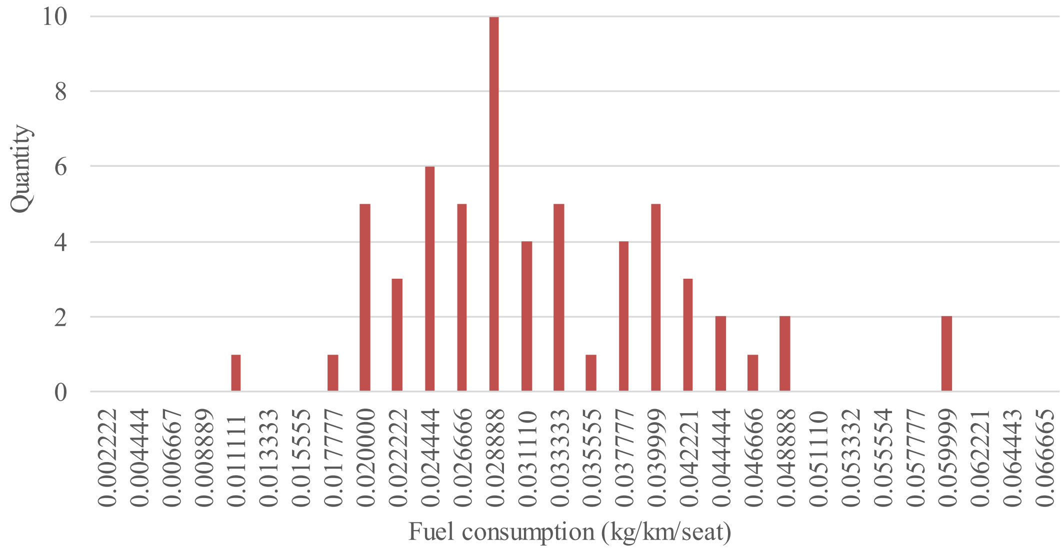

Figure 5.11 Histogram of the fuel consumption for the reference group of aircraft (kg/km/seat)

As previously mentioned, the rating scale consists of 7 classifications (A to G). The range of fuel consumptions for every classification should reflect the approximately normally distributed histogram in Figure 5.11. As there are fewer aircraft with a fuel consumption located at one of the histogram boundaries, the outer classifications should have a more extensive range than the middle ones.

To obtain the final rating scale, the calculated fuel consumptions for the reference group must be divided into the seven classes (A to G). As there are 62 aircraft in the reference group, each classification will consist of 9 reference aircraft. The calculated fuel consumptions from Appendix D must then be sorted from the lowest to the highest value. The range for every classification can now be determined: aircraft 1 to 9 will make up class A, aircraft 9 to 18 make up class B, et cetera. Eventually, the rating scale for every classification can be obtained from Table 5.2. This scale is than transformed to a normalized scale from 0 to 1. This is done by dividing the difference of the maximum and minimum value of a certain class by the difference of the maximum and minimum value of all classes.

Table 5.2 Fuel Performance rating scale (kg/km/seat)

	Range		**Normalized 0-1**	
Rating	min	max	min	max
A	0.0131	0.0241	0.0000	0.1650
B	0.0241	0.0271	0.1650	0.2101
C	0.0271	0.0297	0.2101	0.2487
D	0.0297	0.0339	0.2487	0.3113
E	0.0339	0.0398	0.3113	0.3999
F	0.0398	0.0449	0.3999	0.4762
G	0.0449	0.0798	0.4762	1.0000

5.2.7 Fuel Performance Rating

Every airline can choose the cabin configuration of their aircraft. Only in few cases, this configuration will correspond to the default seating configuration of the aircraft manufacturer. Therefore, to get a good idea of the fuel consumption per seat for an aircraft operated by a specific airline, it is essential to consider the actual number of seats installed in that aircraft. In the end, the calculated fuel consumption is rated according to Table 5.2.

$$C_{airline} = \frac{1}{n_{airline}} \cdot m_{MTO} \cdot \left(1 - \frac{m_{MZF}}{m_{MTO}}\right) \cdot \frac{1}{R_1} \quad \text{[kg/km/seat]} \qquad (5.10)$$

5.2.8 Travel Class Rating

The fuel performance rating, determined in the previous sections, only considers the total number of seats onboard an aircraft but does not consider which travel classes are available. This results in an average fuel consumption per seat. However, the more comfort and, therefore, the more space per seat is desired, the larger the fuel consumption per seat. This is reflected in the travel class rating.

A weighting factor that depends on the travel class should be introduced to achieve a travel class rating. For example, a factor of 1 would mean that every seat in the aircraft belongs to the same class. If the factor is greater or smaller than 1, the fuel consumption per seat will also be greater or smaller than the average fuel consumption. The introduced factor should measure the proportional use of the class concerning the total capacity of the aircraft. A suitable parameter to describe this is the surface area occupied by each seat.

For a specific travel class, the seat surface area (S_{class}) can be defined as the seat pitch multiplied by the seat width, which can both be obtained from the SeatGuru seat map database.

$$S_{class} = (seat\ pitch)_{class} \cdot (seat\ width)_{class} \tag{5.11}$$

Most airliners are fitted with a 2- or 3-class configuration, but generally, there are four possible classes:

- Economy Class (EC);
- Premium Economy Class (PEC);
- Business Class (BC); and
- First Class (FC).

The total area occupied by seats can thus be described as

$$S_{total} = S_{EC} \cdot n_{EC} + S_{PEC} \cdot n_{PEC} + S_{BC} \cdot n_{BC} + S_{FC} \cdot n_{FC} \quad . \tag{5.12}$$

The total number of seats for all classes combined (n_{total}) can subsequently be defined as

$$n_{total} = n_{EC} + n_{PEC} + n_{BC} + n_{FC} \quad . \tag{5.13}$$

Combining Equations (5.12) and (5.13) allows the class-specific seat ratio to be determined. This ratio is given by

$$\frac{S_{class} \cdot n_{class}}{S_{total}} = \frac{S_{class} \cdot n_{class}}{S_{EC} \cdot n_{EC} + S_{PEC} \cdot n_{PEC} + S_{BC} \cdot n_{BC} + S_{FC} \cdot n_{FC}} \quad . \tag{5.14}$$

Finally, the class-specific weighting factor (k) can be determined by dividing the class-specific seat ratio by the ratio n_{class}/n_{total}.

$$k_{class} = \frac{S_{class} \cdot n_{class}}{S_{EC} \cdot n_{EC} + S_{PEC} \cdot n_{PEC} + S_{BC} \cdot n_{BC} + S_{FC} \cdot n_{FC}} \div \frac{n_{class}}{n_{EC} + n_{PEC} + n_{BC} + n_{FC}} \tag{5.15}$$

$$k_{class} = \frac{S_{class} \cdot n_{class}}{S_{EC} \cdot n_{EC} + S_{PEC} \cdot n_{PEC} + S_{BC} \cdot n_{BC} + S_{FC} \cdot n_{FC}} \cdot \frac{n_{EC} + n_{PEC} + n_{BC} + n_{FC}}{n_{class}} \tag{5.16}$$

$$k_{class} = n_{total} \cdot \frac{s_{class}}{s_{total}} \tag{5.17}$$

The class-specific weighting factor k_{class} can be multiplied by the average fuel consumption per seat to obtain the travel class-specific fuel consumption per seat of the chosen class. This fuel consumption can then again be rated on a scale from A to G, according to Table 5.2.

$$C_{class} = \frac{k_{class}}{n_{airline}} \cdot m_{MTO} \cdot \left(1 - \frac{m_{MZF}}{m_{MTO}}\right) \cdot \frac{1}{R_1} \quad \text{[kg/km/seat]} \tag{5.18}$$

In Equation (5.18), $n_{airline}$ represents the number of seats of the chosen travel class for a specific airline. This parameter can therefore be seen as equal to n_{total}.

5.3 Air Quality

The Local Air Quality (LAQ) focuses on human health in the vicinity of airports. Near airports, the air quality is affected by the emission products generated by fuel combustion in aircraft engines. These emission products can harm the well-being of humans as well as the balance of fauna and flora (EASA 2019a).

Health problems are caused mainly by the inhalation of particles and ozone. Once the particles enter the human body through the respiratory system, diseases such as cancer and respiratory infections may develop. A distinction is made between two types of particulate matter (PM). Primary particulate matter is defined as the particles that are emitted directly into the air. When the particles are formed by a chemical reaction of gaseous pollutants such as nitrogen oxides (NO_X), it is defined as secondary particulate matter (WHO 2014). Reactions of NO_X can form ozone which can cause inflammation of the airways and damage to the lungs.

5.3.1 Aircraft Emissions

The air quality in the vicinity of airports is not only impacted by aircraft engine emissions, but also by emissions from ground equipment, road transport to and from the airport, and airport on-site energy generation and heating (EASA 2019a). However, emissions from aircraft engines are generally considered to be the dominant source of airport emissions. Burning Jet A-1 fuel primarily produces carbon dioxide and water. The very high temperatures associated with engine combustors causes oxidation of atmospheric nitrogen, which in turn drives the formation of NO_X, while the presence of traces of sulfur, nitrogen, and some metals in fuels and non-ideal combustion condition within engines lead to the production of pollutants, such as sulfur oxides (SO_X), additional NO_X, unburnt hydrocarbons (HC), carbon monoxide (CO), PM, and soot (Masiol 2014). This is illustrated in Figure 5.12 for a 1-hour flight with 150 passengers. An overview of the aviation-related emission products is given in Table 5.3.

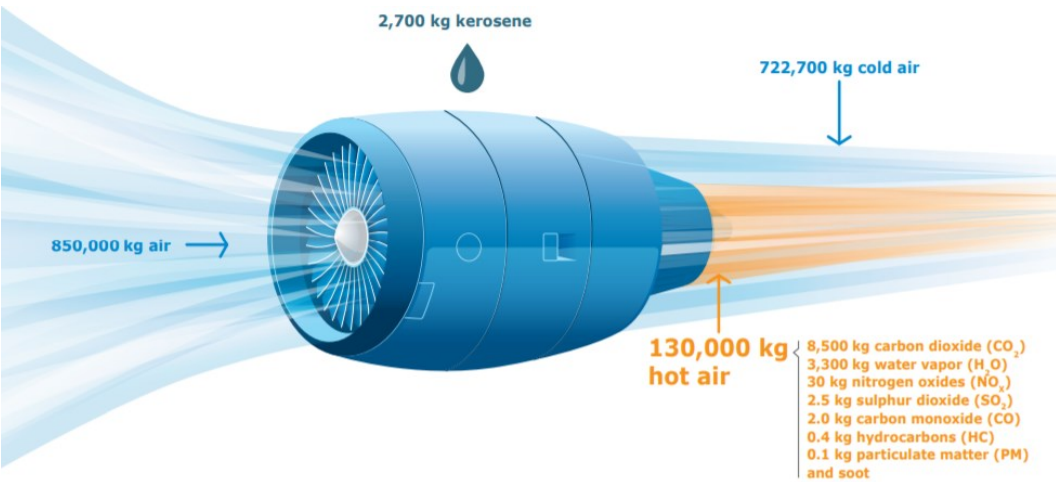

Figure 5.12 Emissions from a 2-engine jet aircraft during 1-hour flight with 150 pax (EASA 2019a)

Table 5.3 Aviation-related emissions (FAA 2015)

Emission product	Description	Emission source	Impacts
CO_2	Carbon dioxide is the product of the complete combustion of hydrocarbon fuels. Carbon in fuel combines with oxygen in the air to produce CO_2.	• Aircraft • APU • Vehicles • Stationary power plants	• Climate change
H_2O	Water vapor is the other product of complete combustion. Hydrogen in the fuel combines with oxygen in the air to produce H_2O. This is the source of water in contrails.	• Aircraft • APU • Vehicles • Stationary power plants	• Climate change
NO_X	Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_X. Contributes to ozone and secondary PM formation.	• Aircraft • APU • Vehicles • Stationary power plants	• Air quality • Climate change
HC	Hydrocarbons are a result of incomplete fuel combustion. Often referred to as unburned HC (UHC) or volatile organic compounds (VOC). Contribute to ozone formation.	• Aircraft • APU • Vehicles • Stationary power plants	• Air quality
CH_4	Methane is the most basic hydrocarbon. Commercial aircraft are net consumers of methane during cruise and are not listed in the emissions source column. The net impact of methane from airport sources is highly dependent on local circumstances.	• APU • Vehicles • Stationary power plants	• Air quality
CO	Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel. Contributes to ozone formation.	• Aircraft • Vehicles	• Air quality
SO_X	Sulfur oxides are produced when small quantities of sulfur, present in essentially all petroleum fuels, combine with oxygen from the air during combustion. Contributes to secondary particulate matter formation.	• Aircraft • APU	• Air quality • Climate change
Particulate Matter (non-volatile)	Small particles of soot that form as a result of incomplete combustion and aerosols from condensed gases, which are small enough to be inhaled	• Aircraft • APU • Vehicles • Stationary power plants	• Air quality • Climate change

In 2016, aviation was accountable for 3.6% of the total European Union (EU) greenhouse gas (GHG) emissions and for 13.4% of the emissions from transport (EASA 2019a). This is also shown in Figure 5.13. GHG emissions from aviation in the EU are increasing and have more than doubled since 1990. Additionally, aviation is also an important source of air pollutants, especially of NO_X and PM. In 2015, it accounted for 14% of all NO_X emissions related to transport in the EU and 7% of the total EU NO_X emissions (EASA 2019a). In absolute terms, NO_X emissions from aviation have doubled since 1990 (EASA 2019a). Although only a tiny fraction of aircraft engine emission products are pollutants, they still affect the environment. Nitrogen oxides are the most severe, and that is why a particular focus is directed at them.

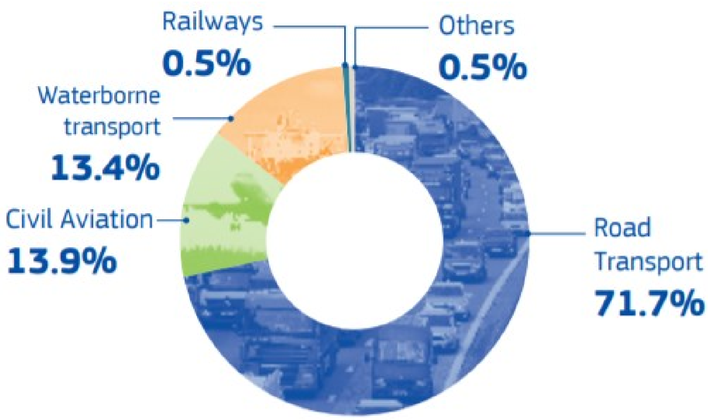

Figure 5.13 Share of GHG Emissions for different modes of transport in 2017 (European Commission 2019)

The emission products CO_2, H_2O, and SO_X are directly related to fuel consumption. This means that the emitted masses of CO_2, H_2O, and SO_X are directly proportional to the amount of fuel consumed, regardless of the engine type (Penner 1999). The relationship between the mass of emission products resulting from the combustion of one kilogram of fuel can be defined as the Emission Index (EI) (AGARD 1980). The EI is a constant value that is independent of altitude or engine performance. Table 5.4 gives an overview of the emission indices for CO_2, H_2O, and SO_X.

Table 5.4 Emission indices (Penner 1999)

Emission product	Emission index (kg/kg fuel)
CO_2	3.16
H_2O	1.23
SO_X	$2.00 \cdot 10^{-4}$

Other emission products such as NO_X cannot be assessed so easily because their production depends on the efficiency with which fuel is burned. This efficiency depends on the engine design, so each engine type and generation must be assessed separately. In addition, the operating condition and the thrust setting play a crucial role in the actual amount of emitted products.

5.3.2 Effects on Air Quality

To determine a metric for the local air quality, predefined characterization factors from ReCiPe are employed. As discussed in Section 5.1, the main objective of this method is to translate a long list of results from the Life Cycle Inventory analysis into a limited list of scores on environmental indicators. These indicators are distinguished on two levels: 18 midpoint indicators and three endpoint indicators. Midpoint indicators focus on particular environmental problems, for example, climate change, terrestrial ecotoxicity, ozone formation, human toxicity, and fossil resource depletion. Endpoint indicators provide a picture of the environmental damage at a higher aggregation level, namely the impact on human health, biodiversity, and resource scarcity (RIVM 2016).

LAQ focuses on human health in the vicinity of airports. Therefore, only the midpoint categories with impact on human health are considered: climate change, photochemical oxidant formation, particular matter formation, human toxicity, and ionizing radiation (RIVM 2016).

Climate change will be discussed in Paragraph 5.4. Only two of the four remaining categories are directly caused by aviation: particulate matter formation and photochemical oxidant formation. Therefore, Van Endert (2017) based the metric of the evaluation of LAQ on Non-Methane Volatile Organic Compound (NMVOC) equivalents or ozone formation potential equivalents and PM-equivalents (particulate matter formation potential), which are calculated by converting relevant emission products and by the NO_X emissions.

Table 5.5 Characterization factors ReCiPe (Goedkoop 2013)

Midpoint category	NO_X	SO_2	PM	CO	HC
Photochemical oxidant formation (ozone)	1.000	0.081	-	0.046	0.467
Particulate matter formation	0.220	0.200	1.000	-	-

When converting the two midpoint categories to the endpoint category 'Human health', it was observed by Goedkoop (2013) that the environmental impact of the ozone formation potential is relatively low compared to the impact of PM. Comparing the amount of particulate matter to the amount of emitted NO_X shows that the NO_X production is remarkably higher. This also becomes evident by considering that the mass of emitted NO_X is significantly larger. Therefore, it can be concluded that the impact of the NO_X is more significant than the impact of the particulate matter and ozone formation potential. This makes the emitted NO_X the critical indicator in the evaluation of LAQ.

Due to their more negligible impact on the environment and for simplicity, it was chosen not to include the ozone and PM formation in the ecolabel. Therefore, the local air pollution rating will solely be based on the NO_X emission.

5.3.3 Local Air Pollution Rating

The local air pollution rating is calculated for a complete LTO cycle as defined in Appendix E. The landing and takeoff cycle consists of four phases of aircraft operations: approach, taxi, takeoff, and climb (ICAO 2020a). As discussed in the previous section, the local air pollution rating will only be based on the NO_X emission of aircraft engines during this LTO cycle.

The emitted NO_X during the LTO cycle for a specific engine can directly be obtained from the ICAO AEED. This databank contains information on exhaust emissions of production aircraft engines, measured according to the procedures in ICAO Annex 16, Volume II (ICAO 2017b). The databank covers emission-regulated engine types, namely turbojet and turbofan engines with a static thrust greater than 26.7 kilonewtons. The information is provided by the engine manufacturers, who are solely responsible for its accuracy (EASA 2021a).

Since the NO_X emission during the LTO cycle can easily be obtained from the ICAO databank, the calculation of the Local Air Pollution is relatively straightforward. To allow for comparisons between different aircraft and engine types, which is the primary goal of the ecolabel, the NO_X emissions should be normalized with a factor that represents the engine capability. Therefore, the amount of emitted NO_X is divided by the maximum rated thrust of the engine at sea level.

$$Normalized\ amount\ of\ emitted\ NO_X = \frac{(NO_X)_{LTO}}{Rated\ thrust} \tag{5.19}$$

A different way of normalizing the NO_X emission is by dividing it by the number of seats in the aircraft cabin. This would be a better fit for the ecolabel as the fuel metric is also a "per seat" metric. However, this poses a problem for the drafting of the rating scale. Suppose the NO_X emission of a particular engine needs to be divided by a number of seats, then the engine type should be coupled to one specific aircraft type. The problem with this is that one engine type can be used on different aircraft types with different seating configurations. Therefore, it would overcomplicate the calculation for the rating scale. Additionally, ICAO Annex 16, Volume II (ICAO 2017b), as well as the Committee on Aviation Environmental Protection (CAEP), present limits for the NO_X emission depending on the rated thrust of the engine and the overall pressure ratio (OPR). This is also shown in Figure 5.14. The figure presents the NO_X emission per kilonewton of rated thrust as a function of the overall pressure ratio. Therefore, it can be concluded that the unit of g/kN is quite common. In order to be consistent with other sources, the air quality will be expressed in g of NO_X/kN of thrust.

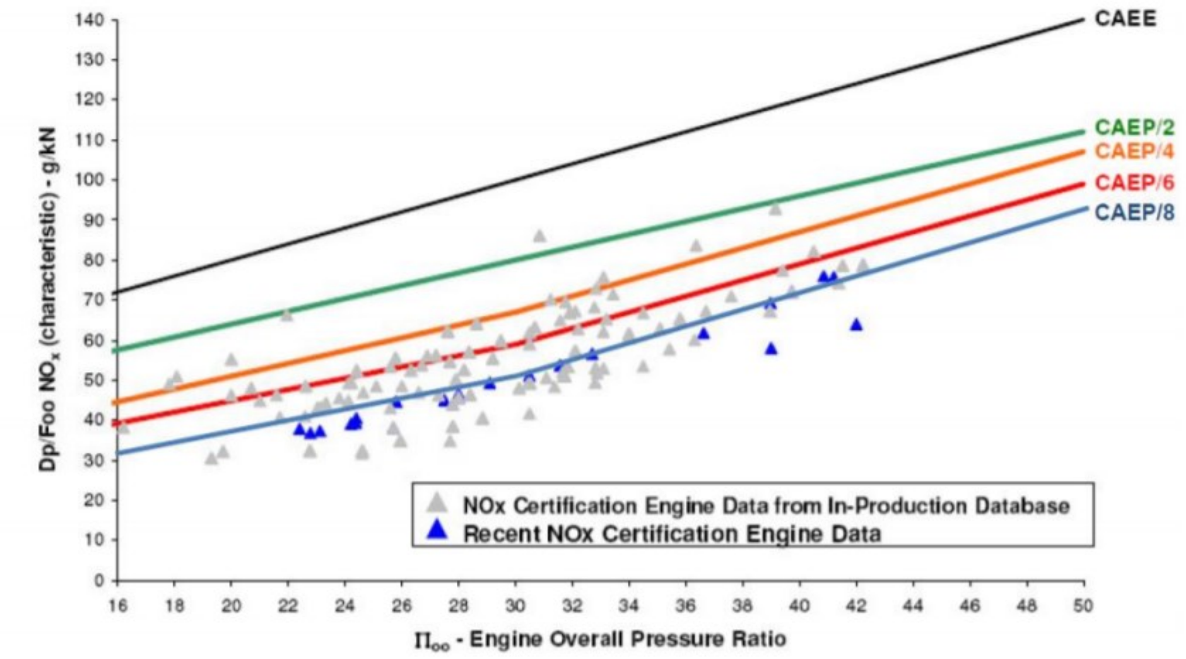

Figure 5.14 Normalized NOx emission (g/kN) as a function of the overall pressure ratio (ICAO 2014)

Defining the rating scale is again done by calculating the normalized NOx emission for every engine in the ICAO AEED. This results in a normalized NOx emission during the LTO cycle for 787 engine types, shown in Figure 5.15.

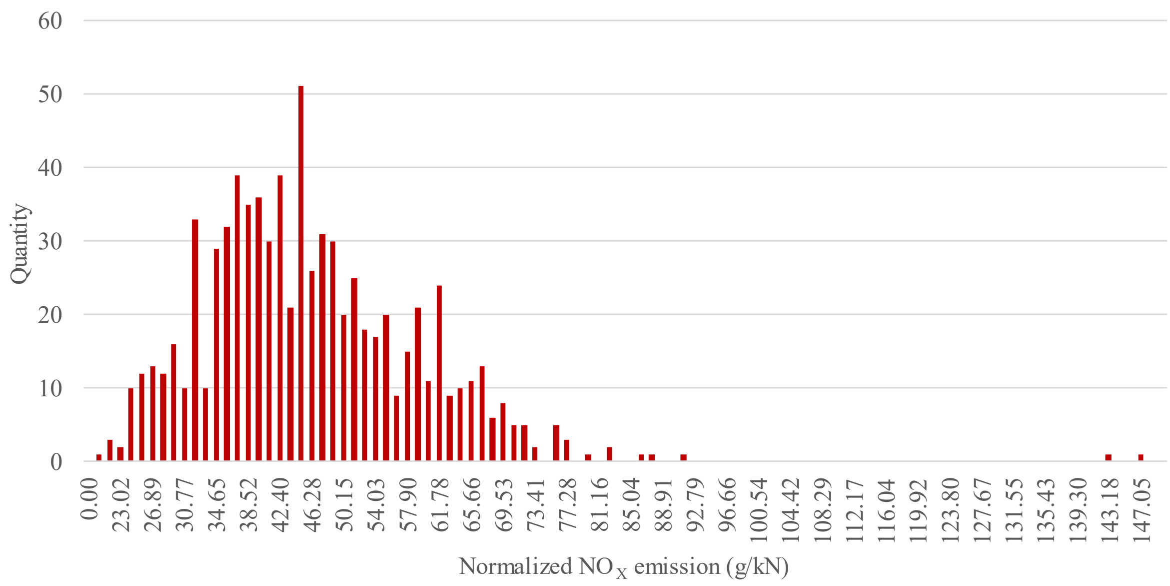

Figure 5.15 Normalized emitted NOx for the LTO cycle (g NOx/kN thrust)

The list of calculated values, sorted from minimum to maximum, determines the range of values for every class (A to G). As there are seven classes, the 787 values are divided into seven groups of 112 engines. The resulting Local Air Pollution rating scale is given in Table 5.6.

Table 5.6 Local Air Pollution rating scale (g NO_X/kN thrust)

	Range		Normalized 0-1	
Rating	min	max	min	max
A	20.4348	33.2583	0.0000	0.0662
B	33.2583	38.7102	0.0662	0.0943
C	38.7102	43.0263	0.0943	0.1166
D	43.0263	46.9653	0.1166	0.1369
E	46.9653	52.5600	0.1369	0.1658
F	52.5600	61.2618	0.1658	0.2107
G	61.2618	214.2387	0.2107	1.000

It must, however, be noted that the ICAO AEED only contains emission data for regulated engine types, namely turbojet and turbofan engines. Emission data for turboprop engines are not publicly available (EASA 2021a). Therefore, the Local Air Pollution rating cannot be calculated for turboprop-powered aircraft using publicly available data.

Nonetheless, the Swedish Defense Research Agency (FOI) maintains a confidential database of emission indices of NO_X, HCs, and CO. Turboprop engine manufacturers have supplied the datasheets in this database, initially to calculate emissions-related landing charges (EEA 2019). The data are presented in the same format as the ICAO Engine Emissions Databank but have not been endorsed by ICAO in a certification process. In addition, it should be noted that the data have many inaccuracies resulting primarily from the unregulated test methodologies. The data are, however, considered as being the best available (FOI 2019).

Since the emission data for turboprop engines are not publicly available and the reliability of the results in the FOI database is questionable, it was chosen not to calculate the Local Air Pollution for turboprop-powered aircraft.

5.4 Climate Change

As described in Paragraph 5.3, operating an aircraft can impact the environment in many ways. It was previously shown in Figure 5.3 that ground operations related to a flight of an Airbus A320-200 only account for around 2% of the environmental impact of the aircraft. Therefore, only the impact of flying the aircraft will be considered in this section. Indirect impact factors or emissions from ground transport at airports, for example, are being neglected.

The most critical emissions related to a flight are the measurable emissions from the combustion of Jet A-1 fuel. These emissions consist of carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_X), and other particulates like sulfur oxides (SO_X) and soot (Masiol 2014). These gasses and particulates are directly emitted into the atmosphere at the cruising altitude, which in practice often corresponds to the tropopause level.

5.4.1 Radiative Forcing

The previously mentioned emission products will have an impact on the climate. However, this climate impact is a lot harder to measure than the emissions themselves. Through radiative forcing (RF), the climate impact of emission components can be compared mutually or to the climate impact of other industries (Caers 2019). RF is the difference between the energy the earth absorbs from the sun and the energy radiated back into space and is expressed in units of Watts per square meter (Caers 2019). When the incoming energy is greater than the outgoing energy, the planet will warm (positive RF). Conversely, the planet will cool if the outgoing energy is greater than the incoming energy (NOAA 2021). This balance between absorbed and reflected energy determines the average global temperature and can be influenced by GHGs. Thus, RF makes it possible to measure climate change in a quantitative way (Caers 2019).

RF is generally determined for a longer period. However, RF cannot reflect the impact of a single flight; instead, it calculates the total influence of all aviation-related emissions during a predefined period, in most cases 100 years (Jardine 2005). For this reason, RF will not be used to measure the environmental impact of a single flight. Instead, a new metric called CO_2 equivalent will be introduced in Section 5.4.4.

The first comprehensive report on the aviation industry's environmental impact was published in 1999 by the Intergovernmental Panel on Climate Change (IPCC), the United Nations (UN) body for assessing the science related to climate change (Penner 1999). The report handles the direct and indirect effects of the aviation industry on the climate (Penner 1999). These effects are put into quantitative results by using radiative forcing, albeit with relatively high levels of uncertainty. Table 5.7 describes the environmental impact of the previously discussed emission products using the radiative forcing.

Table 5.7 Climate impact of different emission products (Penner 1999)

Emitted Species	Role and Major Effect at Earth's Surface
CO_2	*Troposphere and Stratosphere* Direct radiative forcing ⟶ warming
H_2O	*Troposphere* Direct radiative forcing ⟶ warming Increased contrail formation ⟶ radiative forcing ⟶ warming *Stratosphere* Direct radiative forcing ⟶ warming Enhanced PSC formation ⟶ O_3 depletion ⟶ enhanced UV-B Modifies O_3 chemistry ⟶ O_3 depletion ⟶ enhanced UV-B
NO_X	*Troposphere* O_3 formation in upper troposphere ⟶ radiative forcing ⟶ warming ⟶ reduced UV-B Decrease in CH4 ⟶ less radiative forcing ⟶ cooling *Stratosphere* O_3 formation below 18-20 km ⟶ reduced UV-B O_3 formation above 18-20 km ⟶ enhanced UV-B Enhanced PSC formation ⟶ O_3 depletion ⟶ enhanced UV-B
SO_XO and H_2SO_4	*Troposphere* Enhanced sulfate aerosol concentrations Direct radiative forcing ⟶ cooling Contrail formation ⟶ radiative forcing ⟶ warming Increased cirrus cloud cover ⟶ radiative forcing ⟶ warming Modifies O_3 chemistry *Stratosphere* Modifies O_3 chemistry
Soot	*Troposphere* Direct radiative forcing ⟶ warming Contrail formation ⟶ radiative forcing ⟶ warming Increased cirrus cloud cover ⟶ radiative forcing ⟶ warming Modifies O_3 chemistry *Stratosphere* Modifies O_3 chemistry

One area where the IPCC report falls short is its accuracy of the effect of aviation-induced cloudiness (AIC). AIC includes the formation of contrails and aircraft-induced cirrus clouds. In an update (Sausen 2005) to the IPCC report, based on the TRADEOFF project, the radiative forcing of AIC was strongly reduced by a factor of three to four while increasing the accuracy of the results. Figure 5.16 shows a comparison of RF values for different emission products.

Figure 5.16 shows that CO_2 and NO_X emissions combined with AIC make up the majority part of aviation-induced radiative forcing. Therefore, these three types of emissions will be used to calculate the rating scale of the climate impact in the ecolabel. The other components have a more negligible environmental impact and will not be considered.

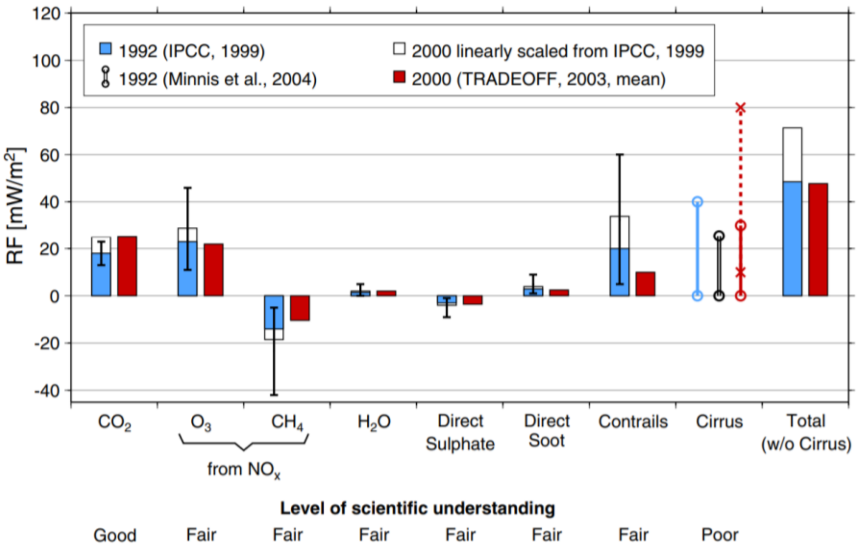

Figure 5.16 Radiative forcing values for different emission products (Sausen 2005)

5.4.2 Aviation-Induced Cloudiness

Condensation trails result from water vapor in the exhaust gasses of jet aircraft flying at typical cruise altitudes of 10-12 kilometers (Caers 2019). The produced water vapor is injected into the atmosphere. At the typical cruise altitude, the temperature is approximately -56 °C causing the water vapor to freeze and produce tiny ice particles (this effect is further enhanced by sulfur oxides and soot, resulting from fuel combustion), forming the familiar trails behind aircraft (EPA 2000). The initially thin lines can last long, depending on the weather conditions, and spread to widths of more than 10 kilometers. In the so-called airways over the North Atlantic Ocean and Europe, contrails can cover 5% of the sky area annually (Caers 2019). Below these airways, contrails could have a more significant environmental impact than all greenhouse gasses combined (Whitelegg 2000).

The presence of contrails can also lead to so-called aviation-induced cirrus clouds, cirrus clouds that would not occur naturally. Aviation-induced cirrus clouds are believed to have a strong warming effect on the atmosphere (Jardine 2005). In Jardine's (2005) update of the IPCC report, it was found that cirrus clouds could account for the same amount of radiative forcing as all other emission products combined. The conclusion, however, was that there is too much uncertainty over the actual RF value to include cirrus clouds in the total RF value of all emission components (Sausen 2005). This lack of scientific understanding is also shown in Figure 5.16.

The formation potential of contrails and aviation-induced cirrus clouds depends on a range of factors, including humidity, temperature, pressure, the EI of water vapor, and the overall propulsion efficiency of the aircraft (Fichter 2005). Furthermore, the atmosphere must be supersaturated with respect to ice to allow for the persistence of contrails. Another significant factor is the influence of latitude and the seasonal cycle, which is illustrated in Figure 5.17 (Fichter 2005).

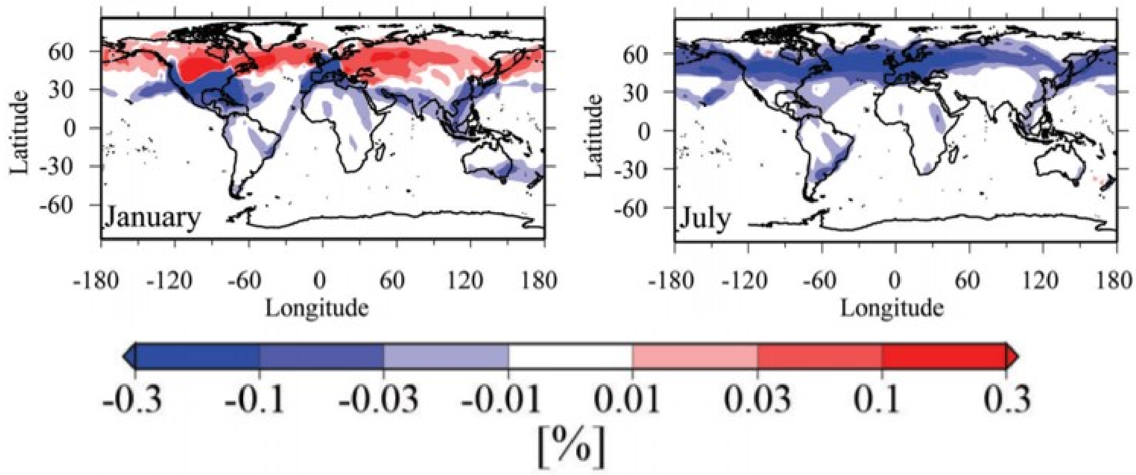

Figure 5.17 Seasonal influence on contrail coverage (6000 ft under the base case) (Fichter 2005)

Following up on the IPCC report, the previously mentioned TRADEOFF project tried to find quantitative results for the impact of cruise altitude changes on the global coverage of contrails and the radiative forcing they cause (Fichter 2005). A summary of the results and a description of the used methods can be found in the following paragraphs.

The study by Ponater (2002) applied a parameterization for line-shaped contrails. This model is based on the Schmidt-Appleman theory (thermodynamic theory of contrail formation), which takes into account that contrails can only form if the air is supersaturated with respect to ice (Caers 2019). Ponater (2002) used the distance traveled to calculate the actual contrail coverage from the potential contrail coverage instead of the amount of fuel used. By using satellite observations, the base case of mean contrail coverage was determined. All climate change effects caused by contrails are measured as radiative forcing.

Generally, a decrease in cruise altitude results in a decrease in global contrail coverage. The relationship between cruise altitude and global contrail coverage is almost linear up to a maximum decrease of 45% in coverage at an altitude of 6000 ft under the base case (Ponater 2005). However, an increase in fuel consumption can be observed when flying at a lower cruise altitude. Conversely, increasing the cruise altitude will cause an increase in global contrail coverage and only a small decrease in fuel consumption (Caers 2019). The global contrail coverage as a function of altitude and latitude is presented in Figure 5.18. Additionally, Table 5.8 presents the effect of cruise altitude on the global mean contrail coverage and fuel consumption.

The values given in Table 5.8 are all average global values. However, as discussed previously, the local values of contrail coverage are heavily dependent on the latitude and the seasonal cycle. Therefore, the local values of contrail coverage vary widely over the globe (Fichter 2005). This can again be observed in Figure 5.17 and Figure 5.18.

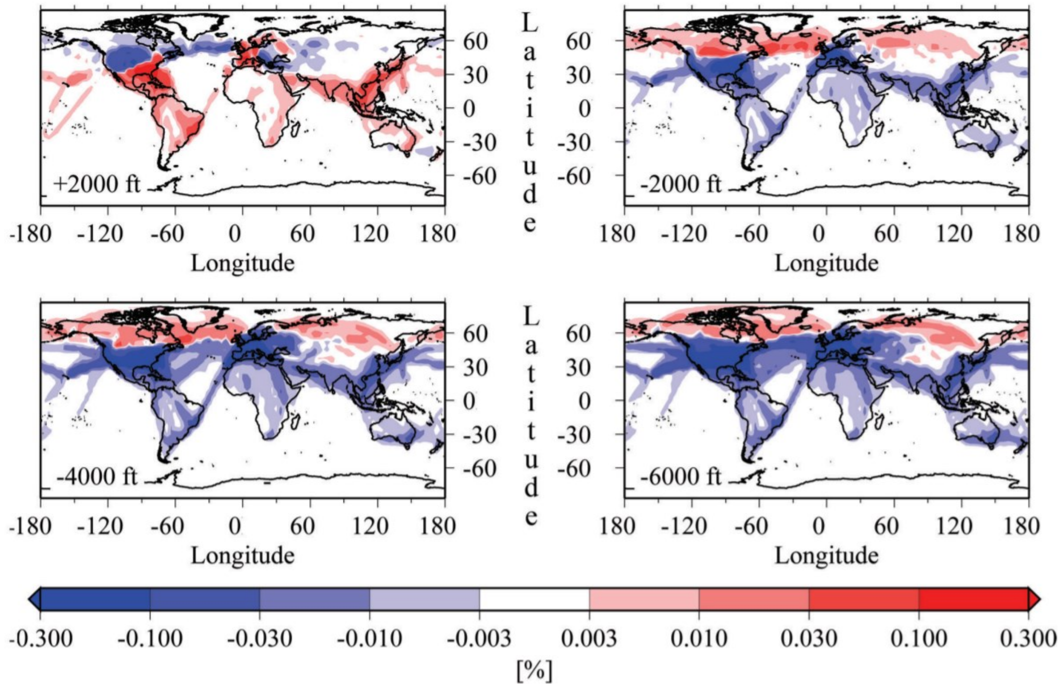

Figure 5.18 Contrail coverage in function of altitude changes (% relative to base case) (Fichter 2005)

Table 5.8 Effect of cruise altitude on contrail coverage and fuel consumption (Fichter 2005)

Inventory	Flown Distance [10^9 km/yr]	Fuel Consumption [Tg/yr]	Global Mean Contrail Coverage [%]	Net RF by Contrails [mW/m²]
DLR2	18.0	112.2	0.052 (distance) 0.057 (fuel)	2.1 (3.2) 2.3 (3.5)
TRADEOFF base case	17.1	111.5	0.047 (distance) 0.052 (fuel)	1.9 (2.9) 2.0 (3.1)
TRADEOFF +2000 ft	17.1	111.0	0.050 (distance)	2.0 (3.1)
TRADEOFF -2000 ft	17.1	114.5	0.041 (distance)	1.6 (2.5)
TRADEOFF -4000 ft	17.1	115.5	0.034 (distance)	1.3 (2.0)
TRADEOFF -6000 ft	17.1	118.0	0.026 (distance)	1.0 (1.6)

5.4.3 Discussion of the ICAO CO_2 Standard

The development of a CO_2 standard for airplanes, as part of the range of measures for addressing GHG emissions from international aviation, was one of the recommended elements within the ICAO Program of Action on International Aviation and Climate Change (ICAO 2012). In line with the ICAO Program of Action, the Eighth Meeting of the Committee on Aviation Environmental Protection (CAEP/8) in February 2010 agreed to develop International Standards and Recommended Practices (SARPs) for Airplane CO_2 Emissions. CAEP developed draft SARPs for airplane CO_2 emissions that were afterward adopted in ICAO Annex 16, Volume III - CO_2 Certification Requirement (Scholz 2017).

However, this important standard has so far (July 2017) not been released by ICAO to the public for further open discussion. Therefore, it seems important to make this standard available in a form easy to read, to foster such a discussion in the wider aviation and scientific communities. (Scholz 2017)

Therefore, Scholz (2017) published a publicly available document about the new ICAO CO_2 standard converted from: European Aviation Safety Agency, NPA 2017-01, 6. Appendices, '6.3.2 Proposed 1st Edition of ICAO Annex 16, VOL III'. The following discussion of ICAO Annex 16, Volume III will mainly be based on the document by Scholz (2017).

The document outlines the metric system in general terms. It is based on three elements associated with aircraft technology and design:

- Cruise point fuel burn performance;
- Aircraft size; and
- Aircraft weight.

The metric value (MV) for evaluating CO_2 emissions was defined as

$$CO_2 \text{ emissions evaluation metric value} = (MV)_{CO_2} = \frac{\left(\frac{1}{SAR}\right)_{AVG}}{(RGF)^{0.24}} \ . \qquad (5.20)$$

Equation (5.20) involves two parameters: the average value of the inverse of the previously defined SAR and the Reference Geometric Factor (RGF), which is a measure of the cabin floor area in square meters. Therefore, the metric value is quantified in units of kilograms/kilometer/meter$^{0.48}$, which is a highly unusual unit.

As previously discussed, SAR is calculated using the following equation:

$$SAR = \frac{V_{TAS}}{W_f} \ . \qquad (5.21)$$

Where V_{TAS} is the true airspeed, and W_f is the total airplane fuel flow during the cruise flight. According to the ICAO CO_2 standard, SAR must be calculated for three reference points, shown in Figure 5.19. These points are defined through three values of the aircraft gross mass:

- High gross mass: 92% MTOM;
- Mid gross mass: Average of high gross mass and low gross mass; and
- Low gross mass: (0.45 × MTOM) + (0.63 × MTOM$^{0.924}$).

Since the gross mass cannot be determined at any time during a flight, it shall be determined by subtracting the fuel used from the mass of the aircraft at the start of the flight.

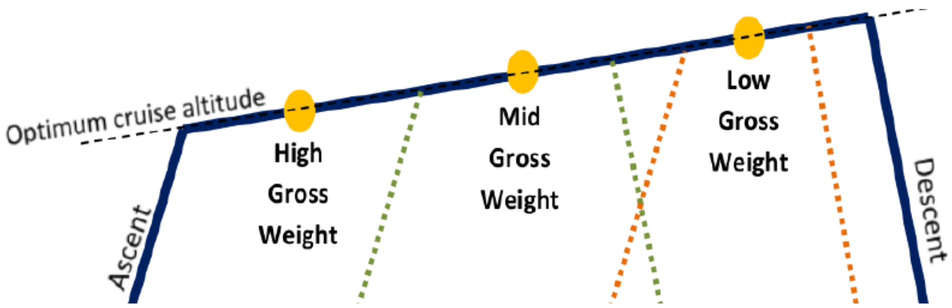

Figure 5.19 Reference points for the determination of SAR (ICAO 2012)

Volume III of Annex 16 also describes the calculation method for SAR:

> *The SAR values for each of the three reference masses shall be calculated either directly from the measurements taken (during a test flight) at each valid test point adjusted to reference conditions, or indirectly from a performance model that has been validated by the test points. (Scholz 2017)*

RGF was previously described as a measure of the cabin floor area in square meters. The following areas must be included or exclude:

> *The RGF includes all pressurized space on the main or upper deck, including aisles, assist spaces, passageways, stairwells, and areas that can accept cargo and auxiliary fuel containers. It does not include permanently integrated fuel tanks within the cabin or any unpressurized fairings, crew rest/work areas, or cargo areas that are not on the main or upper deck (e.g., 'loft' or underfloor areas). RGF does not include the cockpit crew zone. (Scholz 2017)*

Although ICAO's Annex 16, Volume III provides an excellent basis for the initial regulation on the CO_2 emissions of the aviation sector and, further in the future, for developing measures to increase the fuel efficiency of the operational side of civil aviation, there is still room for criticism. The main concerns were formulated by Green and Jupp (2016).

> *Our main criticism of the circular in its current form is that it does not correctly address the ICAO goal of reducing fuel used per revenue tonne-kilometer performed and makes no direct reference to payload. However, regarding the latter, we believe that the factor RGF, as a measure of available cabin floor area, is an acceptable surrogate for the relevant maximum payload – i.e., the maximum number of passengers that could be carried. The main defect of the proposal could be eliminated simply by removing, in the current document, the exponent 0.24 of RGF in the formula for the CO_2 emissions evaluation metric value. Retaining RGF to the power of unity in the metric and multiplying it by an appropriate value of the effective floor loading (EFL) converts it to what the 37th Assembly called for, a statement of fuel used per revenue tonne-kilometer performed. (Green 2016)*

As stated in the concerns of Green (2016), it would be better to express $(MV)_{CO2}$ in units of kilograms per revenue tonne-kilometer performed. These units can be obtained by removing the exponent 0.24 of RGF and multiplying RGF by an appropriate value of EFL, which is the ratio of payload to floor area in tons per square meter.

$$Fuel\ burn\ per\ unit\ payload-range = \frac{1}{SAR_{AVG}} \cdot \frac{1}{RGF \cdot EFL} \tag{5.22}$$

$$EFL = \frac{m_{PL}}{RGF} \tag{5.23}$$

5.4.4 CO_2 Equivalent Emission

The equivalent CO_2 mass is a metric used to quantitatively express the environmental impact of engine emissions (Caers 2019). It compares the emissions from various GHGs based on their global warming potential (GWP) by converting amounts of other gases to the equivalent amount of CO_2 with the same global warming potential (EEA 2001). GWP is defined by the United States Environmental Protection Agency (EPA 2020) as:

> *a measure of how much energy the emissions of 1 ton of a GHG will absorb over a given period of time, relative to the emissions of 1 ton of CO_2. The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years.*

The effects of the three most significant emission contributors, namely CO_2, NO_X, and AIC, are combined in one metric. As discussed in Paragraph 5.4.2, AIC includes contrails and aircraft-induced cirrus clouds. Equation (5.24) is made as generic as possible by dividing the equivalent CO_2 mass by the number of seats in the aircraft cabin. Therefore, $m_{CO2,eq}$ is quantified in units of kg CO_2 per flown kilometer and per seat.

$$m_{CO2,eq} = \frac{EI_{CO2} \cdot f_{km}}{n_{airline}} \cdot 1 + \frac{EI_{NOX} \cdot f_{km}}{n_{airline}} \cdot CF_{midpoint,NOX} + \frac{L_{km}}{L_{km} \cdot n_{airline}} \cdot CF_{midpoint,AIC} \tag{5.24}$$

In Equation (5.24), EI is the emission index, f_{km} is the fuel consumption per kilometer, $n_{airline}$ is the number of seats in the aircraft cabin, CF is a characterization factor, and L_{km} is the stage length in kilometers.

The equation comprises two types of unknown parameters: emission indices (EI) and characterization factors (CF). EI is defined as the mass of emitted product per mass amount of fuel burned (Caers 2019). As previously shown in Table 5.4, EI_{CO2} is a constant, independent of the aircraft's altitude, equal to 3.16 kg CO_2 per kg of fuel burned. On the other hand, the emission index of NO_X is a highly variable value that depends on the combustion efficiency of the engines and the altitude.

CF may be considered a conversion factor to convert NO_X or AIC emissions to equivalent CO_2 emissions (Caers 2019). The altitude dependence of both emission products is taken into account by introducing a forcing factor s.

$$CF_{midpoint,NOX} = \frac{SGTP_{O3S,100}}{SGTP_{CO2,100}} \cdot s_{O3S}(h) + \frac{SGTP_{O3L,100}}{SGTP_{CO2,100}} \cdot s_{O3L}(h) + \frac{SGTP_{CH4,100}}{SGTP_{CO2,100}} \cdot s_{CH4}(h) \tag{5.25}$$

$$CF_{midpoint,AIC} = \frac{SGTP_{contrails,100}}{SGTP_{CO2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus,100}}{SGTP_{CO2,100}} \cdot s_{cirrus}(h) \tag{5.26}$$

The ReCiPe method typically uses the GWP as the characterization factor to determine the midpoint categories. In this case, only the midpoint category climate change has to be calculated. GWP uses radiative forcing to express the impact of a system, but, as discussed in Paragraph 5.4.1, RF is not the best metric for estimating the impact of a single flight. Therefore, an alternative metric is introduced: the sustained global temperature potential (SGTP). $SGTP_{i,t}$ was defined by Schwartz (2009) as:

> *The $SGTP_{i,t}$ for a species is defined as the global mean temperature change after t years (mostly 100 years) of sustained emissions of 1 kg per year of species i (or one nautical mile per year for contrails and cirrus).*

SGTP is quantified in units of Kelvin per relevant unit for each emission contributor (per kg CO_2, per kg NO_X, or per NM for AIC). SGTP values can be found in (Schwartz 2009) and are presented in Table 5.9.

Table 5.9 SGTP for different emission species (Schwartz 2009)

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3.58 \cdot 10^{-14}$
Short O_3 (K/kg NO_X)	$7.97 \cdot 10^{-12}$
Long O_3 (K/NO_X)	$-9.14 \cdot 10^{-13}$
CH_4 (K/kg NO_X)	$-3.90 \cdot 10^{-12}$
Contrails (K/NM)	$2.54 \cdot 10^{-13}$
Contrails (K/km)	$1.37 \cdot 10^{-13}$
Cirrus (K/NM)	$7.63 \cdot 10^{-13}$
Cirrus (K/km)	$4.12 \cdot 10^{-13}$

As previously stated, the environmental impacts resulting from NO_X emission and AIC vary significantly depending on emissions altitude. Therefore, altitude-dependent forcing factors *s* were introduced in Equations (5.25) and (5.26). Figure 5.20 illustrates the altitude dependence of these forcing factors. The forcing factors for short-lived ozone, long-lived ozone, and methane increase with increasing altitude. The AIC forcing factor reveals a clear maximum around the typical cruise altitude for jet aircraft and is almost equal to zero at lower altitudes. Exact values for all forcing factors were included in Van Endert's master thesis (2017) and can be found in Appendix G.

The forcing factors from Figure 5.20 were taken from (Schwartz 2011). However, a second method to determine the altitude-dependent impact of emission species was found in the Dissertation of Katrin Dahlmann (2012). The two methods were compared in (Scholz A. 2021) and will briefly be discussed based on Figure 5.21.

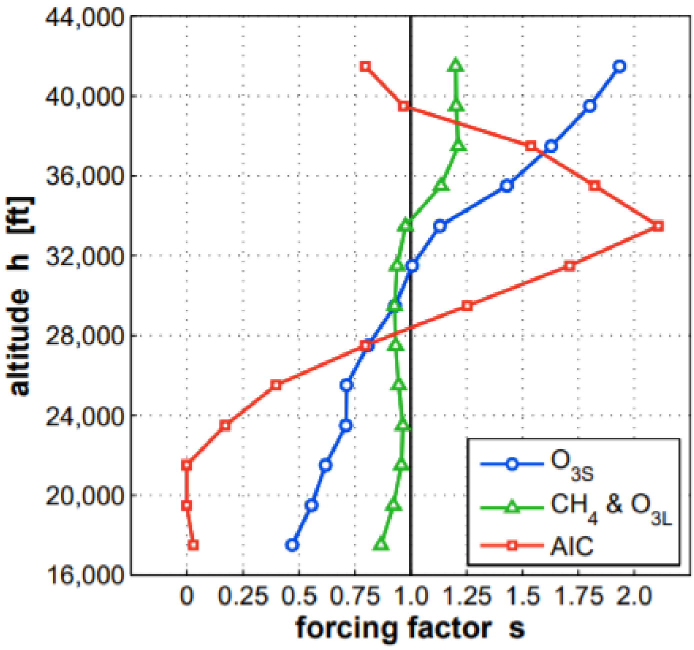

Figure 5.20 Forcing factor *s* as a function of altitude (Schwartz 2011)

Figure 5.21 presents the results from Schwartz (2011) on the left graph, while Dahlmann's (2012) results are presented on the right graph. It can be seen that both sets of functions show the same general trends in terms of altitude variation and the cooling or warming effect. Nevertheless, the absolute values differ, and so do the altitudes of peaks. For flight altitudes below 16500 ft, which are not covered by the functions, the value of each function at 16500 ft is taken. Both methods have their pros and cons (see Scholz A. 2021); however, it is hard to say which method is best as there is still much uncertainty about the altitude dependence of the impact of certain pollutants. It was chosen to go with the model presented by Schwartz (2011) as this model was also used by Van Endert (2017) and Haß (2015) to define the ecolabel.

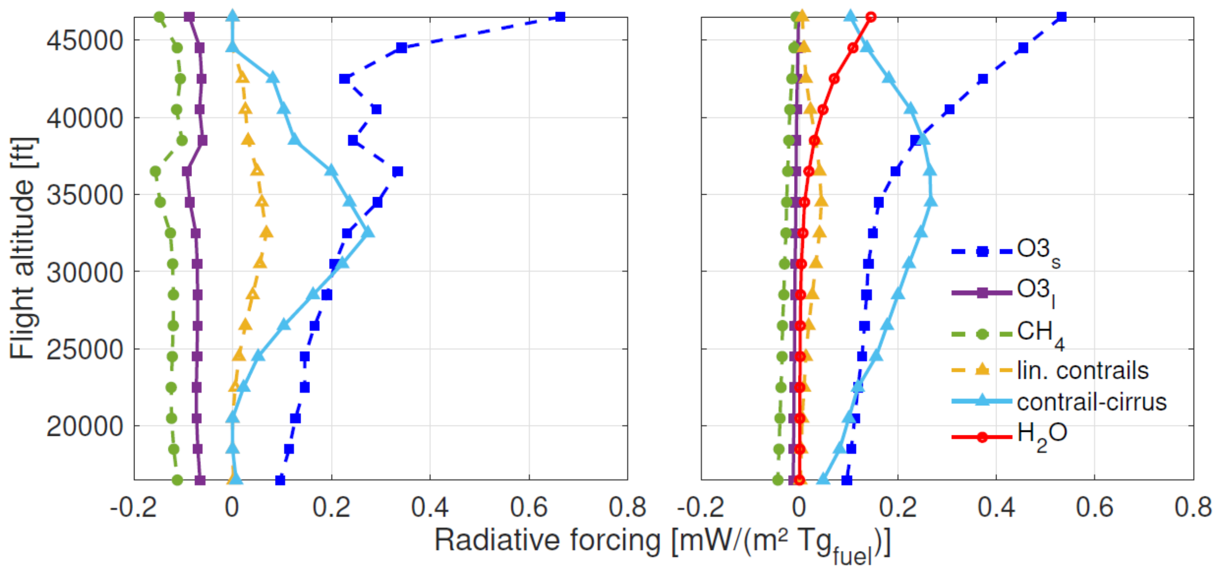

Figure 5.21 Comparison between Schwartz (2011) and Dahlmann (2011) (Scholz A. 2021)

In Figure 5.16, it was shown that CO_2 and NO_X emissions combined with AIC make up the majority part of aviation-induced radiative forcing. Therefore, these three types of emissions were chosen to rate the climate impact in the ecolabel. The NO_X emission induces methane (CH_4) and long-lived ozone (O_{3L}) as well as short-lived ozone (O_{3S}). Therefore, Figure 5.20 does not mention the NO_X emission on its own. In addition, it can be seen from Figure 5.20 that the forcing factors for methane and long-lived ozone are the same as well as those for contrails and cirrus clouds.

$$s_{O3L}(h) = s_{CH4}(h) \tag{5.27}$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h) \tag{5.28}$$

Going back to Equation (5.24), there is only one unknown variable left: EI_{NOX}. There exist several methods to calculate the emission index of NO_X. The most accurate procedure is called P3T3. However, the P3T3 method requires knowledge of the engine's internal gas path parameters at the high-pressure compressor exit. These parameters are the total pressure (P_3) and the total temperature (T_3), along with the engine fuel flow, hence the name P3T3 (DuBois 2006). Unfortunately, this method is useless as the necessary data is not publicly available. A second method to determine the emission index of NO_X is using a database (see 5.4.5). Finally, EI_{NOX} can also be calculated with the Boeing fuel flow method 2 (see 5.4.6).

5.4.5 EI_{NOX} – EEA Database

As previously discussed in Section 5.2.5, it was found that the EEA maintains a database called "1.A.3.a Aviation 1 Master emissions calculator 2019" (EEA 2019). The calculations in this database are done using the most recent empirical data available. If an airplane is included in the database, only a representative cruise stage length, or cruise range, should be entered. Depending on the entered stage length, the database presents the cruise altitude, the amount of emitted NO_X, and used fuel. Finally, the emission index of NO_X can be calculated by dividing the amount of NO_X by the amount of burned fuel.

$$EI_{NOX} = \frac{Amount\ of\ emitted\ NO_X}{Amount\ of\ burned\ fuel} \tag{5.29}$$

The cruise stage length (L_{km}) could be determined by taking half of the range for maximum payload. The range for maximum payload (R_1) was previously defined in Paragraph 5.2.1, using Figure 5.5. As R_1 is already used to calculate the fuel consumption, the stage length can be obtained by dividing R_1 by two. Paragraph 5.2.5 explains this choice in more detail.

5.4.6 EI_{NOX} – Boeing Fuel Flow Method 2

Unfortunately, the EEA database does not contain data for every aircraft in service. Therefore, the Boeing Fuel Flow Method 2 (BFFM2) is introduced as an alternative. BFFM2 is a method for calculating the emission index of NO_X based on fuel flow and emission index data from the ICAO AEED (Cars 2019). As the emission indices of NO_X given in the databank are reference values under ISA conditions at sea level, the emission indices must be corrected for actual meteorological conditions (such as temperature, pressure, relative humidity, etc.) (Li 2020). To account for the effects of the meteorological conditions on emissions, BFFM2 is used to correct the EIs of NO_X. This method reduces the uncertainty of the direct use of the EIs in the AEED to estimate aircraft emissions more accurately (Li 2020).

The Boeing Fuel Flow Method is adapted from Baughcum (1996) and Kim (2005). The aim is to generate a value for the emission index of NO_X as a function of the aircraft's fuel flow. The method will be explained in a stepwise manner.

1. The method uses the fuel flows (W_f) and the corresponding emission indices from the ICAO AEED. The ICAO values for fuel flow must be adjusted for installation effects on the aircraft. Therefore, the values must be multiplied by a correction factor (r) determined by Boeing. This factor depends on the operation mode of the aircraft and is given in Table 5.10 for the four defined modes.

$$W_{f,adapted} = W_{f,unadapted} \cdot r \tag{5.30}$$

Table 5.10 Fuel flow correction factors (Kim 2005)

Operation mode	Boeing's correction factor '*r*'
Takeoff	1.010
Climb-out	1.013
Approach	1.020
Idle	1.100

2. In this step, the adapted fuel flow data and the corresponding EI_{NOX} values from the ICAO databank must be plotted in a log-log plot. An example of such a plot is given in Figure 5.22.

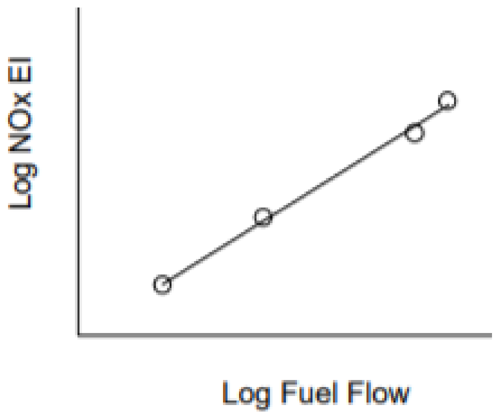

Figure 5.22 Log-log plot of EI_{NOX} as a function of fuel flow (Kim 2005)

3. The next step is to derive an equation for EI_{NOX} as a function of fuel flow by generating a regression line that will provide the equation for the relation between the two parameters.

4. The aircraft's uncorrected fuel flow (in kg/s) is given by

$$W_{f,uncorr} = \frac{1}{SAR} \cdot V \quad \text{[kg/s]} \quad . \tag{5.31}$$

The velocity V (TAS) is expressed in km/s and can be calculated using

$$V = \frac{a \cdot M}{1000} \quad \text{[km/s]} \quad . \tag{5.32}$$

In Equation (5.32), the speed of sound (a) is given by:

$$a = \sqrt{\gamma \cdot R_{air} \cdot T_{amb}} \quad \text{[m/s]} \quad . \tag{5.33}$$

Where γ is defined as the adiabatic gas constant for dry air equal to 1.4 and R_{air} is the specific gas constant for dry air, equal to 287.053 J/kgK.

The ambient temperature (T_{amb}) depends on the altitude. The average altitude of the tropopause, used in the standard atmosphere model, is 11000 m. It is assumed that in the region from the tropopause at 11000 m up to 20000 m, the temperature is a constant 216.65 K or -56.5°C. Below 11000 m, the temperature changes with altitude. It is assumed that T_0 is equal to 288.15 K.

$$T_{amb} = 216.65\, K\ if\ h > 11000 \text{ m} \tag{5.34}$$

$$T_{amb} = T_0 - 0.0065 \cdot h\ if\ h < 11000 \text{ m} \tag{5.35}$$

To be able to calculate the ambient temperature, the cruise altitude must be calculated. This can be done by using results from the preliminary sizing phase of aircraft design. In this phase, some requirements are demanded and subsequently put together in a matching chart to determine the optimum design point of the aircraft. An example of a matching chart is given in Figure 5.23.

When the matching chart is analyzed for the two requirements of the 'landing phase' and 'cruise phase', it is possible to find an expression for the pressure at a certain altitude. This pressure can be calculated by finding the crossing point between the landing and cruise phase requirements. In this point, the wing loading (m_{MTO}/S_W) of both phases must be equal.

$$\left(\frac{m_{MTO}}{S_W}\right)_{landing} = \frac{k_L \cdot \sigma \cdot C_{L,max,landing} \cdot s_{LFL}}{\frac{MLW}{MTOW}} \tag{5.36}$$

$$\left(\frac{m_{MTO}}{S_W}\right)_{cruise} = \frac{C_L \cdot M_{cr}^2}{g} \cdot \frac{\gamma}{2} \cdot p_{amb} \tag{5.37}$$

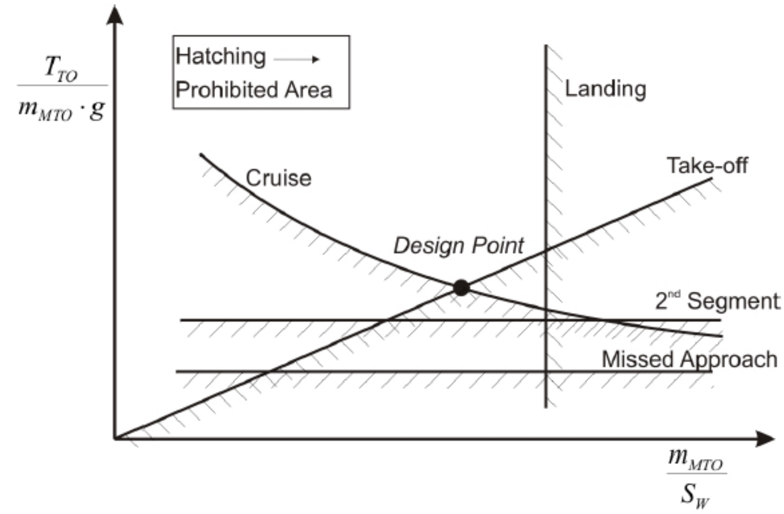

Figure 5.23 Example of a matching chart (Scholz 2015)

Equations (5.36) and (5.37) must be equal; this allows the pressure to be determined.

$$p_{amb} = \frac{2 \cdot k_L \cdot \sigma \cdot C_{L,max,landing} \cdot g}{C_L \cdot \gamma} \cdot \frac{s_{LFL}}{M_{cr}^2 \cdot \frac{MLW}{MTOW}} \tag{5.38}$$

It is possible to determine the cruise altitude from Equation (5.38) using the International Standard Atmosphere (ISA). However, this equation consists of factors depending on the aerodynamics that cannot be found or which are very difficult to calculate. Therefore, Van Endert (2017) defined a statistic to calculate p_{amb} based on available aircraft data for 47 aircraft.

First, Van Endert (2017) calculated the ambient pressure at cruise altitude for the 47 reference aircraft using Equation (5.39), which defines the standard atmosphere. Additionally, the cruise altitude was found in the literature (Janes 2020) (Roux 2007).

$$p_{amb} = p_0 \cdot \left(1 - 0.0065 \cdot \frac{h_{cr}}{T_O}\right)^{5.2561} \quad \text{[Pa]} \tag{5.39}$$

Where p_0 is the pressure at sea level on a standard day equal to 101325 Pa and T_0 is the temperature at sea level on a standard day equal to 288.15 K.

Subsequently, different parameters "x" were defined based on the known parameters from Equation (5.38). The different "x" parameters were then plotted against the known ambient pressure to find an equation to determine the ambient pressure, which only depends on known parameters. In the end, the best fit was obtained when the variable "x" was defined as

$$x = \frac{1}{M_{cr}^2} \quad \text{[-]} \quad . \tag{5.40}$$

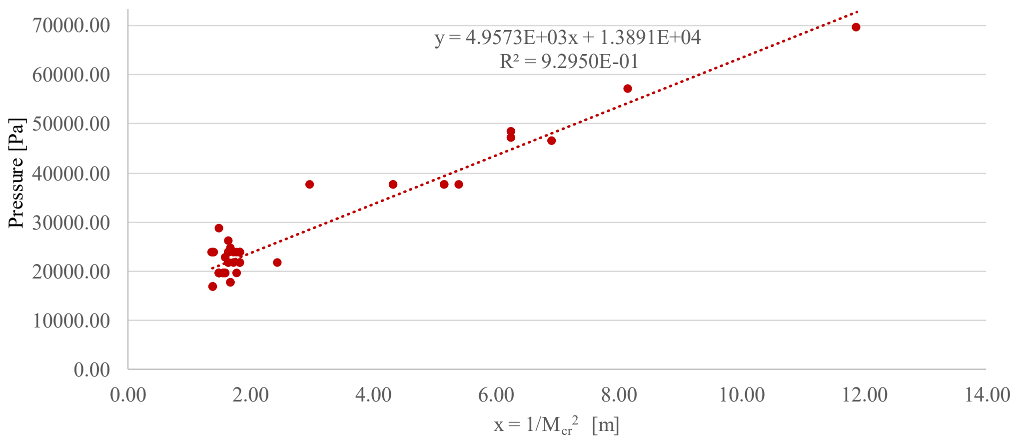

Figure 5.24 Statistic to calculate the ambient pressure

From Figure 5.24, a new equation to calculate the ambient pressure was derived. The equation only considers the Mach number in cruise (M_{cr}). M_{cr} was again found in the literature (Janes 2020) (Roux 2007). The ambient pressure is given by

$$p_{amb} = 4.9573 \cdot 10^3 \cdot \frac{1}{{M_{cr}}^2} + 1{,}3891 \cdot 10^4 \quad [\mathrm{Pa}] \quad . \tag{5.41}$$

Finally, the cruise altitude can be calculated using the ISA equation

$$h = \left(1 - \left(\frac{p_{amb}}{p_0}\right)^{1/5.2561}\right) \cdot \frac{T_0}{0.0065} \quad [\mathrm{m}] \quad . \tag{5.42}$$

5. Then, the corrected fuel flow is calculated with the following equation from Boeing.

$$W_{f,corr} = \frac{W_{f,uncorr}}{\delta_{amb}} \cdot {\theta_{amb}}^{3.8} \cdot e^{0.2 \cdot M^2} \quad [\mathrm{kg/s}] \tag{5.43}$$

With:

$$\delta_{amb} = \frac{p_{amb}}{p_0} \quad [\text{-}] \tag{5.44}$$

$$\theta_{amb} = \frac{T_{amb}}{T_0} \quad [\text{-}] \tag{5.45}$$

6. A linear trendline is plotted over the log-log plot in Excel. The equation from the trendline is then used to calculate the corresponding EI_{NOX} value and has the following general structure:

$$EI_{NOX,graph} = a \cdot W_{f,corr} + b \quad . \tag{5.46}$$

7. In this final step, the calculated $EI_{NOX,graph}$ value from step 6 is uncorrected to reflect the at-altitude flight conditions. This is done by using factors that take the effect of humidity into account.

$$EI_{NOX} = EI_{NOX,graph} \cdot e^{k_H} \cdot \left(\frac{\delta^{1.02}}{\theta^{3.3}}\right)^{0.5} \quad [\mathrm{kg\ NO_X/kg\ fuel}] \tag{5.47}$$

With k_H defined as the humidity correction factor:

$$k_H = -19 \cdot \left(\frac{0.37318 \cdot p_v}{P_{amb} - 0.6 \cdot p_v} - 0.0063\right) \quad [-] \quad . \tag{5.48}$$

Where the saturation vapor pressure p_v is equal to

$$p_v = 6895 \cdot 0.014504 \cdot 10^{\beta} \quad [Pa] \quad , \tag{5.49}$$

and the coefficient for saturation vapor pressure equals

$$\beta = 7.90298 \cdot (1 - k_T) + 3.00571 + 5.02808 \cdot \log_{10}(k_T) + 1.3816 \cdot 10^{-7} \cdot \left(1\text{-}10^{11.344 \cdot \left(1 - \frac{1}{k_T}\right)}\right) + 8.1328 \cdot 10^{-3} \cdot \left(10^{3.49149 \cdot (1 - k_T)} - 1\right) \quad [-] \quad . \tag{5.50}$$

With:

$$k_T = \frac{373.16}{T_{amb} + 0.01} \quad [-] \tag{5.51}$$

The EI_{NOX} values from the EEA database were compared to the values obtained using BFFM2. It was found that EI_{NOX} is a lot higher when using the Boeing method compared to the EEA database. Therefore, it is not a good idea to fill in the missing data from the EEA databank by using the Boeing method. In the end, it was chosen to use BFFM2 to calculate EI_{NOX} as this method can be used for every aircraft.

5.4.7 CO_2 Equivalent Emission Rating

To determine the CO_2 equivalent emission rating scale, the reference group of aircraft defined in Section 5.2.6 will be used. However, four aircraft are excluded due to a lack of emission data: the De Havilland Canada Dash 8 Q100, the De Havilland Canada Dash 8 Q200, the De Havilland Canada Dash 8 Q400, and the Dornier 228. For the other reference aircraft, the equivalent CO_2 emissions were determined using BFFM2. Calculating the CO_2 equivalent emission for all the reference aircraft results in the distribution given in Figure 5.25.

The rating scale is determined according to the same method used for the other rating tables: the calculated equivalent CO_2 emissions are sorted from minimum to maximum and subsequently divided into seven classes (A to G). The resulting rating scale is presented in Table **5.11**.

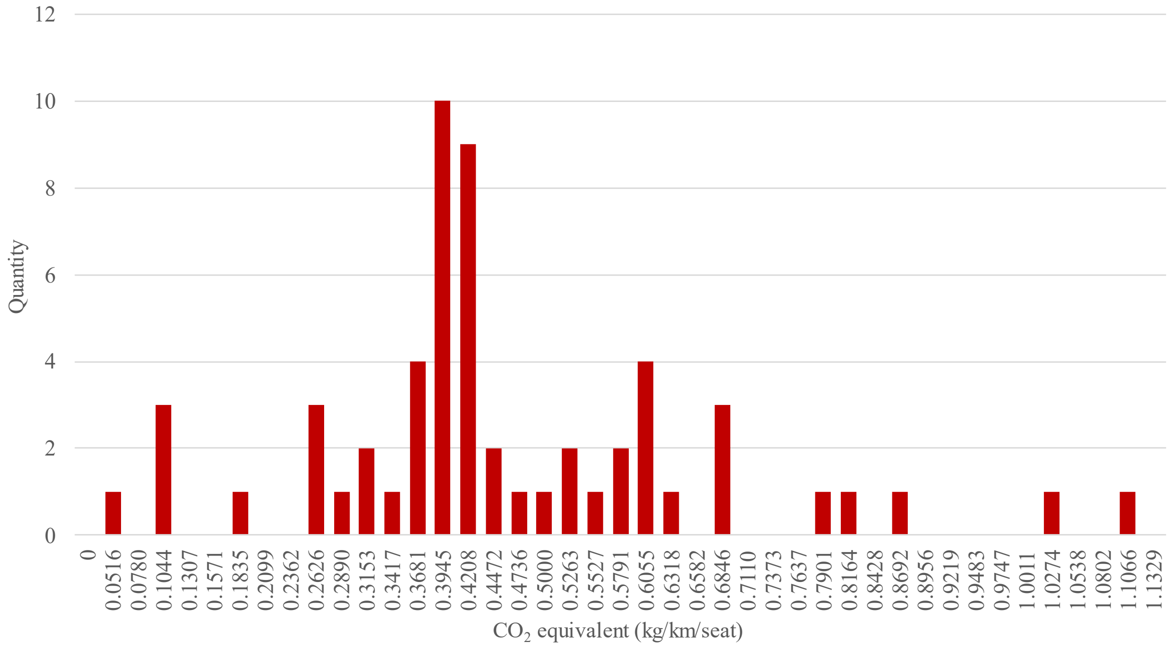

Figure 5.25 Distribution of the normalized equivalent CO_2 emission (kg CO_2/km/seat)

Table 5.11 Equivalent CO_2 Emission rating scale (kg CO_2/km/seat)

	Range		**Normalized 0-1**	
Rating	min	max	min	max
A	0.05161	0.30296	0	0.2383
B	0.30296	0.39682	0.2383	0.3272
C	0.39682	0.41634	0.3272	0.3457
D	0.41634	0.43659	0.3457	0.3649
E	0.43659	0.57690	0.3649	0.4979
F	0.57690	0.68554	0.4979	0.6009
G	0.68554	1.10655	0.6009	1.0000

5.5 Noise Pollution

Environmental noise was defined by Murphy (2014) as:

> *any unwanted sound created by human activities that is considered harmful or detrimental to human health and quality of life. Specifically, environmental noise refers only to noise affecting humans and is concerned exclusively with outdoor sound caused generally by transport, industry, and recreational activities. Thus, environmental noise is a form of pollution.*

Aircraft noise is often considered a significant noise pollutant and is especially an issue near airports and densely populated areas surrounding them. According to the World Health Organization (WHO 2021), "excessive noise seriously harms human health and interferes with people's daily activities at school, at work, at home, and during leisure time. It can disturb sleep, cause cardiovascular and psychophysiological effects, reduce performance, and provoke annoyance responses and changes in social behavior."

5.5.1 Noise Measurement

Noise levels produced by aircraft are required to be certified by an aviation authority, for example, EASA (EASA 2021b) or the Federal Aviation Administration (FAA), as part of the certification process of the aircraft. These noise levels are established in compliance with the applicable noise standards defined in ICAO Annex 16, Volume I (ICAO 2017a). The noise measuring procedure according to ICAO Annex 16, Volume I, is described in Appendix F.

In the aviation sector, the metric to measure noise pollution is called the Effective Perceived Noise Level (EPNL), expressed in units of Effective Perceived Noise in Decibels (EPNdB). EPNdB is defined by Depitre (2006) as:

> *a measure of human annoyance to aircraft noise which has special spectral characteristics and persistence of sounds. It accounts for human response to spectral shape, intensity, tonal content, and duration of noise from an aircraft.*

This metric is derived from the Perceived Noise Level (PNL).

> *The perceived noise level is intended to measure the perceived noisiness of aircraft by observers on the ground. (Truax 1999)*

PNL considers the duration of the noise and the presence of discrete frequency tones. The method for conversion from PNL to EPNL is again defined in ICAO's Annex 16, Volume I (ICAO 2017a), and is also discussed in Appendix F of this work.

5.5.2 Aircraft Noise Databases

EASA publishes a regularly updated database of certification noise levels containing all approved aircraft configurations. The database mainly covers aircraft for which EASA has issued a type certificate data sheet for noise (TCDSN). Unlike the ICAO AEED, the EASA TCDSN database does include data for turboprop-powered aircraft. The database consists of noise levels for four distinct aircraft types: jet airplanes, heavy propeller-driven airplanes, light propeller-driven airplanes, and rotorcraft (EASA 2021b).

A second database called NoisedB is maintained by the French DGAC (Direction Générale de l'Aviation Civile française) under the aegis of ICAO. NoisedB is a public database containing the noise levels of aircraft certified according to ICAO SARPs or the US Federal Aviation Regulations (FAR) (DGAC 2020).

Both databases provide the following information:

- Type certificate holder;
- Aircraft type designation and variant;
- Engine manufacturer and type designation;
- Noise certification standard;
- Modifications concerning noise levels;
- MTOW;
- MLW;
- Lateral EPNL;
- Flyover EPNL; and
- Approach EPNL.

5.5.3 Local Noise Level Rating

Larger and heavier aircraft require more engine power resulting in more noise production than smaller and lighter aircraft. Therefore, the maximum allowed noise level is a function of the maximum takeoff weight. The noise level is to be determined according to Annex 16, Volume I (ICAO 2017a). Normalizing the noise level with this calculated limit will allow for comparison between different aircraft. This normalized noise level is called the Noise Index Value (NIV).

Since noise is relatively independent of environmental factors, unlike other emissions, defining a noise level metric is straightforward. The metric can be calculated by taking the average of the noise index values for the three reference points described in Appendix F: lateral, flyover, and approach.

$$\text{NIV}_{lateral} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{lateral} \quad (5.52)$$

$$\text{NIV}_{flyover} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{flyover} \quad (5.53)$$

$$\text{NIV}_{approach} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{approach} \quad (5.54)$$

$$\text{NIV}_{average} = \frac{(NIV)_{lateral}+(NIV)_{flyover}+(NIV)_{approach}}{3} \quad (5.55)$$

The rating scale is determined by calculating the average noise index value for every airplane in EASA's TCDSN database. Because EASA has a different database for the four distinct aircraft types, a distinction will first be made between jet-powered and turboprop-powered aircraft.

The distribution of the noise index values for jet-powered aircraft is presented in Figure 5.26. The EASA TCDSN database for jet aircraft consists of 20408 aircraft configurations.

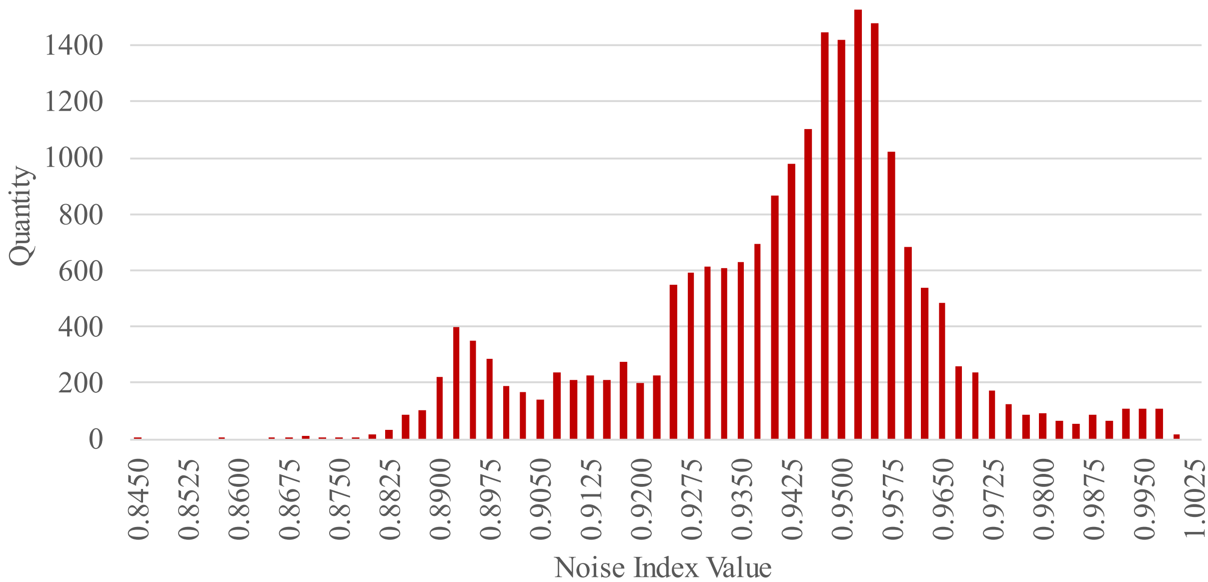

Figure 5.26 Distribution of the noise index values for jet aircraft (EPNdB/EPNdB)

The distribution of the noise index values for turboprop aircraft is shown in Figure 5.27.

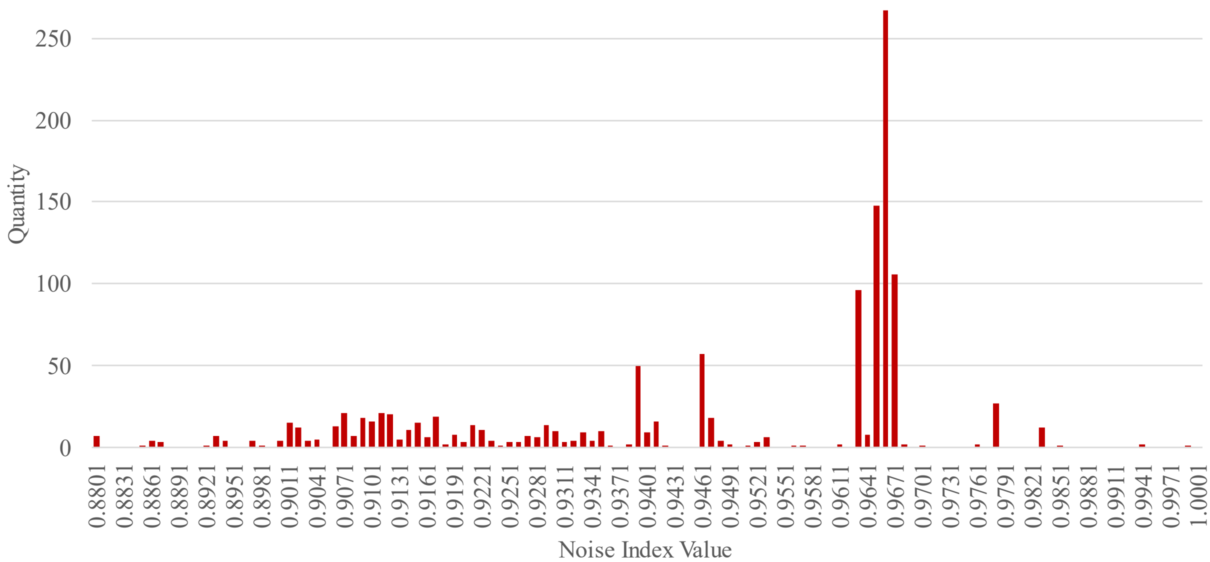

Figure 5.27 Distribution of the noise index values for turboprop aircraft (EPNdB/EPNdB)

Finally, the data from the two TCDSN databases are combined into one new database containing 21615 configurations. The distribution of the noise index values for all these configurations is shown in Figure 5.28. The average noise index value is calculated for every configuration and then sorted from smallest to largest value. Dividing the calculated values into seven groups of 3088 aircraft configurations specifies the range for every classification (A to G). The local noise level rating scale is given in Table 5.12.

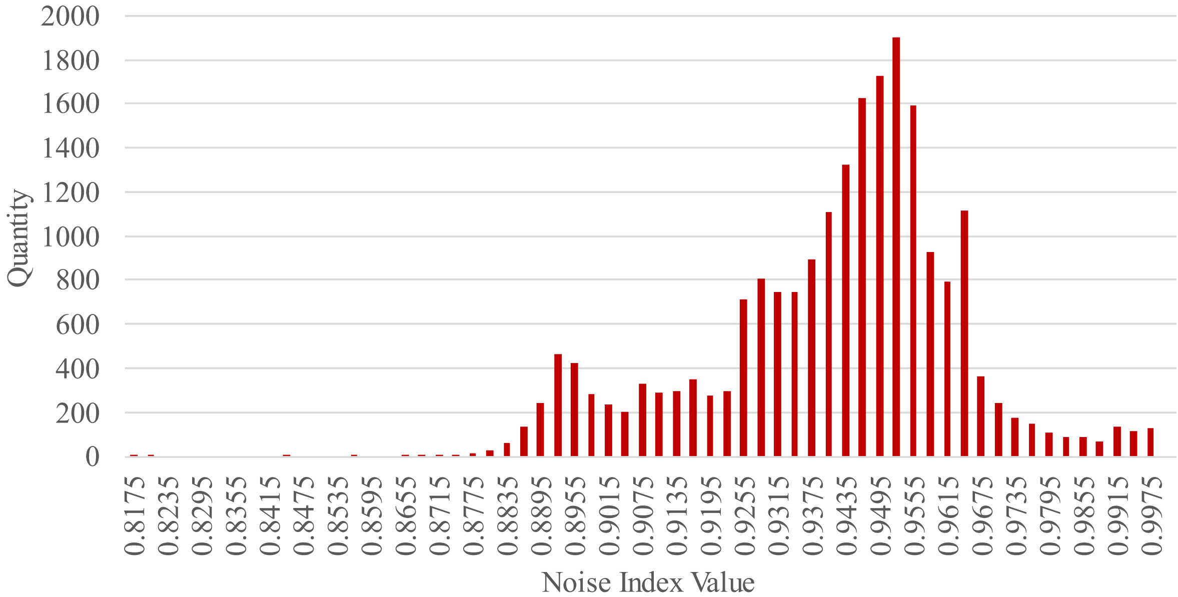

Figure 5.28 Distribution of the noise index values for jet aircraft and turboprop aircraft (EPNdB/EPNdB)

Table 5.12 Local Noise Level rating scale (EPNdB/EPNdB)

	Range		Normalized 0-1	
Rating	min	max	min	max
A	0.8175	0.9171	0.0000	0.5445
B	0.9171	0.9344	0.5445	0.6388
C	0.9344	0.9442	0.6388	0.6927
D	0.9442	0.9503	0.6927	0.7259
E	0.9503	0.9554	0.7259	0.7540
F	0.9554	0.9633	0.7540	0.7972
G	0.9633	1.0000	0.7972	1.0000

5.6 Overall Rating

So far, the four critical indicators of the ecolabel, rated according to a scale from A to G, have been established: fuel performance, local air pollution, CO_2 equivalent emissions, and local noise level. However, the label should also include an overall rating, summarizing these indicators in one single rating. Therefore, weighting factors for each indicator should be introduced. It was chosen to use a fixed factor for each category based on the results of the life cycle assessment derived in the PhD thesis of Johanning (2016).

In Johanning (2016), fossil depletion and climate change have the largest share in the impact on the environment. This is visualized in Figure 5.29. The fuel consumption of the aircraft determines both categories. Therefore, the weighting factor of the fuel consumption is chosen to be 60%. This percentage should be split into two unequal parts: resource depletion and climate change.

$$Ratio = \frac{Climate\ change}{Fossil\ depletion} = \frac{68\%}{26\%} \approx 2.62 \tag{5.56}$$

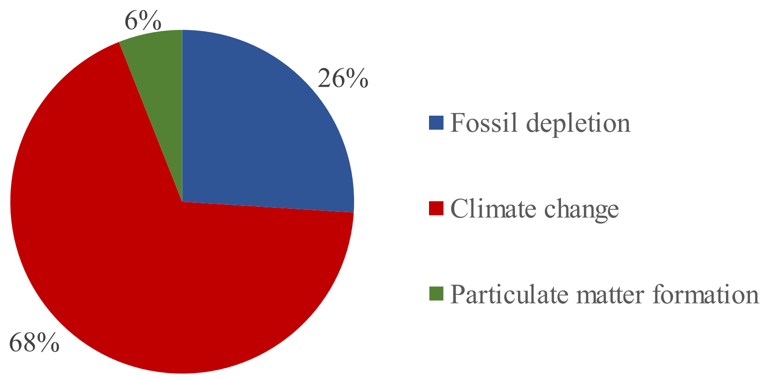

Figure 5.29 Share of the different midpoint categories in the environmental impact of an Airbus A320-200 adapted from (Johanning 2016)

Equation (5.56) shows that the ratio between the midpoint categories 'climate change' and 'fossil depletion' is around 2.6. It was chosen to round down this figure to two, meaning that the environmental impact of the category 'climate change' is twice the impact of the 'fossil depletion'. Therefore, climate change is accounted for two-thirds of the 60%. This means the climate impact gets a weighting factor of 40% and the fossil depletion of 20%.

The remaining 40% will be equally divided between the local air pollution and the local noise level. In this manner, the relatively small shares of the local air pollution and the local noise level still have a noticeable impact on the overall rating. The overall rating (OR) for an airplane is therefore defined as:

$$OR = 0.4 \cdot CO_2\ eq._{norm.} + 0.2 \cdot FC_{norm.} + 0.2 \cdot LAP_{norm.} + 0.2 \cdot LNL_{norm.} \quad . \tag{5.57}$$

In Equation (5.57), only normalized parameters are used. $CO_2\ eq._{norm.}$ represents the normalized CO_2 equivalent emissions, $FC_{norm.}$ represents the normalized fuel consumption, $LAP_{norm.}$ represents the normalized local air pollution, and $LNL_{norm.}$ represents the normalized local noise level.

As stated in Section 5.3.3, the local air pollution cannot be calculated for turboprop aircraft due to a lack of publicly available emission data. Therefore, the overall rating for a turboprop-powered aircraft is only based on the fuel performance, the CO_2 equivalent emissions, and the local noise level. The overall rating for turboprop aircraft is given by:

$$OR_{turboprop} = \frac{0.4 \cdot CO_2\ eq._{norm.} + 0.2 \cdot FC_{norm.} + 0.2 \cdot LNL_{norm.}}{0.8} \quad . \tag{5.58}$$

Because a distinction was made between jet and turboprop aircraft, two different rating scales will also be established. The overall rating scale can be determined using Equations (5.57) and (5.58) and the previously defined rating scales. The results are given in Table 5.13 and Table **5.14** for jet and turboprop aircraft, respectively.

Table 5.13 Overall rating scale for jet-powered aircraft

	Range	
Rating	min	max
A	0.0000	0.2504
B	0.2504	0.3195
C	0.3195	0.3499
D	0.3499	0.3808
E	0.3808	0.4631
F	0.4631	0.5372
G	0.5372	1.0000

Table 5.14 Overall rating scale for turboprop-powered aircraft

	Range	
Rating	min	max
A	0.0000	0.2965
B	0.2965	0.3758
C	0.3758	0.4082
D	0.4082	0.4418
E	0.4418	0.5374
F	0.5374	0.6188
G	0.6188	1.0000

6 Design of the Ecolabel

The use of ecolabels is not new. In 1994, the European Union introduced the EU Energy Labels. These energy labels are often applied to household products, like lightbulbs, fridges, or washing machines and provide a clear and simple indication of the energy efficiency and other key features of products at the point of purchase. This makes it easier for consumers to save money on their household energy bills and contribute to reducing GHG emissions (European Commission 2020). In an EU-wide survey conducted in 2019, 93% of consumers confirmed that they recognized the label, and 79% confirmed that it had influenced their decision on what product to buy (European Commission, 2021). The design of the ecolabel for aircraft is therefore based on the EU Energy Label.

6.1 Previous Work

The ecolabel presented by Van Endert (2017) is shown in Figure 6.1 and is based on the old EU Energy Label. The label provides some general information, such as the airline, the type of aircraft, the type of engines, and the number of seats available on the specific airplane. The overall rating is the most important and is prominently displayed using a color code at the top of the label. The previously discussed impact categories and their respective ratings are also shown. However, Van Endert also added the normalized non-methane volatile organic compound (NMVOC) and particulate matter (PM) emission to the ecolabel, although these emissions are not rated from A to G and are not considered in the overall rating.

In order to remove the language barrier, simple symbols that represent the key indicators were introduced, enabling users who do not understand the English language to understand the ecolabel. English is, however, the go-to language in the aviation and travel industry. Therefore, the text on the label is exclusively available in English.

Alejandro Ridao Velasco (2020) slightly simplified Van Endert's (2017) ecolabel. First of all, the NMVOC and PM emissions were removed as these indicators are quite complex and do not add much value to the ecolabel. Additionally, the names of the environmental indicators were changed to reflect their meaning better and meaningful names (airline, aircraft, seats, and engine) were added to the general information section. The most significant change is the updated overall rating scale. While Van Endert (2017) uses a scale from 0 to 1 to present the overall rating, Ridao Velasco (2020) thought it would be better to use a scale from 0 to 10. Finally, a few minor layout-related improvements can be noticed. The simplified ecolabel is displayed in Figure 6.2.

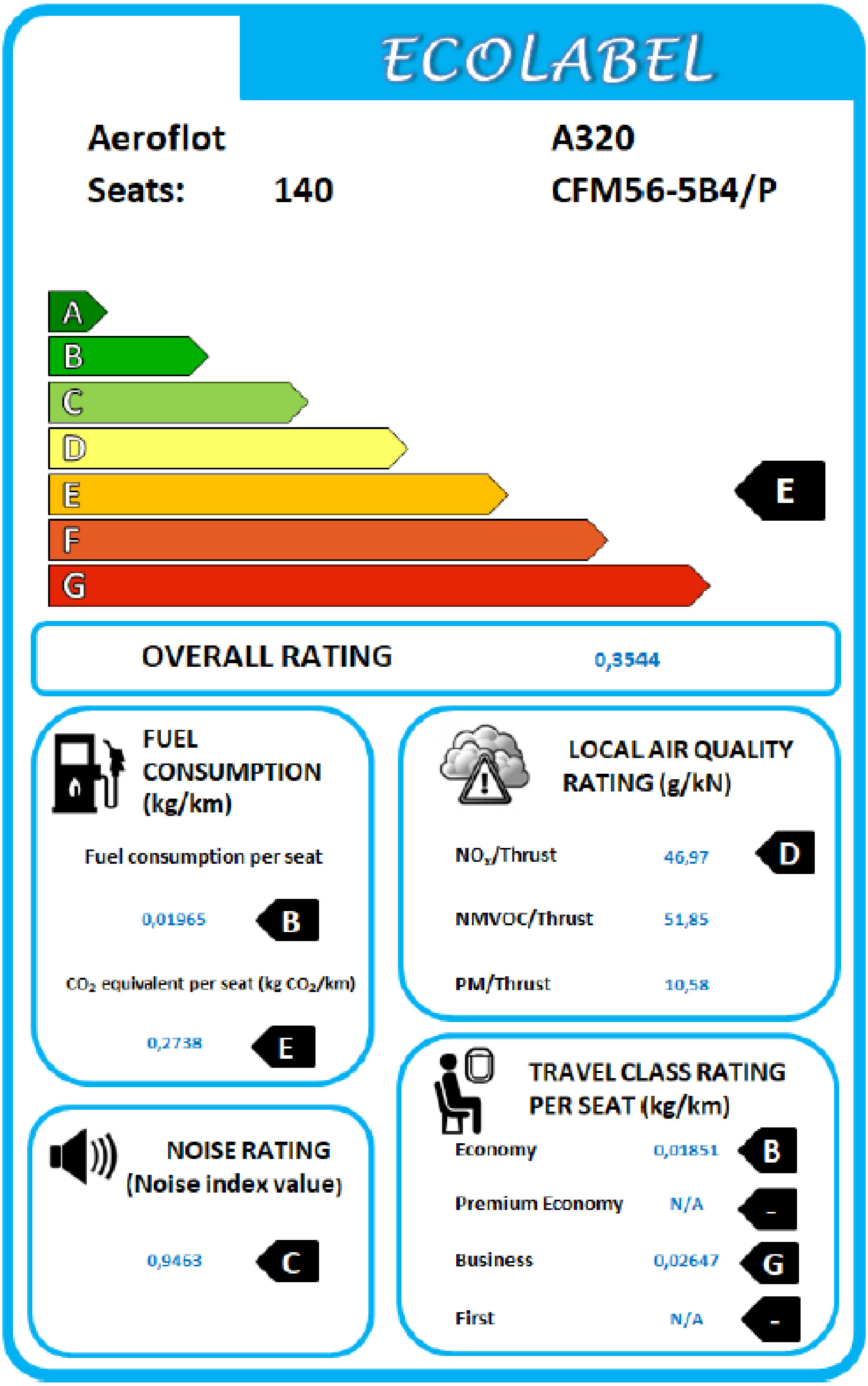

Figure 6.1 Ecolabel for Aircraft designed by Van Endert (2017)

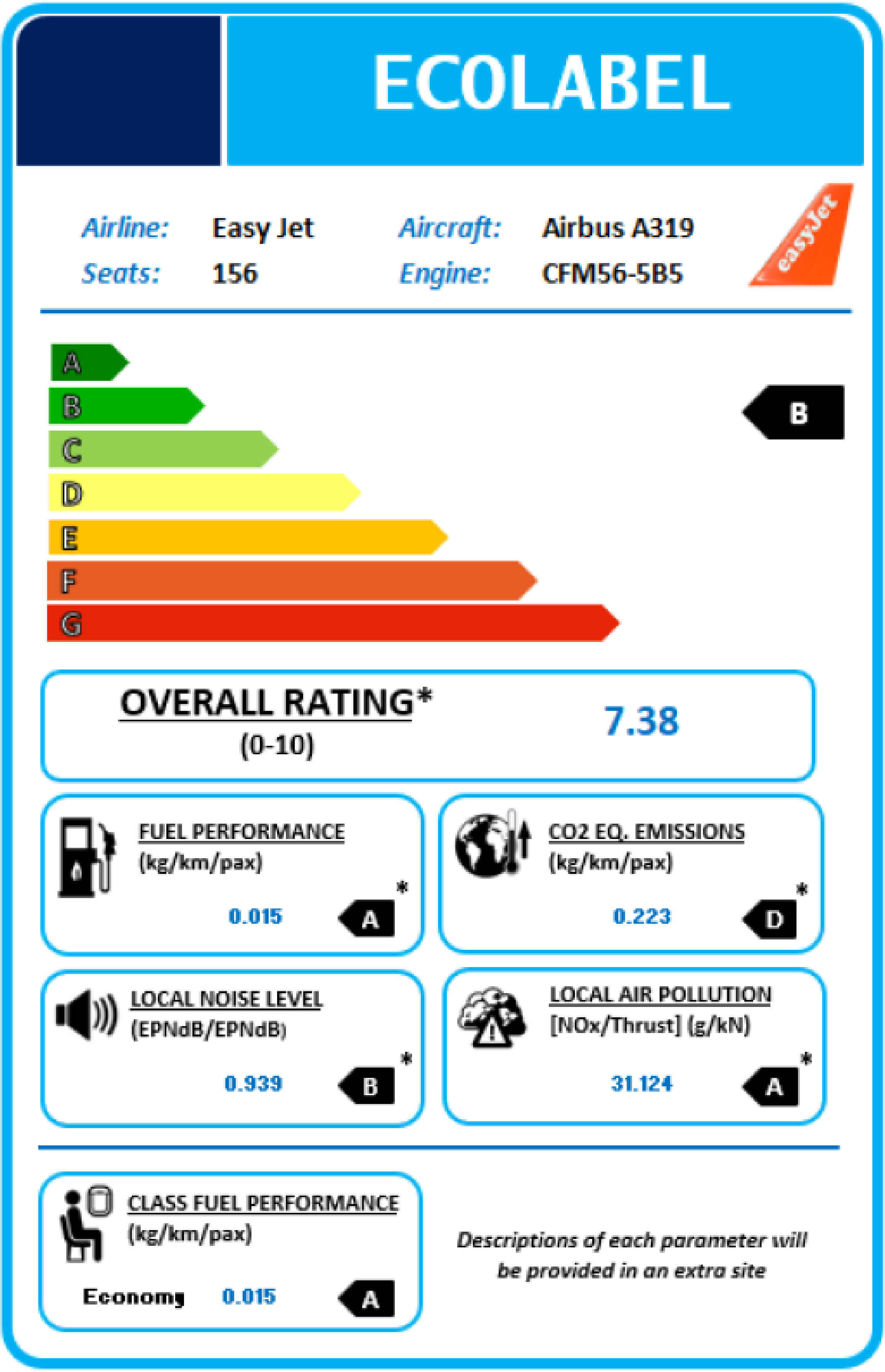

Figure 6.2 Ecolabel for Aircraft designed by Ridao Velasco (2020)

6.2 New Design

As discussed, Van Endert's (2017) Ecolabel was based on the EU Energy Label. However, as of March first, 2021, the EU uses a new energy label. The new labels are initially only applied to fridges and freezers, dishwashers, washing machines, and television sets, but new labels for light bulbs and lamps with fixed light sources will follow on September first, 2021, with other products following in the coming years (European Commission 2021). The difference between the old and new EU Energy Label is shown in Figure 6.3.

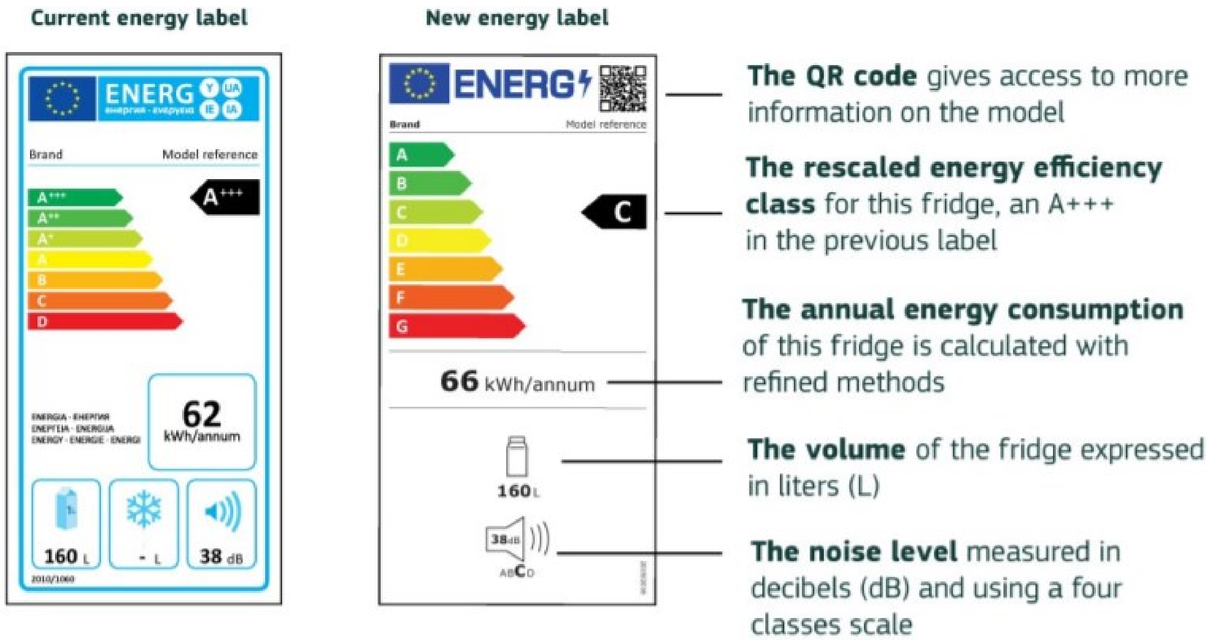

Figure 6.3 Comparison between old and new EU Energy Label (European Commission 2021)

The information found in the new Ecolabel for Passenger Aircraft is identical to the information in Van Endert's ecolabel, apart from the fact that the databases have been updated, so the rating scales are different. However, the QR code in the top right corner of the label shown in Figure **6.4** is a new addition to the Ecolabel for Passenger Aircraft. The QR code directs to a flyer that explains every part of the ecolabel. This document will be discussed in Chapter 8. However, in the future, the QR code should direct the interested passenger to a website dedicated to the Ecolabel for Passenger Aircraft.

Additionally, some minor adjustments were made. Firstly, the color code of the overall rating scale was adjusted to match the color code on the EU Energy Label. Secondly, the logo of the program operator (HAW Hamburg) was added in the top left corner. Lastly, the ratings are now rounded to three significant digits instead of three decimal places.

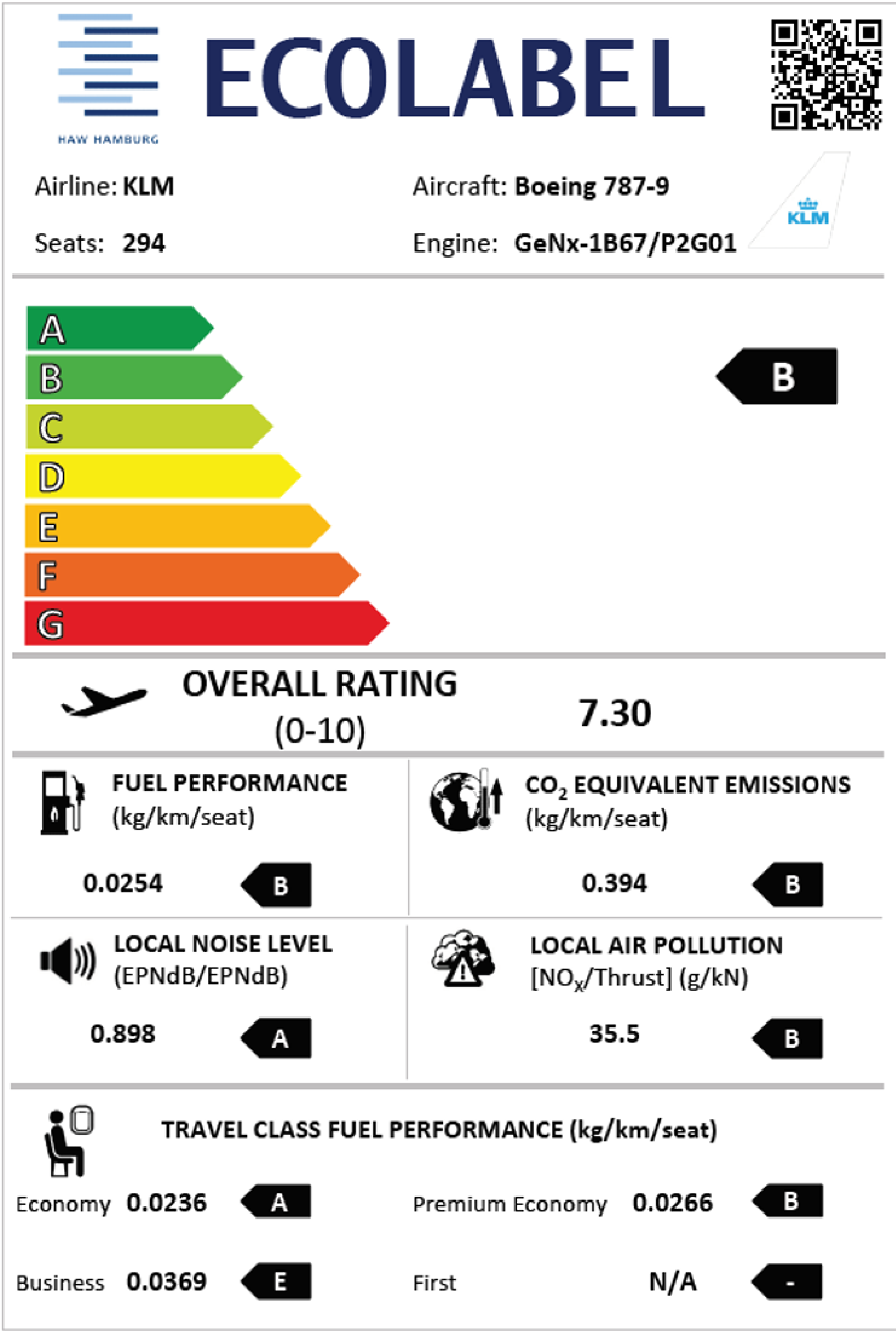

Figure 6.4 Ecolabel for Passenger Aircraft new design

As discussed in Chapter 2, the Ecolabel for Passenger Aircraft is defined as a type III environmental declaration according to ISO 14025. This ISO standard defines requirements to which the environmental declaration must conform. According to ISO 14025 (2006), the following information must be included in any type III environmental declaration:

- Identification and description of the organization making the declaration;
- Description of the product;
- Product identification;
- Name of the program and the program operator's address, if relevant, logo and website;
- PCR identification;
- Date of publication and period of validity;
- Data from LCA, LCI, or information modules;
- Additional environmental information;
- Statement that environmental declarations may not be comparable; and
- Information on where explanatory material may be obtained.

Additionally, the information in Table 6.1 must be provided.

Table 6.1 Additional information required for a type III environmental declaration according to ISO 14025 (2006)

PCR review was conducted by <name and organization of the chair, and information on how to contact the chair through the program operator>	
Independent verification of the declaration and data, according to ISO 14025:2006 internal	external
Third-party verifier <name of the third-party verifier>	

Trying to fit all this information on the ecolabel itself would cause an overload of information. When looking at the environmental product declaration (EPD) provided by Bombardier (2016) for the C series (now Airbus A220), it was found that a separate document was created to include the required information. Therefore, most of the required information can be collected on the Ecolabel for Passenger Aircraft website. However, at this point, not all the required information is available. Additionally, as previously discussed, this website should be developed in the near future.

7 Ecolabel Tools

7.1 Ecolabel Calculator

Van Endert (2017) introduced an ecolabel calculator that gathered all the relevant information from the different databases into one comprehensive database allowing for a straightforward calculation of the different ecolabel metrics. Sophie Sokour and Tobias Bähr (2018) continued the work by adding functions to the calculator to automatically create and print the ecolabels.

7.1.1 Description

The ecolabel calculator was first introduced by Van Endert (2017) and had not been updated ever since. In the scope of this thesis, the latest aircraft emission data were added, and all existing databases and tables were checked in detail. In addition, work was carried out on improving the ease of use of the tool as well as the layout of the Excel file.

The updated tables introduced new aircraft and engine types as well as updated emission data for the already included types. Updating the tables and adding new data caused significant changes in the environmental impact category rating scales. Additionally, the list of reference aircraft was updated according to the World Airliner Census 2020, influencing the rating scales even further. Therefore, the rating scales were redefined using the newly available data. In addition, the previously discussed calculation methods were checked and adjusted or corrected as necessary.

7.1.2 Use

In order to generate an ecolabel using the tool, the user has to choose an aircraft type, an airline, and an engine type from the extensive database included in the tool. This information can be selected from a dropdown list for every input category, so no extensive knowledge of aircraft and engine types is required. The general information window is illustrated in Figure 7.1.

General Information	
Aircraft type	Boeing 787-9
Airline	KLM
Engine type	GeNx-1B67/P2G01
Thrust (kN)	308.7
MTOW (kg)	254011
Number of Seats	294

Figure 7.1 General information input window

The major problem with the input window from Figure 7.1 is that only specific combinations of aircraft type, airline, and engine type available in the database can be chosen. Because the number of possible combinations is almost infinite, the database can only contain a very limited number of combinations. Therefore, an automated input tab allowing the user to insert the data of a new aircraft into the existing database was added to the tool.

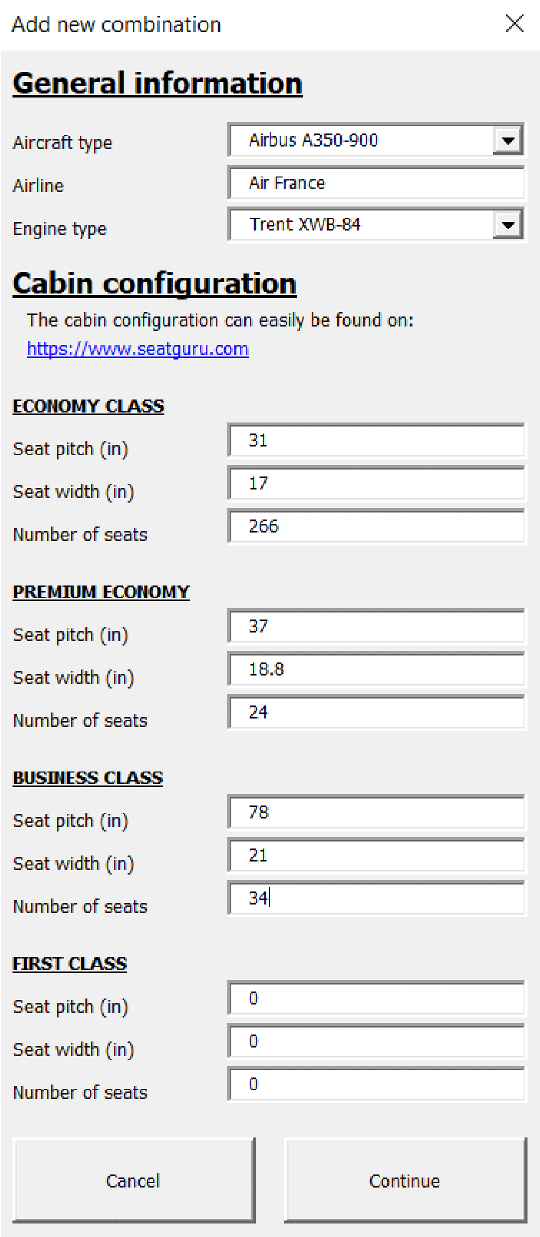

Figure 7.2 User input window

Figure 7.2 illustrates the new input window. The user first has to choose an aircraft type from the list of available aircraft. Depending on this choice, an engine type can be chosen. Afterward, the cabin configuration of the specific aircraft has to be inserted. A hyperlink to the website of SeatGuru, which has a database of airline-specific cabin configurations, is given. After clicking 'continue', the new combination is added to the database. The ecolabel for the new combination can now be calculated by following the instructions in the tool.

Additionally, the database contains a 'manufacturer standard configuration' for the most used aircraft. This means that a specific combination of an aircraft, engine type, and seating configuration specified by the manufacturer can be chosen if the exact seating configuration or the engine type is unknown. The standard configuration gives the public a general idea of the environmental impact, although the exact configuration is unknown.

The previously discussed updates to the ecolabel calculator allow anyone to calculate the ecolabel for a specific flight. Using the latest available data and the updated equations, the resulting ecolabel is a reliable source of easily accessible, easy-to-understand data that enables traveling passengers to make an educated choice among different airline offers.

7.2 Trip Emission Calculator

7.2.1 First Concept

As previously mentioned, the Ecolabel for Passenger Aircraft discussed in this thesis is only suitable to compare aircraft on a direct flight. Therefore, a first concept for a Trip Emission Ecolabel is presented. This Trip Emission Ecolabel presents the same information as the Ecolabel for Passenger Aircraft; however, it considers that a flight between two airports is not always a direct flight.

The Trip Emission Ecolabel will be explained through an example. Suppose a passenger wants to book a flight from Hamburg to Faro. Since there are no direct flights, the Lufthansa flight with a stopover in Frankfurt is chosen. On the flight between Hamburg and Frankfurt, Lufthansa operates an Airbus A320neo, while an Airbus A321 flies between Frankfurt and Faro. The environmental impact of both flights is presented in two different ecolabels, which are shown in Figure 7.3.

The environmental information from the two ecolabels should be combined into one ecolabel for the complete flight executed with two different aircraft. The fuel performance (*FP*) and the CO_2 equivalent emission ($CO_2\ eq.$) are both expressed in units of kg/km/seat. Therefore, the average fuel consumption (FP_{avg}), the average travel class fuel performance, and the average CO_2 equivalent emission ($CO_2\ eq._{avg}$) can be calculated as follows:

$$FP_{avg} = \frac{FP_1 \cdot R_1 + FP_2 \cdot R_2 + \cdots}{R_1 + R_2 + \cdots} \quad \text{and} \tag{7.1}$$

$$CO_2\ eq._{avg} = \frac{CO_2\ eq._1 \cdot R_1 + CO_2\ eq._2 \cdot R_2 + \cdots}{R_1 + R_2 + \cdots} \quad . \tag{7.2}$$

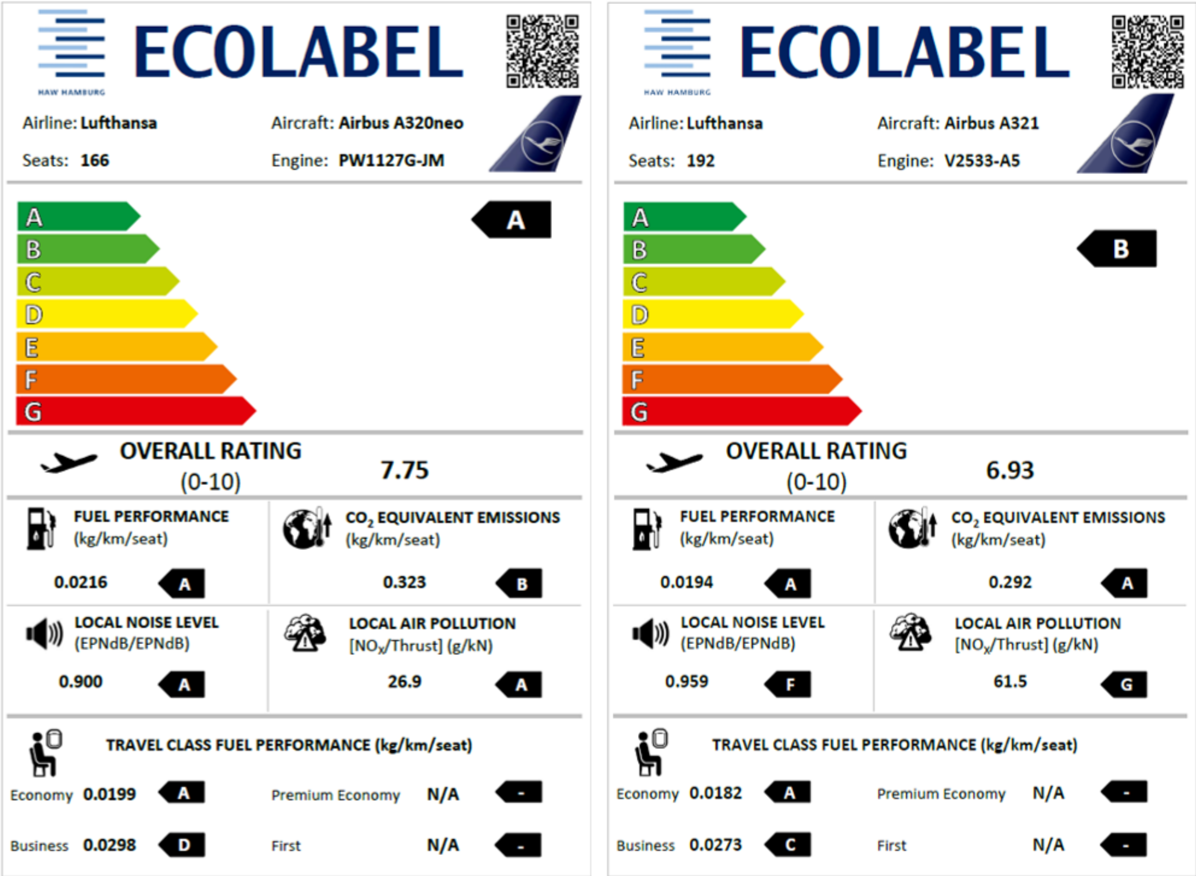

Figure 7.3 Ecolabels for the Lufthansa flight from Hamburg to Faro via Frankfurt

Equations (7.1) and (7.2) require the shortest distance (R) between the airports in question. As the earth can be approximated by a sphere, this distance cannot be represented by a straight line. Instead, the two airports are connected with a curve. Therefore, the shortest distance between two points on the earth is called the great circle distance. This is shown in Figure 7.4.

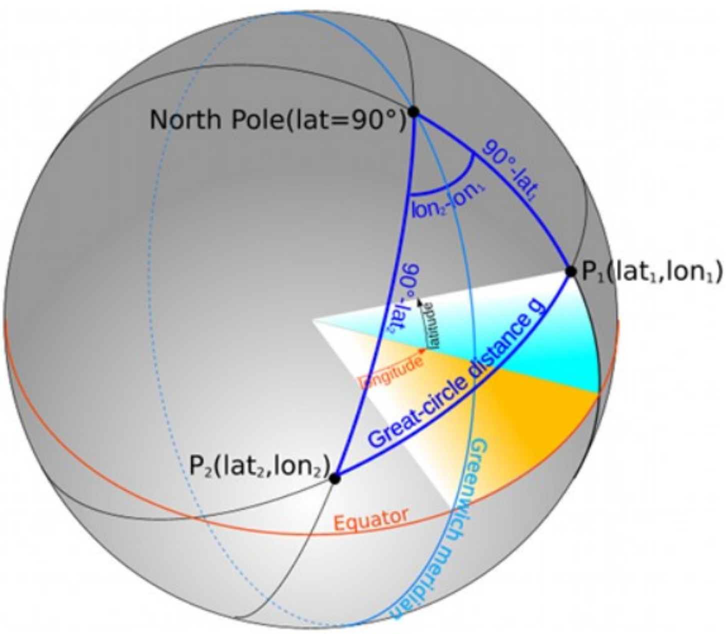

Figure 7.4 Representation of the shortest distance between two points on a sphere (Kompf 2019)

To calculate the distance between two airports, the spherical trigonometry method is used. In order to be able to use this method, the coordinates of the airports must be known. As can be seen in Figure 7.4, each airport is represented by two angles: a latitude (lat) and a longitude (lon). Kompf (2019) defines the latitude as:

> *The angle that spans itself between the center of the earth, the searched point P, and the equator (blue area in Figure 7.4). Points on the equator always have a latitude of 0, while the north pole has a latitude of 90 degrees and the south pole -90 degrees.*

Conversely, the longitude is also defined by Kompf (2019) as:

> *The angle between the center of the earth, the searched point P, and the prime meridian (yellow area in Figure 7.4). A meridian passes through the North Pole, South Pole, and all points of equal longitude. The meridian that runs through the old Greenwich Observatory was arbitrarily assigned a value of 0, making it the prime meridian or Greenwich meridian. Points east of Greenwich have a longitude between 0 and 180 degrees and points west of it from 0 to -180 degrees.*

Figure 7.4 is marked with two points: P_1 and P_2. The great circle distance between these points is to be determined. P_1 and P_2 form a spherical triangle together with the North Pole. Consequently, two sides of the triangle and one angle are known. The length of the known sides is equal to the distance between the point and the North Pole, so 90 degrees minus its latitude. The angle between the two known sides is calculated from the difference in the lengths of the two geographical points (Kompf 2019). The length of the third side can now be determined using the cosine rule.

$$\cos(R) = \cos(90° - lat_1) \cdot \cos(90° - lat_2) + \sin(90° - lat_1) \cdot \sin(90° - lat_2) \cdot \cos(lon_2 - lon_1) \tag{7.3}$$

Where

$$\cos(90° - a) = \sin(\mathrm{a}) \quad \text{and} \tag{7.4}$$

$$\sin(90° - a) = \cos(a) \quad . \tag{7.5}$$

Using Equations (7.4) and (7.5), Equation (7.3) can be simplified to

$$\cos(R) = \sin(lat_1) \cdot \sin(lat_2) + \cos(lat_1) \cdot \cos(lat_2) \cdot \cos(lon_2 - lon_1) \quad . \tag{7.6}$$

The great circle distance (R) can now be calculated by taking the arcsine of Equation (7.6) and multiplying it by the radius of the earth. In addition, Equation (7.6) must be multiplied by π/180 because the latitude and longitude are expressed in degrees instead of radians.

$$R = 6378.388 \cdot \frac{\pi}{180} \cdot \arcsin(\sin(lat_1) \cdot \sin(lat_2) + \cos(lat_1) \cdot \cos(lat_2) \cdot \cos(lon_2\text{-}lon_1)) \text{ [km]} \tag{7.7}$$

Equation (7.7) is used to calculate the great circle distance between Hamburg and Frankfurt and between Frankfurt and Faro. To check the equation, the calculated distances are compared to the great circle distance obtained from an online calculator (Great Circle Mapper). The coordinates of Hamburg are (53.63333°, 9.98333°), the coordinates of Frankfurt are (50.03333°, 8.57056°), and those of Faro are (37.01666°, -7.95°). The results are presented in Table 7.1.

Table 7.1 Great circle distance calculation

	Equation (7.7) (km)	Great Circle Mapper (km)
HAM-FRA	412	413
FRA-FAO	1961	1959
HAM-FAO	2308	2308

It must, however, be noted that the flight from Hamburg to Faro via Frankfurt deviates from the great circle distance between Hamburg and Faro. As shown in Figure 7.5, the deviation from the great circle distance is around 15% of the great circle distance when making one stop.

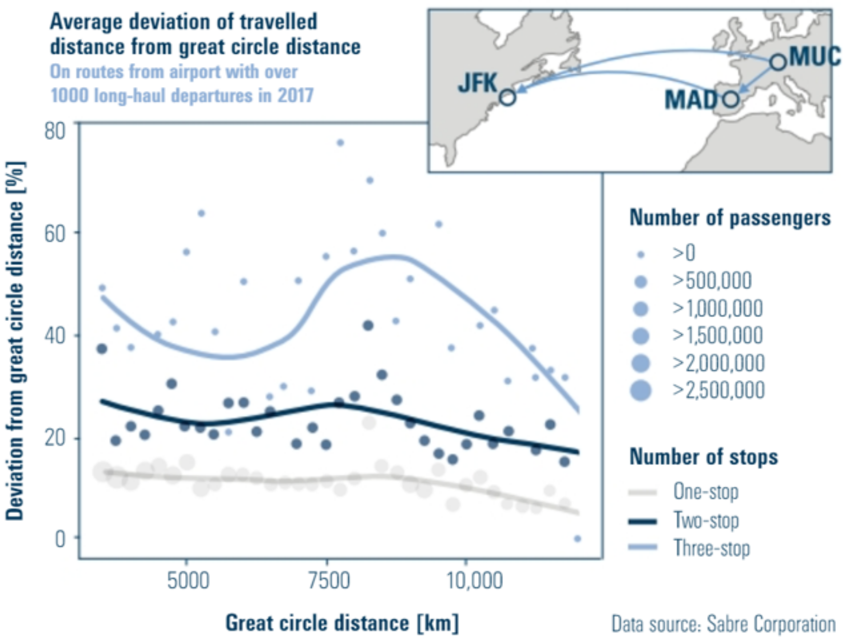

Figure 7.5 Deviation from the great circle distance as a function of the great circle distance and the number of stops (Batteiger 2019)

In addition to the deviation from the great circle distance due to stopovers, the actually flown distance also depends on inefficiencies in the air traffic system caused by air traffic management (ATM). Much of the flight inefficiency is due to the terminal area procedures, airspace fragmentation, and military zones that have to be avoided, but also the choice of departure and arrival runway has an impact on the flown distance (Kettunen 2005). The 50 NM circles around the departure and arrival airports in Figure 7.6 represent the inefficiency of the departure and arrival part of the flight. The enroute inefficiency (presented by the blue line) and the great circle distance (green line) are also shown in Figure 7.6.

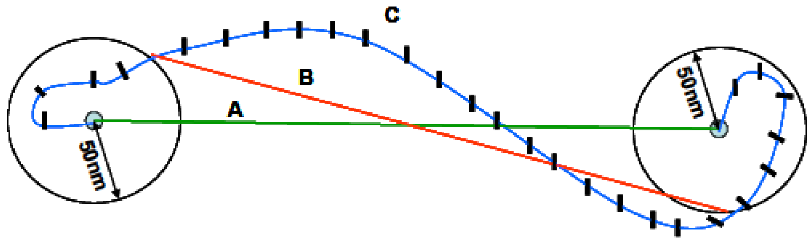

Figure 7.6 Representation of flight inefficiency (Kettunen 2005)

Kettunen (2005) found that the inefficiency of a flight of between 200 and 1100 km within Europe is approximately 10.2% of the great circle distance. However, Eurocontrol published data on flight efficiency for 2007 in its "Performance Review Report 2007" (DLR 2008). The conclusion was that the average distance of all flights is approximately 5.8% longer than the great circle distance. This 5.8% corresponds to an extra distance of on average 48.9 km per flight, based on all flights recorded by Eurocontrol (DLR 2008). Therefore, it was decided to charge an additional distance of 27 nautical miles or 50 kilometers for each flight to account for the flight inefficiencies caused by ATM. This number of 50 kilometers is also used in the Atmosfair Flight Emissions Calculator (Atmosfair 2016).

The remaining two indicators are independent of the flown distance. The local noise level (*LNL*) and the local air pollution (*LAP*) are both determined for one LTO cycle. Therefore, to calculate the average local noise level (LNL_{avg}) and the average local air pollution (LAP_{avg}), it is sufficient to take the average value of the indicator in question.

$$LNL_{avg} = \frac{LNL_1 + LNL_2 + \cdots}{n_{flights}} \tag{7.8}$$

$$LAP_{avg} = \frac{LAP_1 + LAP_2 + \cdots}{n_{flights}} \tag{7.9}$$

The average values calculated with Equations (7.1), (7.2), (7.8), and (7.9) are rated according to the in Chapter 5 defined rating scales. Additionally, the overall rating can be calculated with Equation (5.57) and is also rated according to the rating scale defined in Section 5.6. The Trip Emission Ecolabel for the flight between Hamburg and Faro with a stopover in Frankfurt is presented in Figure 7.7.

For now, the calculation of this Trip Emission Ecolabel has to be done manually by collecting all the data in a new Excel table. However, all the required information to calculate the Trip Emission Ecolabel can be obtained from the ecolabels for each part of the flight; only the great circle distance has to be calculated using Equation (7.7) or an online calculator. In the future, an automated tool should be developed.

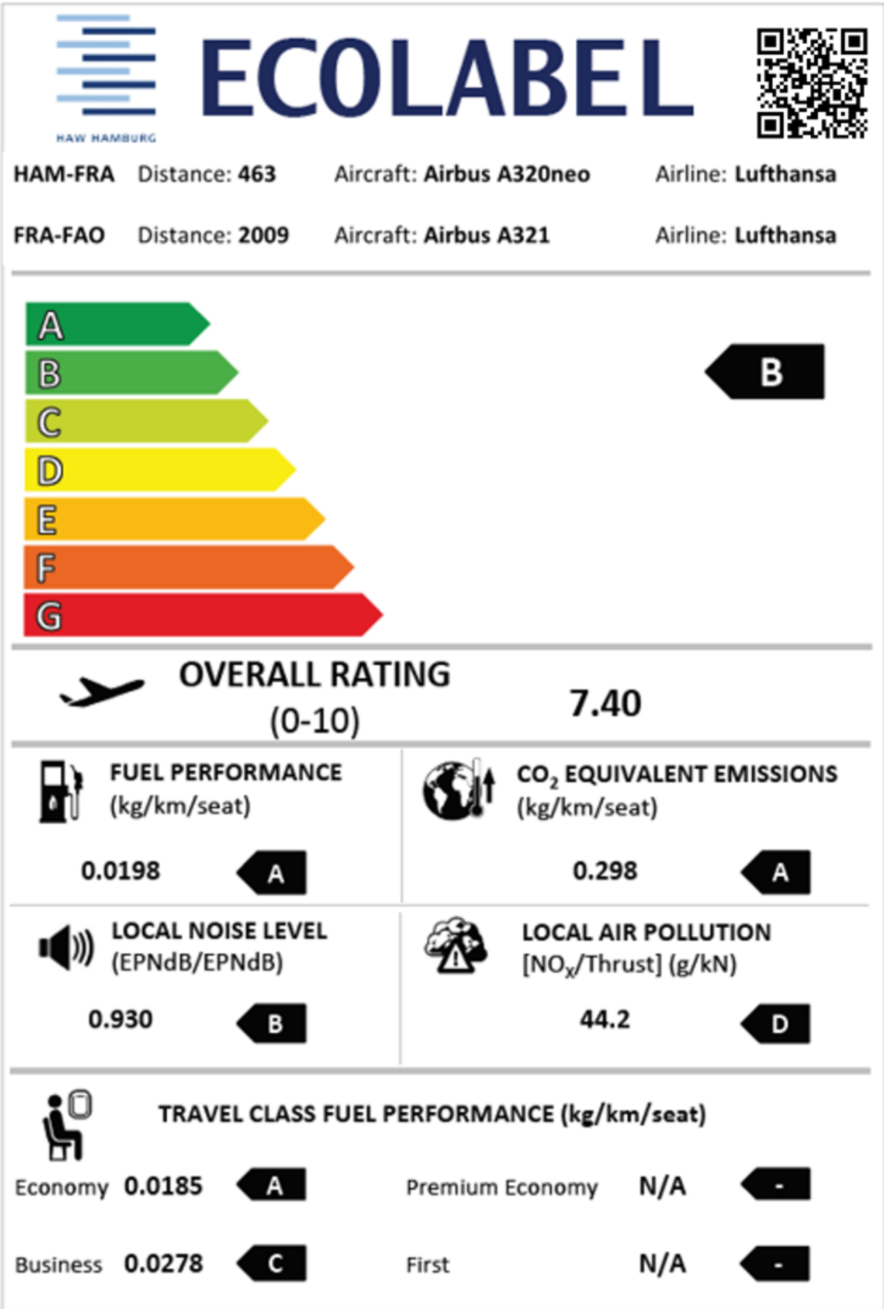

Figure 7.7 Trip Emission Ecolabel for a flight between Hamburg and Faro via Frankfurt

7.2.2 Second Concept

The previously discussed concept of a Trip Emission Ecolabel can be helpful to inform interested passengers of the environmental impact of the chosen flight. However, this ecolabel has its shortcomings. First of all, the presented numbers are average values which only give a rough idea of the environmental impact of a flight. The flown distance and, therefore, the total environmental impact is not considered. Secondly, the difference in environmental impact between a direct flight and a flight with one or more stopovers is not presented. Lastly, the averaging of the local noise level and the local air pollution should be adjusted. As a journey consists of multiple legs flown by different aircraft, the impact of the noise should scale up with the number of flights. If, for example, one of the legs is flown on an extremely noisy aircraft and another leg on a very quiet aircraft, the average local noise pollution does not give an accurate impression of the total impact regarding noise pollution in the vicinity of airports. Additionally, the local air pollution is presented as the amount of emitted NO_X per kilonewton of thrust. If, for example, a big aircraft is used for a short flight and a relatively small aircraft for a long flight, the average local air pollution will strongly be influenced by the big aircraft's emissions, although it only represents a small percentage of the total distance of the journey.

The second concept of the Trip Emission Calculator presents the total mass of fuel the aircraft consumes per passenger, the total equivalent CO_2 emission per passenger, and the total local air pollution (NO_X) per passenger for the entire trip. In addition, the local noise levels of the different flights within the journey are added together.

$$\mathrm{FP} = FP_1 \cdot R_1 + FP_2 \cdot R_2 + \cdots \quad \text{[kg/seat]} \tag{7.10}$$

$$CO_2\ eq. = CO_2\ eq._1 \cdot R_1 + CO_2\ eq._2 \cdot R_2 + \cdots \quad \text{[kg/seat]} \tag{7.11}$$

$$LNL = LNL_1 + LNL_2 + \cdots \quad \text{[EPNdB/EPNdB]]} \tag{7.12}$$

$$LAP = \frac{LAP_1 \cdot T_1}{n_{airline,1}} + \frac{LAP_2 \cdot T_2}{n_{airline,2}} + \cdots \quad \text{[g/seat]} \tag{7.13}$$

The required distance in Equations (7.10) and (7.11) is again the great circle distance discussed in Section 7.2.1 plus the additional distance of 27 nautical miles or 50 kilometers for each flight to account for the flight inefficiencies caused by ATM. In Equation (7.13), T represents the rated thrust of the engines at sea level, and n is the number of seats.

The Trip Emission Ecolabel (TEE) also compares the results from Equations (7.10) to (7.13) to the emissions of a reference flight. This reference flight has to be defined as a flight of a particular reference distance flown by a reference aircraft. According to the DLR (2008), the average length of a flight is around 2400 kilometers. In addition, the Boeing 737-800 was chosen as the reference aircraft because the World Airliner Census 2020 (Appendix B) shows that in 2020 the Boeing 737-800 represented over 16% of the active global aircraft fleet. In conclusion, the average flight is a direct flight of 2400 km, performed by a Boeing 737-800.

An additional key figure was introduced for each indicator in Equations (7.10) to (7.13) to enable comparison between the chosen trip and the reference flight. This new key figure is defined as the ratio between the indicator in question from the TEE and the same indicator for the reference flight.

$$Comparison = \frac{Indicator_{TEE}}{Indicator_{ref}} \tag{7.14}$$

The new key figures for every environmental indicator on the Trip Emission Ecolabel are again combined into one score: the environmental score. The lower this score, the smaller the environmental impact of the chosen flight(s) will be. If this score is equal to one, the impact is the same as the Boeing 737-800. Conversely, if the score is lower or higher than one, the impact is lower or higher than the impact of the reference flight. The environmental score can be calculated by using the weighting factors defined in Section 5.6.

$$Environmental\ score = 0.2 \cdot FP_{comp.} + 0.4 \cdot CO_2\ eq._{comp.} + 0.2 \cdot LNL_{comp.} + 0.2 \cdot LAP_{comp.} \quad (7.15)$$

In Figure 7.8, the previous example of a flight from Hamburg to Faro via Frankfurt is presented in the form of the second concept of a Trip Emission Ecolabel. To explain the above equations further, some example calculations are performed below.

The fuel performance, CO_2 equivalent emissions, local noise level, and local air pollution for the two flights were given in Figure 7.3. Additionally, the distance of each leg of the flight was given in Figure 7.7. Using Equations (7.10) to (7.13), the following results are found:

$$\mathrm{FP} = 0.0216 \cdot 463 + 0.0194 \cdot 2009 = 49.0 \quad \text{[kg/seat]} \quad (7.16)$$

$$CO_2\ eq. = 0.323 \cdot 463 + 0.292 \cdot 2009 = 736 \quad \text{[kg/seat]} \quad (7.17)$$

$$LNL = 0.900 + 0.959 = 1.86 \quad \text{[EPNdB/EPNdB]]} \quad (7.18)$$

$$LAP = \frac{26.9 \cdot 120.44}{166} + \frac{61.5 \cdot 140.56}{192} = 64.5 \quad \text{[g/seat]} \quad (7.19)$$

With these results, a comparison can be made to the reference flight. Only one example is given: the comparison between the fuel consumptions.

$$Comparison = \frac{49.0}{2400 \cdot 0.0271} = 0.753 \quad (7.20)$$

This result means that for a flight between Hamburg and Faro, with a stopover in Frankfurt, only 75% percent of the fuel required for the reference flight is consumed. Therefore it can be concluded, that the flight with a stopover is better than the reference flight as less fuel is consumed.

Finally, the environmental scare can be calculated:

$$Environmental\ score = 0.2 \cdot 0.753 + 0.4 \cdot 0.897 + 0.2 \cdot 1.95 + 0.2 \cdot 2.95 = 1.42\,. \quad (7.21)$$

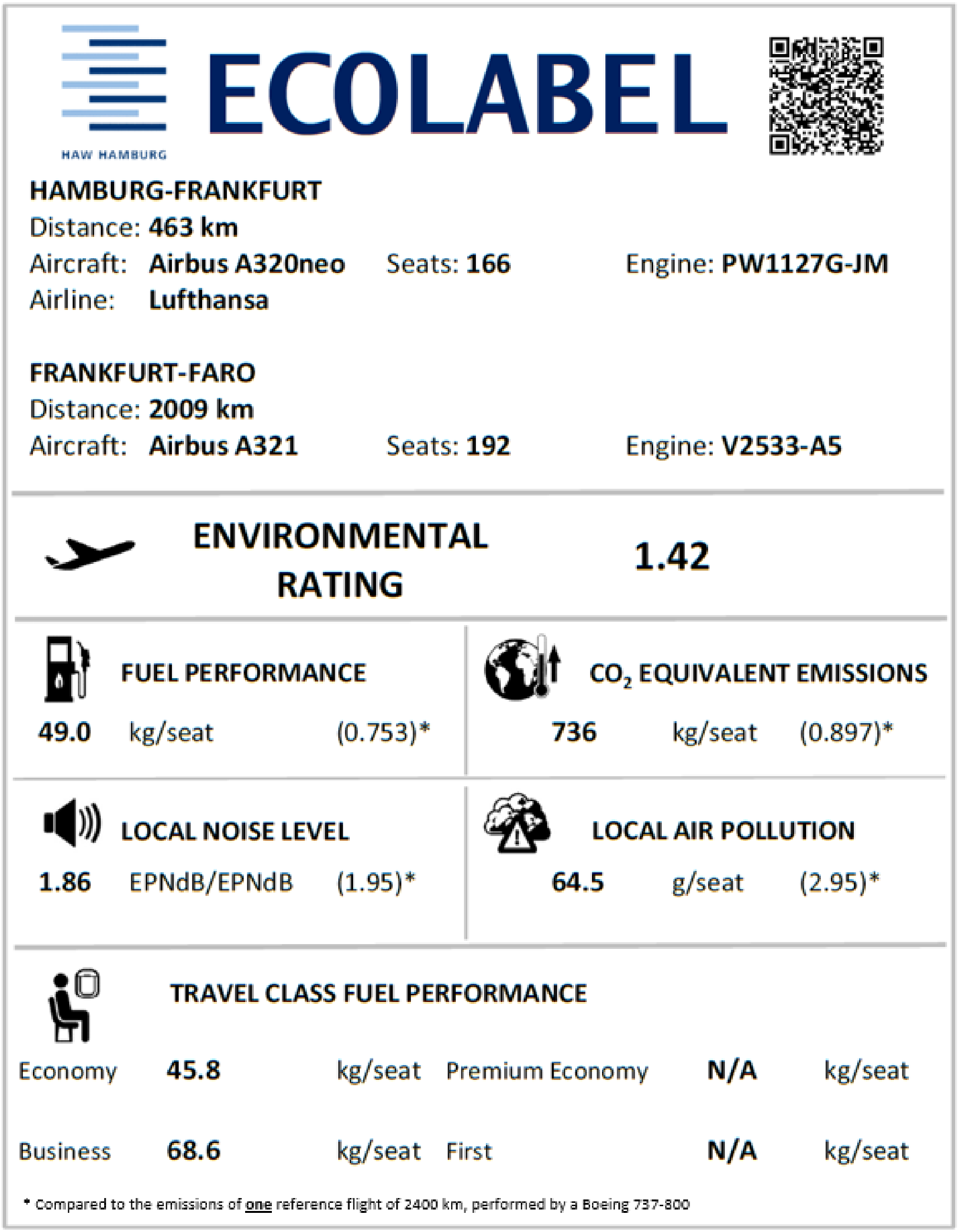

Figure 7.8 Second concept of a Trip Emission Ecolabel

7.2.3 Third Concept

As a third option for the Trip Emission Calculator, it is proposed to integrate the Trip Emission Calculator into the booking engines. Some booking engines already give customers the option to sort the suggested flights based on their CO_2 emissions. Therefore, the passenger can easily choose the flight that emits the least CO_2. In this chapter, the Momondo booking engine is presented.

Momondo calculates the average amount of equivalent CO_2 emitted per person for a particular route. The CO_2 emission of the different flight options is given as a percentage of the average amount of emitted CO_2. For the CO_2 calculation, Momondo uses Atmosfair's Flight Emissions Calculator (Atmosfair 2016). Based on the customer's input, Momondo searches for flight options, separates each trip into airport-to-airport segments, sends the individual segments to Atmosfair to calculate the CO_2 emissions, and bundles the flight options back together to show the final CO_2 emissions for each option (Momondo 2020). The drawback with Momondo is that a full environmental approach including also local air pollution, noise (and maybe also resource depletion due to fuel burn) is missing. The presented metrics from the Trip Emission Calculator should be included in a booking engine. This can only be done in cooperation with the operator of such a booking engine.

As is the case with the Ecolabel for Passenger Aircraft, Atmosfair bases its CO_2 calculation on the aircraft type, engine type, and cabin configuration. Additionally, the following factors are taken into account (Momondo 2020):

- **Airline rating:** gives an overall efficiency rating on more than 200 airlines based on detailed information like aircraft type, seating capacity, and load factor.
- **Passenger load:** the percentage of the airplane's seats that are occupied during a flight. This percentage comes from the individual airlines and depends on factors like ticket prices, aircraft type, and flight region.
- **Cargo load and capacity:** factors that take into account the cargo load and maximum load capacities of the airlines. These both depend on factors like passenger load, distance, aircraft type, and cargo prices.
- **Flight profile:** calculates the fuel consumption of all the different phases of a flight (departure to take-off, climb phase, cruise phase, descent phase, and landing) based on flight distance, altitude, aircraft type, and passenger and cargo load.
- **Airplane taxiing before and after the flight:** a fixed amount of 2.5 kg kerosene per passenger is included for each airport-to-airport segment of the trip to take into account taxiing times before take-off and after landing.
- **Non-carbon emissions and warming effects:** nitrogen oxides and ozone emissions, as well as the formation of condensation trails and ice clouds, are taken into account. As with the Ecolabel for Passenger Aircraft, those warming effects are converted into CO_2 equivalents.

Figure 7.9 presents the different flight options found by Momondo, sorted from lowest to highest CO_2 emission. As can be seen, the travel time and price are not taken into account. Additionally, effects like local air pollution and local noise levels are also not considered. The complete calculation method is described by Atmosfair (2016).

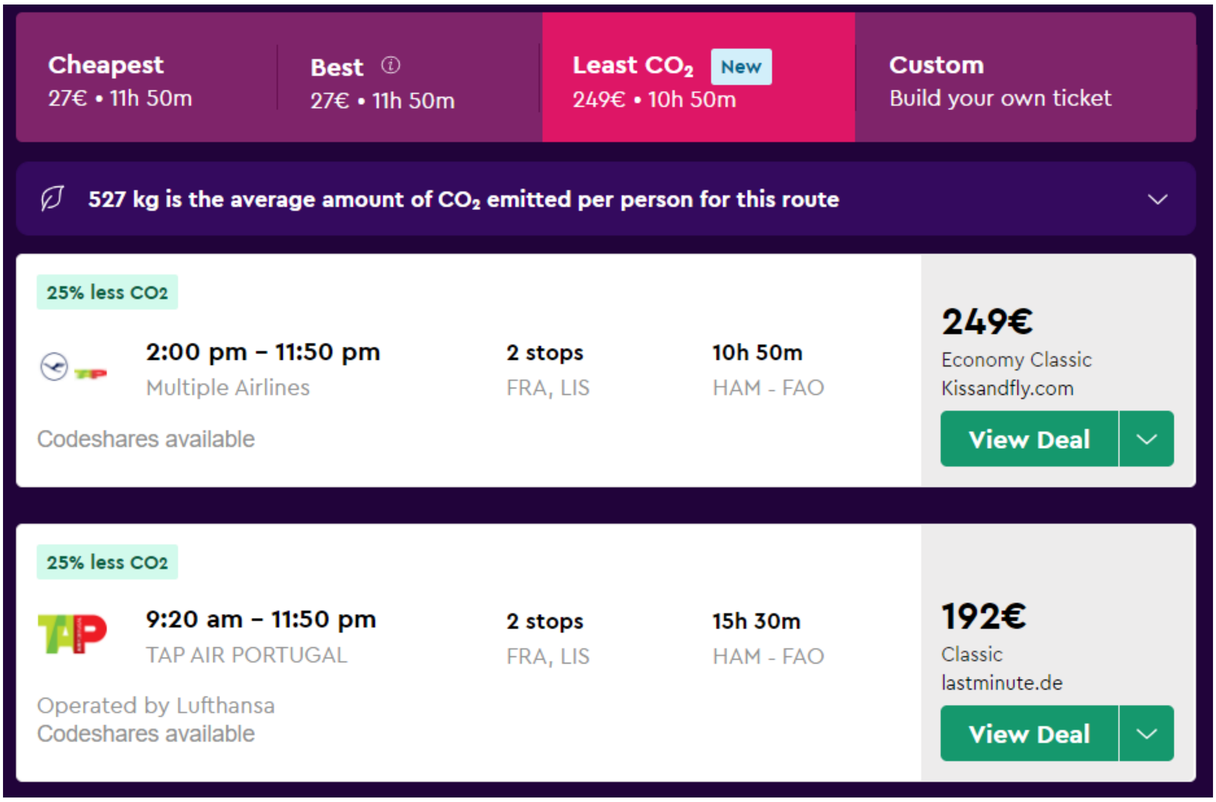

Figure 7.9 Different flight options for a trip between Hamburg and Faro, sorted according to the CO_2 emission (Momondo 2021)

7.2.4 Aircraft versus Train

The Ecolabel for Passenger Aircraft and the Trip Emission Ecolabel only allow comparing different aircraft and different airline offers. However, sometimes there is an alternative to flying. In this chapter, the Excel tool that was designed by Scholz (2021) to compare the environmental impact of aircraft to the impact of trains is briefly discussed. The metrics energy consumption (resource depletion), CO_2, and equivalent CO_2 (global warming) are studied.

Each means of transport has its character in terms of energy consumption. In the case of trains, the energy consumption is usually dominated by the energy consumed for compensating the air drag and the energy consumed to accelerate the train to the cruising speed (Andersson 2006). The faster a train travels in between stops and the more stops there are, the higher the energy consumption (Feng 2014). This is illustrated in Figure 7.10. However, regenerative braking can reclaim approximately 5% of the consumed energy. The higher energy consumption of trains due to frequent stops is generally accepted without any compensation due to the advantage of the extra service to stations on the way. The rail characteristics mean that trains' energy consumption always has to be specified together with the route. This makes it challenging to provide general information on the energy consumption of trains. It can, however, be seen from Figure 7.11 that the energy consumption per passenger kilometer is decreasing steadily.

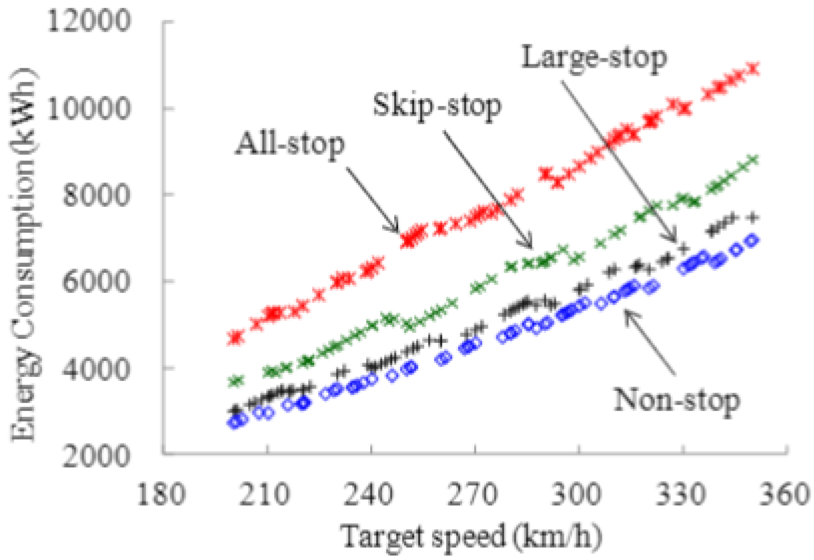

Figure 7.10 Energy consumption of trains as a function of the target speed and the number of stops (Feng 2014)

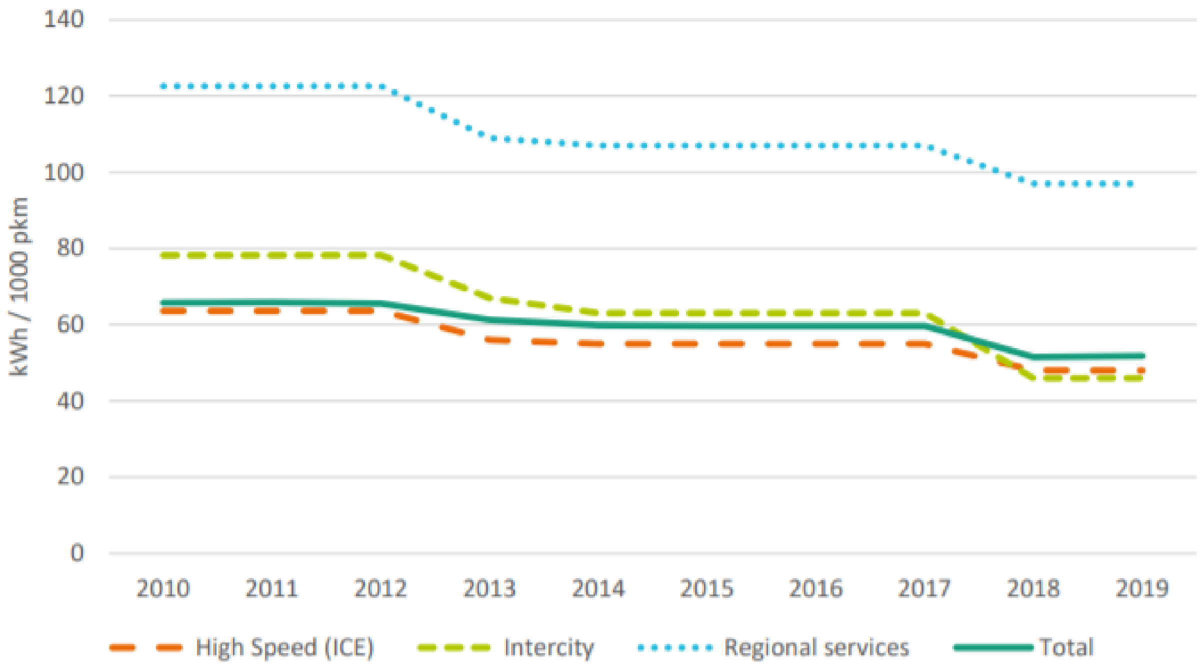

Figure 7.11 Energy consumption of a train per passenger kilometer over time (Fraunhofer ISI 2020)

Airplanes consume kerosene, while trains consume electricity. However, these resources are expressed in different units. Luckily, both energy sources can be converted to an amount of required primary energy:

- **Airplane:** How much primary energy has to be supplied to the refinery?
- **Rail:** How much primary energy has to be supplied to the power plant?

Since the environmental impact is not just about energy consumption, the amount of consumed fuel or electricity must be converted to the corresponding amount of CO_2. As shown in Table **5.4**, an aircraft emits 3.16 kilograms of CO_2 per burned kilogram of Jet A-1 fuel. The calculation of the CO_2 emission related to trains is more complex. First, one has to know how much of the primary energy in electricity is fossil energy and convert this amount of fossil energy to a mass of fossil fuel. This amount of fossil fuel can then be converted to a mass of CO_2 with the factor of 3.16 kilograms of CO_2 per burned kilogram of the fossil resource. In Figure 7.12 it can be seen that the CO2 emission for trains (in 2018) is approximately 35 grams per passenger kilometer.

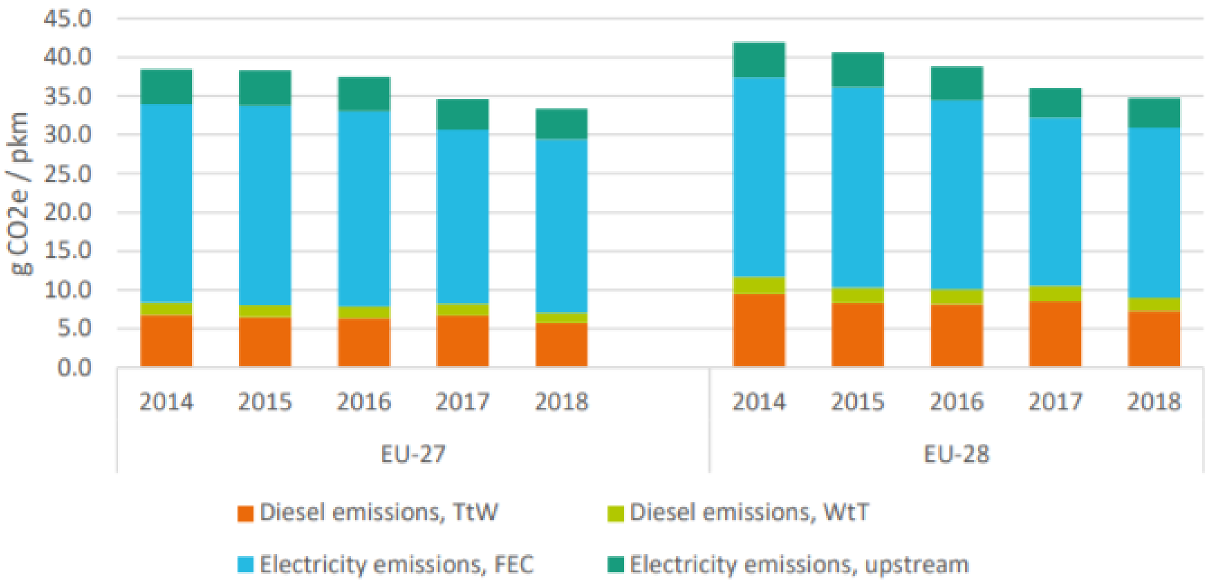

Figure 7.12 CO_2 emission for trains per passenger kilometer (Fraunhofer ISI 2020)

As discussed in Chapter 5.4, an aircraft also causes non-CO_2 effects. Therefore, the term equivalent CO_2 was introduced. The complete calculation of the CO_2 equivalent can be found in Chapter 5.4; However, a multiplication factor of 2.7 will be used to go from CO_2 emission to equivalent CO_2 emission, as discussed by Jungbluth (2019).

Using the previous information, Scholz (2021) compared aircraft to trains. The conclusion, based on a German electricity mix, was that in 2021 aircraft

- use 2.8 times as much primary energy as trains,
- produce 6.3 times as much CO_2 as trains, and
- produce 17 times as much equivalent CO_2 as trains.

Since the electricity (and with it the train) is getting greener over time, the difference between the airplane and the train increases. Therefore, Scholz (2021) concluded that in 2050 aircraft

- use 4.1 times as much primary energy as trains,
- produce 17 times as much CO_2 as trains, and
- produce 46 times as much equivalent CO_2 as trains.

Additionally, Scholz (2021) also discussed aircraft flying on Sustainable Aviation Fuel (SAF). This will not be discussed here; only the findings of Scholz (2021) are presented. In 2021, aircraft flying on SAF

- use 26 times as much primary energy as trains,
- produce 26 times more CO_2 as trains, and
- produce 49 times as much equivalent CO_2.

It seems aircraft are far away from zero-emission and have no chance to reach the environmental friendliness level of trains. Their burden to the environment is a factor between 2.8 and 49 higher than the environmental burden of trains. The environmental burden depends on the applied metric: energy consumption, CO_2, or equivalent CO_2. Sustainable Aviation Fuel makes the plane's absolute values as well as the comparison with trains rather worse than any better.

8 Documentation

Thus far, this thesis extensively discussed the environmental impact of aircraft and how this impact can be translated into four representative impact categories. However, if the traveling public wants to know more about the ecolabel, it is doubtful that this thesis will be chosen as a source of information. Therefore, every part of the ecolabel was explained in a short and understandable text. These texts were then combined into one flyer with the same layout as the ecolabel. This flyer is shown in Figure 8.1. This is the text that will be displayed when the reader scans the QR code on the ecolabel. The QR code leads to a persistent URL (PURL), which is https://purl.org/ecolabel/info.

RATING METHOD

Each score in the ecolabel is valid for a specific type of aircraft with a particular type of engine operated by a given airline. All these variables are defined at the top of the label.

The ecolabel consists of several environmental impact indicators, each with its score. The lower this score is, the better. This is also represented by a scale from A to G. An A score is very good, while a G score is relatively weak.

OVERALL RATING

The overall rating summarizes the four impact indicators in one single rating: fuel performance, CO_2 equivalent emissions, local noise level and local air pollution. This results in a score out of 10, which can be translated into an A to G rating. A higher score means a better overall rating and, therefore, a more environmentally friendly aircraft.

FUEL PERFORMANCE

The fuel performance rating expresses the amount of fuel (in kilograms) an aircraft burns per travelled kilometer and per available seat. The fuel performance can also be expressed as an A to G rating.

CO_2 EQUIVALENT EMISSIONS

The carbon dioxide (CO_2) equivalent is used to compare the emissions from various greenhouse gases based on their global warming potential (GWP). This global warming potential is the amount of heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that the same mass of CO_2 would absorb.

In short, the CO_2 equivalent emission is the amount of emitted CO_2 plus the amount of other emitted gases like nitrogen oxides (NO_X) and water vapor converted to the equivalent amount of carbon dioxide with the same global warming potential.

LOCAL NOISE LEVEL

The local noise level is a metric that describes the average noise level produced by a specific aircraft during 3 phases of a flight in the vicinity of airports.

LOCAL AIR POLLUTION

Aircraft engines form pollutants in the air. Besides carbon dioxide (CO_2), water (H_2O) and sulfur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), unburned hydrocarbons (HC) and soot are generated. The amount of emitted nitrogen oxides is defined as the key indicator to rate the local air quality. Therefore, the local air pollution is a measure of the amount of emitted NO_X.

TRAVEL CLASS FUEL PERFORMANCE

The travel class fuel performance is the same as the standard fuel performance. However, it does consider the travel classes that are available on the specific aircraft. The more comfort and, therefore, the more space per seat is desired, the larger the fuel consumption per seat will be. This is reflected in a rating per travel class.

Figure 8.1 Flyer to explain the ecolabel to the general public

In addition to this flyer, an article that could be published in an inflight magazine was written. The article explains more of the background of the ecolabel and why it is needed in today's world. Additionally, the text from the flyer is also included. An example of an inflight magazine article is included in Appendix H.

For now, the previously mentioned documents are only available in English. However, the flyer and even the inflight magazine article can easily be translated and made available on the future website for the Ecolabel for Passenger Aircraft.

9 Summary and Conclusions

9.1 Summary

After studying the ISO 14020 family of standards, it was chosen to define the Ecolabel for Passenger Aircraft as a type III environmental declaration according to ISO 14025: Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures. The Hamburg University of Applied Sciences was chosen as the program director, and the first steps to comply with the ISO standard were made, including the drafting of the General Program Instructions.

Based on the life cycle impact assessment method called ReCiPe, it was found that the environmental impact related to aviation is mainly caused by three impact categories: fuel performance, CO_2 equivalent emissions, and local air pollution. Additionally, due to adverse effects on health, quality of life, and well-being, local noise pollution was also considered an impact category, although ReCiPe does not mention it. These environmental impact categories were quantified using different sources of official, certified, and publicly available emission data.

It is important to note that not all data necessary to calculate the ecolabel are directly ascertainable. For example, certified data for aircraft fuel consumption are still not made accessible to the public. Therefore, the fuel consumption was determined by using the extended payload-range diagram and data published by the manufacturer in the airport planning document. In order to allow for comparison between different aircraft, the fuel consumption was normalized by dividing it by the actual number of seats. The normalized fuel consumption was afterward rated using the fuel performance rating scale.

Regarding aircraft fuel consumption, a correction factor for the fuel consumption based on the extended payload-range diagram was introduced. This correction factor, multiplied by the cruise fuel consumption, estimates the fuel consumption for the entire flight, including the LTO cycle. Although this multiplication factor is not named in the ecolabel, it can be used to compare the total fuel consumption of different flights on the same route.

It was found that the air quality in the vicinity of airports is affected by the emission products generated by (incomplete) fuel combustion in aircraft engines. After studying the different pollutants emitted by an aircraft engine, the impact of the NO_X emission appeared to be far more significant than the impact of the particulate matter and ozone formation potential. Therefore, the emitted NO_X was used as the critical indicator in evaluating the local air pollution. The NO_X emission was again normalized by dividing it by the maximum rated thrust at sea level of the engine, allowing for comparison with other engines. However, emission data for turboprop engines are not publicly available. Therefore, the Local Air Pollution rating cannot be calculated for turboprop-powered aircraft using publicly available data.

Previous research showed that CO_2 and NO_X emissions combined with aviation-induced cloudiness (AIC) make up the majority part of aviation-induced radiative forcing. Therefore, these three types of emissions were used to define the rating scale of the climate impact in the ecolabel. The climate impact was expressed in terms of the CO_2 equivalent emission, which was defined as the amount of emitted CO_2 plus the emission contributions of NO_X and AIC converted to the equivalent amount of carbon dioxide with the same global warming potential. It was, however, recently discovered that the influence of the contrails and cirrus clouds is more severe for the environment than thought before. Even so, there is still much uncertainty over the actual RF value of AIC. Therefore, the CO_2 equivalent emission is based on the best available data regarding the AIC RF value, although this data is highly uncertain.

Notwithstanding that noise pollution is not considered an impact category by ReCiPe, aircraft noise is often considered a significant noise pollutant and is especially an issue near airports and the densely populated areas surrounding them. Therefore, the local noise level was included as an additional environmental impact category. The noise levels produced by aircraft are measured in compliance with the applicable noise standards defined in ICAO Annex 16, Volume I – Aircraft Noise. The local noise level was subsequently defined as the average noise index value for the three reference points described in ICAO Annex 16, Volume I.

Ultimately, an overall rating that summarizes the four indicators in one single rating was established. Therefore, weighting factors for each indicator were introduced, based on the results of previous research regarding the life cycle assessment. As the local air pollution for turboprop-powered aircraft could not be calculated, two different overall rating scales were established. However, it is still possible to compare jet and turboprop aircraft.

The four indicators and their ratings and the overall rating were collected in the Ecolabel for Passenger Aircraft, which is based on the EU Energy Label. In addition, two documents were developed to help the traveling public understand the ecolabel and its purpose: a flyer and an inflight magazine article.

Chapter 7 discussed the ecolabel calculator tool. Through updates of the ICAO, EASA, and EMEP/EEA databases and by adding new aircraft-engine-airline combinations to the tool, the final ecolabel calculator tool was obtained.

Finally, different Trip Emission Ecolabels were introduced to compare different flight options when a stopover has to be made. The first proposal looks the same as the Ecolabel for Passenger Aircraft. However, it was found that this label has its shortcomings. Therefore, a second label that illustrated the total environmental impact of a flight and compared this impact to a reference flight was introduced.

9.2 Conclusions

The COVID-19 pandemic combined with the growing environmental awareness of humankind has caused the passenger numbers to drop significantly. Nevertheless, aviation is still indispensable in today's globalizing world, and people should never have to stop flying. However, to make this happen, it is crucial to adequately inform the traveling public about the impact of their choices. Passengers have to understand that they should select a flight on the shortest possible route and select the best combination of aircraft and airline. Therefore, the Ecolabel for Passenger Aircraft is an indispensable tool in the fight against global warming.

Regardless of the imperfections, the Ecolabel for Passenger Aircraft will help the traveling public make more sustainable choices when choosing to fly. The ecolabel as a single source of easily accessible, easy-to-understand data will enable the traveling passengers to make an educated choice among different airline offers (a specific aircraft with a particular seating arrangement) such that the selected flight is the least environmentally damaging. Additionally, the ecolabel should encourage aircraft manufacturers and airlines to optimize their products to achieve a good score for every environmental impact category and an excellent overall rating. In the end, the ecolabel can be used as a marketing tool for both aircraft manufacturers and airlines.

However, the most important conclusion is that using an ecolabel will not solve the environmental issue. It should make passengers aware of their choices. Aware of the environmental impact, not only of a flight but of all alternatives. It should help them decide if the environmental impact is worth the trip or if the trip can be undertaken using a different, more environmentally friendly mode of transport. The ecolabel should foster the debate on the environmental impact of different transport options based on the neutral scientific methods and data presented in this work. As the metrics for the Ecolabel for Passenger Aircraft were defined in terms of a consumed amount of energy per passenger and per unit of distance, the ecolabel is an excellent foundation to develop similar metrics for different modes of transport. This will allow comparing different transport options for a specific route.

10 Recommendations

As mentioned in Chapter 3, the type III environmental label requires a PCR document. It was found that a PCR document for "passenger commercial airplanes" was prepared by Bombardier Aerospace (2015). Unfortunately, this document was only valid until June of 2020; however, the PCR is being updated, but the new version was not yet published at the moment of writing. Therefore, it is important to verify that the new document meets the requirements whenever it is released. If the updated PCR does not meet the requirements, a new one will have to be drawn up. This thesis can, however, serve as a basis for the new PCR document.

The total fuel consumption of a complete flight, including the LTO cycle, can be calculated with the multiplication factor of 0.84, mentioned in Section 5.2.5. It might be useful if the amount of emitted CO_2 per passenger for an entire flight is calculated using this fuel consumption and the emission index of CO_2. This emitted CO_2 mass should enable the passenger to compensate for the CO_2 emission of the flight. Alternatively, the second Trip Emission Ecolabel can be used for the same purpose.

The local air pollution could not be calculated for turboprop aircraft due to a lack of publicly available data. However, it was found that the Swedish Defense Research Agency (FOI) maintains a database of emission indices of NO_X, HCs, and CO for turboprop engines. The data is considered as being the best available (FOI 2019). Unfortunately, the database is not publicly available; however, it can be distributed on certain conditions and after the International Coordinating Council of Aerospace Industries Associations' (ICCAIA) concurrence. Therefore, in order to obtain a better comparison between jet aircraft and turboprop aircraft, it is recommended to request access to the FOI database.

There is still much uncertainty about the environmental impact of aviation-induced cirrus clouds. Additionally, a lot of uncertainty exists over the forcing factors that represent the altitude effects of certain pollutants. Therefore, it would be good to research these topics or keep an eye on the ongoing research on these subjects to establish a better equivalent CO_2 emission rating in the future.

Section 5.4.7 presented a method to calculate the cruise altitude based on the known cruise altitude of a group of reference aircraft. However, this group of reference aircraft was defined by Van Endert (2017) and does not represent the modern commercial airliners that are in service today. The list of aircraft has not yet been updated because it was tough to find the most recent necessary information in the literature as the access to libraries was limited due to the coronavirus. An update of the reference group of aircraft and the required data is therefore recommended.

The Ecolabel for Passenger Aircraft is based on a lot of data from different publicly available databases. These databases are regularly supplemented and updated. Additionally, the World Airliner Census, which is the base for the list of reference aircraft needed to calculate some of the metrics, is updated every year. It goes without saying that the group of reference aircraft and the databases for the Ecolabel for Passenger Aircraft must also be updated at regular intervals.

The QR code on the ecolabel directs to the flyer that explains the different parts of the label. In the future, the code should direct to an Ecolabel for Passenger Aircraft website. This website should include the information about the ecolabel, but also the Ecolabel Calculator and the supplementary information required for a type III environmental label (see Section 6.2). Additionally, the website and the information about the ecolabel should be available in different languages.

Finally, the Trip Emission Calculator should be automated and made more user-friendly.

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Appendix A – Fuel: EEA Master Emission Calculator

Table A.1 Defining a multiplication factor to calculate the total fuel consumption

Aircraft type	$C_{extende\ payload\text{-}range\ diagram}$ (kg/km)	Stage length (km)	$m_{fuel,total}$ (kg)	C_{total} (kg/km)	% $C_{extende\ payload\text{-}range\ diagram}$
Airbus A319	3.672	2315	6699.3	2.894	0.79
Airbus A320	3.993	1941	6329.1	3.261	0.82
Airbus A321	3.725	2108	8487.5	4.027	1.08
Airbus A330-200	8.388	4291	29023.3	6.764	0.81
Airbus A330-300	8.675	3861	25163.4	6.517	0.75
Airbus A340-300	10.248	5000	40351.0	8.070	0.79
Airbus A340-600	11.412	5389	53982.3	10.017	0.88
Airbus A350-900	7.808	5399	31964.9	5.921	0.76
Airbus A380-800	16.981	6065	90508.4	14.922	0.88
ATR 42	1.961	484	787.7	1.626	0.83
ATR 72	2.160	463	874.6	1.889	0.87
Boeing 717-200	4.255	1092	3593.4	3.289	0.77
Boeing 737-300	3.759	1719	6045.9	3.516	0.94
Boeing 737-400	4.595	1629	6229.2	3.824	0.83
Boeing 737-500	4.832	1455	4970.4	3.416	0.71
Boeing 737-700	3.771	1972	6265.9	3.177	0.84
Boeing 737-800	4.342	1875	6489.6	3.461	0.80
Boeing 737-900	3.147	1852	6710.2	3.623	1.15
Boeing 747-400	14.269	5285	58833.1	11.132	0.78
Boeing 757-200	5.878	2160	10489.9	4.855	0.83
Boeing 757-300	6.416	2120	11132.0	5.250	0.82
Boeing 767-300ER	6.658	3815	22436.4	5.881	0.88
Boeing 777-200	8.534	3056	23214.5	7.596	0.89
Boeing 777-200ER	7.370	2924	22323.5	7.635	1.04
Boeing 777-300	11.087	3375	29991.7	8.886	0.80
Boeing 777-300ER	10.809	5266	50679.0	9.623	0.89
Boeing 787-8	6.568	5093	28234.6	5.544	0.84
Boeing 787-9	7.471	4857	28953.0	5.961	0.80
Bombardier CRJ900	3.415	963	2477.9	2.573	0.75
Embraer E170	3.285	972	2349.0	2.415	0.74
Embraer E175	3.196	907	2241.1	2.470	0.77
Embraer E190	3.881	900	2904.3	3.225	0.83
Embraer E195	4.244	741	2563.6	3.460	0.82
Embraer ERJ-135	1.836	926	1341.8	1.449	0.79
Embraer ERJ-140	2.160	694	1113.4	1.603	0.74
Embraer ERJ-145	1.990	879	1609.7	1.830	0.92
				Average	0.84
				Standard deviation	0.09

Appendix B – World Airliner Census 2020

Table B.1 List of all commercial passenger aircraft in service in august 2020

Aircraft type	Total number of passenger A/C	Cumula-tive sum	Ranking	Percentage of total passenger A/C
Boeing 737-800	4788	4788	1	16.39%
Airbus A320	4132	8920	2	30.53%
Airbus A321	1637	10557	3	36.13%
Airbus A319	1243	11800	4	40.39%
Airbus A320neo	1009	12809	5	43.84%
Boeing 737-700	979	13788	6	47.19%
Boeing 777-300ER	805	14593	7	49.95%
ATR 72	795	15388	8	52.67%
Airbus A330-300	707	16095	9	55.09%
Embraer 175	624	16719	10	57.22%
Bombardier CRJ100/200	601	17320	11	59.28%
Boeing 737-900	556	17876	12	61.18%
Boeing 787-9	540	18416	13	63.03%
Airbus A330-200	502	18918	14	64.75%
Embraer 190	501	19419	15	66.46%
Embraer ERJ-145	479	19898	16	68.10%
Bombardier CRJ900	471	20369	17	69.72%
De Havilland Canada Dash 8 Q400	462	20831	18	71.30%
Boeing 777-200/200ER	391	21222	19	72.64%
Boeing 767-300	365	21587	20	73.89%
Boeing 787-8	363	21950	21	75.13%
Airbus A321neo	355	22305	22	76.34%
Boeing 737 Max 8	347	22652	23	77.53%
Airbus A350-900	321	22973	24	78.63%
Viking Air Twin Otter	315	23288	25	79.71%
Boeing 757-200	302	23590	26	80.74%
Bombardier CRJ700	291	23881	27	81.74%
Airbus A380	237	24118	28	82.55%
Boeing MD-80	232	24350	29	83.34%
Beechcraft 1900D	220	24570	30	84.09%
Fairchild Metro/Merlin	220	24790	31	84.85%
Boeing 737-300	214	25004	32	85.58%
ATR 42	208	25212	33	86.29%
Saab 340	188	25400	34	86.94%
Boeing 737-500	161	25561	35	87.49%
Embraer 195	161	25722	36	88.04%
De Havilland Canada Dash 8 Q300	157	25879	37	88.58%
Embraer 170	157	26036	38	89.11%
De Havilland Canada Dash 8 Q100	152	26188	39	89.63%
Boeing 717-200	145	26333	40	90.13%
Boeing 747-400	142	26475	41	90.62%

Boeing 737-400	141	26616	42	91.10%
Sukhoi Superjet 100	131	26747	43	91.55%
Embraer EMB-120 Brasilia	127	26874	44	91.98%
Beechcraft 1900C	121	26995	45	92.39%
Fokker 100	109	27104	46	92.77%
Beechcraft B99	107	27211	47	93.13%
BAe Jetstream 31	101	27312	48	93.48%
Antonov An-24	97	27409	49	93.81%
Fokker 50	86	27495	50	94.11%
Airbus A340-300	78	27573	51	94.37%
Airbus A220-300	72	27645	52	94.62%
Embraer ERJ-140	70	27715	53	94.86%
Bombardier CRJ1000	63	27778	54	95.07%
Embraer ERJ-135	61	27839	55	95.28%
Boeing 787-10	58	27897	56	95.48%
Airbus A340-600	57	27954	57	95.68%
BAe Jetstream41	54	28008	58	95.86%
Boeing 757-300	53	28061	59	96.04%
RUAG Dornier 228	53	28114	60	96.22%
Boeing 777-200LR	50	28164	61	96.40%
Boeing 777-300	50	28214	62	96.57%
Airbus A330-900	47	28261	63	96.73%
Xian MA60	47	28308	64	96.89%
Airbus A350-1000	43	28351	65	97.04%
De Havilland Canada Dash 8 Q200	42	28393	66	97.18%
Airbus A220-100	40	28433	67	97.32%
BAe Systems Avro RJ85	39	28472	68	97.45%
Embraer EMB-110 Bandeirante	39	28511	69	97.58%
Boeing 767-400ER	37	28548	70	97.71%
Airbus A300	35	28583	71	97.83%
Boeing 747-8	35	28618	72	97.95%
Fokker 70	35	28653	73	98.07%
BAe Systems Avro RJ100	34	28687	74	98.19%
Boeing 737-600	31	28718	75	98.29%
Comac ARJ21	31	28749	76	98.40%
Boeing 737-200	29	28778	77	98.50%
Boeing 737 Max 9	28	28806	78	98.59%
Yakovlev Yak-42	28	28834	79	98.69%
Dornier 328	27	28861	80	98.78%
Boeing MD-90	26	28887	81	98.87%
Airbus A318	24	28911	82	98.95%
Airbus A310	22	28933	83	99.03%
De Havilland Canada Dash 7	21	28954	84	99.10%
BAe 146-200	20	28974	85	99.17%
Yakovlev Yak-40	20	28994	86	99.24%
Dornier 328Jet	18	29012	87	99.30%
Tupolev Tu-204	18	29030	88	99.36%
Boeing 767-200	16	29046	89	99.41%

Saab 2000	16	29062	90	99.47%
Embraer 190 E2	15	29077	91	99.52%
Airbus A340-500	12	29089	92	99.56%
Boeing 727-200	10	29099	93	99.60%
Fokker F27	10	29109	94	99.63%
BAe 146-300	9	29118	95	99.66%
Tupolev Tu-154	9	29127	96	99.69%
Embraer 195 E2	8	29135	97	99.72%
McDonnell Doulgas DC-3	8	29143	98	99.75%
Antonov An-148	7	29150	99	99.77%
McDonnell Doulgas DC-8	7	29157	100	99.79%
RUAG Dornier 228NG	7	29164	101	99.82%
Ilyushin Il-18	6	29170	102	99.84%
Ilyushin Il-62	5	29175	103	99.86%
Boeing 747-200	4	29179	104	99.87%
Ilyushin Il-96	4	29183	105	99.88%
Lockheed L-188 Electra	4	29187	106	99.90%
McDonnell Doulgas DC-10	4	29191	107	99.91%
McDonnell Doulgas DC-9	4	29195	108	99.92%
Xian MA600	4	29199	109	99.94%
Antonov An-38	3	29202	110	99.95%
BAe (HS) 748	2	29204	111	99.96%
BAe 146-100	2	29206	112	99.96%
BAe ATP	2	29208	113	99.97%
NMAC YS-11	2	29210	114	99.98%
Tupolev Tu-134	2	29212	115	99.98%
Airbus A330-300F	1	29213	116	99.99%
Airbus A340-200	1	29214	117	99.99%
Antonov An-140	1	29215	118	99.99%
BAe Systems Avro RJ70	1	29216	119	100.00%
Boeing 747-300	1	29217	120	100.00%
Airbus A319neo	0	29217	121	100.00%
Airbus A330-200F	0	29217	122	100.00%
Airbus A350-800	0	29217	123	100.00%
Boeing 727-100	0	29217	124	100.00%
Boeing 737 Max 7	0	29217	125	100.00%
Boeing 737 Max 10	0	29217	126	100.00%
Boeing 747SP	0	29217	127	100.00%
Boeing 777-8X	0	29217	128	100.00%
Boeing 777-9X	0	29217	129	100.00%
Boeing 777F	0	29217	130	100.00%
Boeing MD-11	0	29217	131	100.00%
Comac C919	0	29217	132	100.00%
Embraer 175 E2	0	29217	133	100.00%
Fokker F28	0	29217	134	100.00%
Irkut MC-21	0	29217	135	100.00%
Mitsubishi MRJ	0	29217	136	100.00%
TOTAL	29217			

Appendix C – Group of Reference Aircraft

Table C.1 List of reference aircraft

Aircraft type	Accumulated number of passenger A/C	Accumulated percentage passenger A/C
Boeing 737-800	4788	16.39%
Airbus A320	8920	30.53%
Airbus A321	10557	36.13%
Airbus A319	11800	40.39%
Airbus A320neo	12809	43.84%
Boeing 737-700	13788	47.19%
Boeing 777-300ER	14593	49.95%
ATR 72	15388	52.67%
Airbus A330-300	16095	55.09%
Embraer 175	16719	57.22%
Bombardier CRJ100/200	17320	59.28%
Boeing 737-900	17876	61.18%
Boeing 787-9	18416	63.03%
Airbus A330-200	18918	64.75%
Embraer 190	19419	66.46%
Embraer ERJ-145	19898	68.10%
Bombardier CRJ900	20369	69.72%
De Havilland Canada Dash 8 Q400	20831	71.30%
Boeing 777-200/200ER	21222	72.64%
Boeing 767-300	21587	73.89%
Boeing 787-8	21950	75.13%
Airbus A321neo	22305	76.34%
Boeing 737 MAX 8	22652	77.53%
Airbus A350-900	22973	78.63%
Viking Air Twin Otter	23288	79.71%
Boeing 757-200	23590	80.74%
Bombardier CRJ700	23881	81.74%
Airbus A380	24118	82.55%
Boeing MD-80	24350	83.34%
Beechcraft 1900D	24570	84.09%
Boeing 737-300	24784	84.83%
ATR 42	24992	85.54%
Saab 340	25180	86.18%
Boeing 737-500	25341	86.73%
Embraer 195	25502	87.28%
De Havilland Canada Dash 8 Q300	25659	87.82%
Embraer 170	25816	88.36%
De Havilland Canada Dash 8 Q100	25968	88.88%
Boeing 717-200	26113	89.38%

Boeing 747-400	26255	89.86%
Boeing 737-400	26396	90.34%
Sukhoi Superjet 100	26527	90.79%
Embraer EMB-120 Brasilia	26654	91.23%
Fokker 100	26763	91.60%
Fokker 50	26849	91.90%
Airbus A340-300	26927	92.16%
Airbus A220-300	26999	92.41%
Embraer ERJ-140	27069	92.65%
Bombardier CRJ1000	27132	92.86%
Embraer ERJ-135	27193	93.07%
Boeing 787-10	27251	93.27%
Airbus A340-600	27308	93.47%
Boeing 757-300	27361	93.65%
RUAG Dornier 228	27414	93.83%
Boeing 777-200LR	27464	94.00%
Boeing 777-300	27514	94.17%
Airbus A330-900	27561	94.33%
Airbus A350-1000	27604	94.48%
De Havilland Canada Dash 8 Q200	27646	94.62%
Airbus A220-100	27686	94.76%

Appendix D – Fuel Consumption for Reference Group of Aircraft

Table D.1 Normalized fuel consumption of the reference group of aircraft

Aircraft type	Normalized OEM based fuel consumption (kg/km/seat)	Ranking
Saab 340	0.0131	1
Boeing 737-900	0.0178	2
Airbus A321	0.0201	3
Airbus A321neo	0.0204	4
Airbus A220-300	0.0212	5
Boeing 737 MAX 8	0.0213	6
Airbus A320neo	0.0217	7
Boeing 787-10	0.0241	8
Airbus A220-100	0.0241	9
Boeing 777-200ER	0.0242	10
Airbus A350-900	0.0248	11
Airbus A350-1000	0.0251	12
Boeing 787-9	0.0258	13
Airbus A330-900	0.0263	14
Boeing 767-300ER	0.0264	15
Airbus A320	0.0266	16
Boeing 737-800	0.0271	17
Boeing 787-8	0.0271	18
Airbus A319	0.0274	19
Bombardier CRJ1000	0.0281	20
Airbus A330-300	0.0289	21
Boeing 757-300	0.0294	22
Boeing 737-700	0.0295	23
Airbus A380-800	0.0295	24
Boeing 777-300ER	0.0296	25
De Havilland Canada Dash 8 Q400	0.0297	26
Boeing 737-300	0.0298	27
Boeing 757-200	0.0300	28
Airbus A340-600	0.0300	29
Boeing 777-300	0.0301	30
Airbus A340-300	0.0306	31
Boeing 737-400	0.0313	32
Boeing 777-200	0.0317	33
ATR 72	0.0318	34
Boeing 777-200LR	0.0327	35
Boeing MD-80	0.0339	36
Airbus A330-200	0.0341	37
Embraer E195	0.0342	38
Boeing 747-400	0.0343	39
Bombardier CRJ700	0.0345	40
Fokker 50	0.0376	41

Bombardier CRJ900	0.0379	42
Embraer E190	0.0388	43
Fokker 100	0.0390	44
Embraer ERJ-145	0.0398	45
Boeing 717-200	0.0401	46
Sukhoi Superjet 100	0.0407	47
ATR 42	0.0408	48
Embraer E175	0.0410	49
De Havilland Canada Dash 8 Q200	0.0419	50
Boeing 737-500	0.0439	51
De Havilland Canada Dash 8 Q300	0.0442	52
Embraer E170	0.0444	53
Bombardier CRJ200	0.0449	54
De Havilland Canada Dash 8 Q100	0.0464	55
Bombardier CRJ100	0.0467	56
Embraer ERJ-140	0.0491	57
Embraer ERJ-135	0.0496	58
Dornier 228	0.0611	59
Embraer EMB-120 Brasilia	0.0621	60
Beechcraft 1900D	0.0798	61

Appendix E – ICAO Annex 16, Volume II – Aircraft Engine Emissions

Standards for certification of emissions produced by aircraft engines are determined in Volume II of Annex 16 of the International Civil Aviation Organization (ICAO) (ICAO 2017b). It is focused on the measurements of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_X), and smoke. Volume II of Annex 16 also sets a regulatory limit on the concentration of the mentioned emission products during the landing and takeoff cycle (LTO).

To provide standardized and comparable measurements, a reference procedure was defined, simulating an LTO cycle. Every movement of the aircraft below 3000 feet is included in this cycle, shown in Figure E.1. This means that taxi-out, takeoff, climb-out, final approach, landing, and taxi-in aircraft are included.

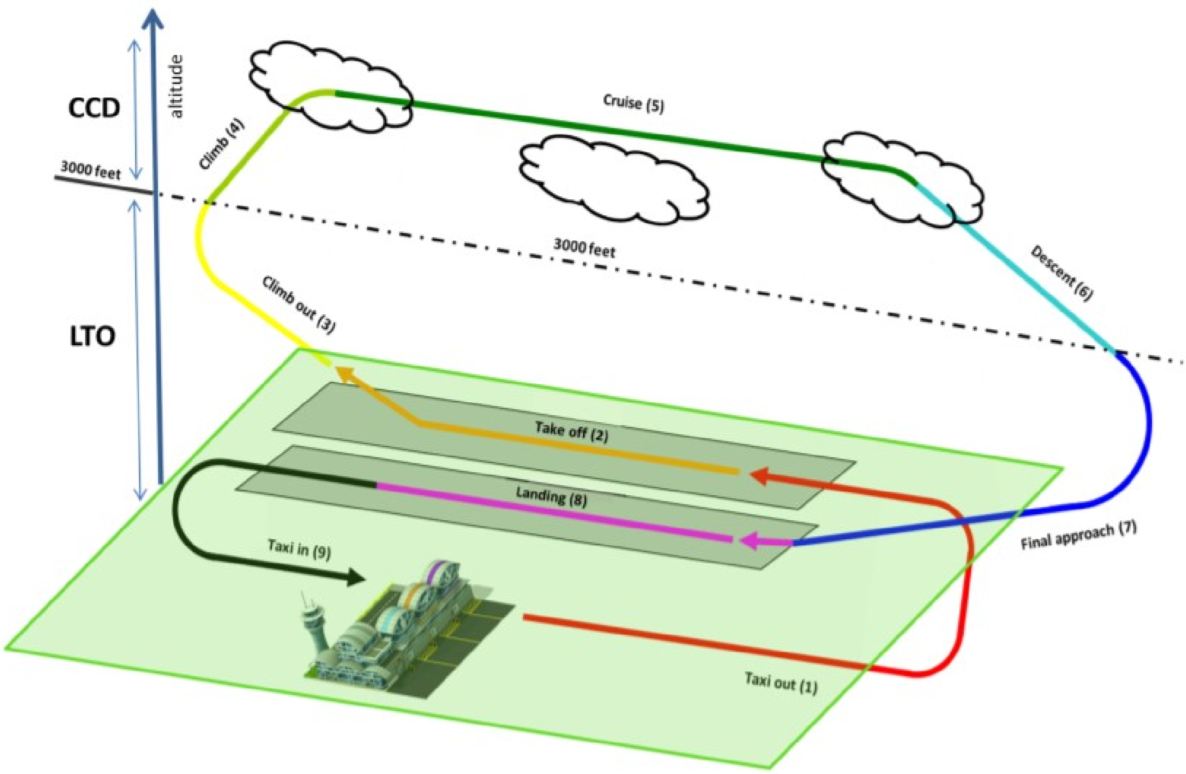

Figure E.1 Definition of the landing and takeoff cycle (Eurocontrol 2016)

According to certification procedures, the engine must be tested at various thrust settings representing the operation modes during the LTO cycle. This must be done for a certain amount of time. Both the trust setting and the required operating time are given for each mode in Table E.**1**.

Table E.1 Engine thrust and operating time for each operating mode (Eurocontrol 2016)

Operating mode	Engine thrust (%)	Operating time (min)
Taxi-out	7	7.0
Takeoff	100	0.7
Climb-out	85	2.2
Approach	30	4.0
Taxi-in	7	19

During this test, the concentrations of the defined emission are measured at different probe sampling positions. From this, emission indices can be calculated by dividing the mass of the emitted emission products by the mass of fuel burned.

Appendix F – ICAO Annex 16, Volume I – Aircraft Noise

Standard procedures and reference conditions for aircraft noise certification are defined in Volume I of ICAO Annex 16 (ICAO 2017a). The ICAO document 9501-AN/929 'Environmental Technical Manual on the Use of Procedures in the Noise Certification of Aircraft' provides guidance in applying the procedures.

Noise levels should be measured at the three predefined reference points shown in Figure F.1. The points are defined as follows:

- **Lateral:** lateral point on a line parallel to the runway at 450 meters from the runway centerline where the noise level is at its maximum during takeoff;
- **Flyover:** flyover point at takeoff on the extended centerline of the runway at 6500 meters from the brake release point/start of the takeoff roll; and
- **Approach:** flyover point at approach on the extended centerline of the runway at 2000 meters distance from the runway threshold.

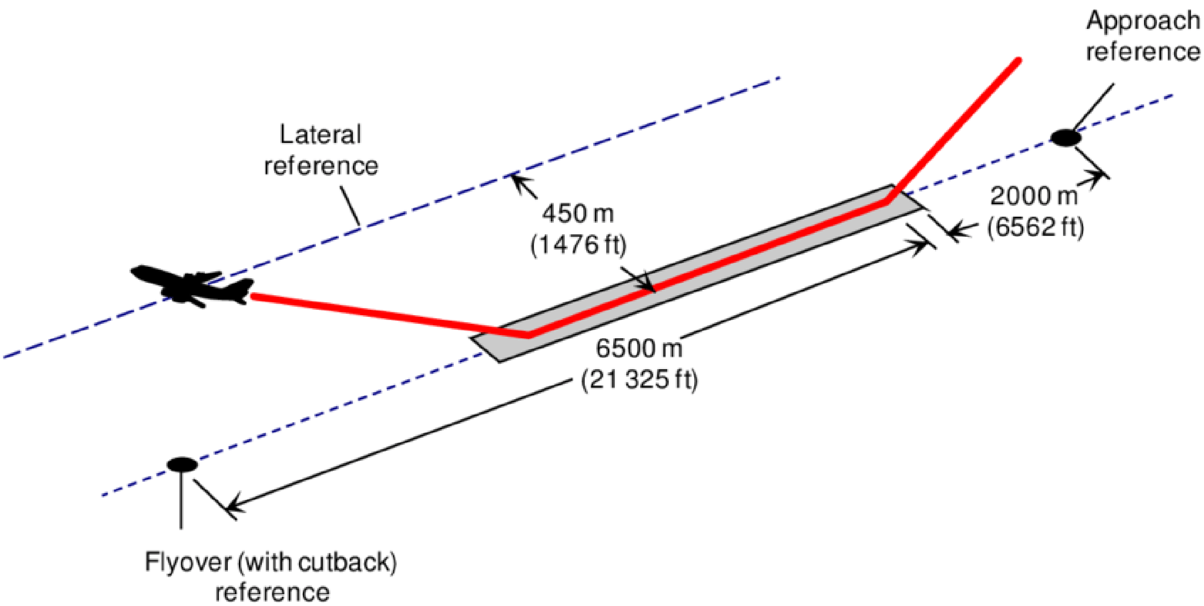

Figure F.1 Reference points for the noise measurement (Berton 2012)

Noise limits are defined as a function of MTOW and consider the number of engines. A distinction is made between aircraft with two or fewer, three, and four or more engines. The applicable limit is either set by a predefined minimum or maximum value or a logarithmic function, depending on MTOW.

Noise levels are expressed in Effective perceived noise level (EPNL). Values for EPNL cannot be measured directly but must be calculated according to specifications:

1. Conversion of Sound Pressure Level (SPL) to Perceived Noise Level (PNL) using a "noy" table.
2. Calculation of a tone correction factor (C)
3. Summation of tone correction and perceived noise level to obtain tone corrected perceived noise level (PNLT) and determination of the maximum value (PNLTM)
4. Calculation of a duration correction factor (D)
5. Determination of effective perceived noise level by adding the maximum tone corrected perceived noise level and the duration correction factor (EPNL= PNLTM+D)

Appendix G – Forcing Factors

The following values are based on a graph from Schwartz (2011). The original graph only shows data for altitudes above 17000 feet, but according to Schwartz, the forcing factor at lower altitudes can be set equal to the first available value.

Table G.1 Forcing factor for AIC

Altitude (ft)	Forcing factor
16000.0	0.028450
17470.3	0.028450
19547.9	0.000000
21529.7	0.000000
23511.4	0.173542
25525.1	0.395448
27506.8	0.799431
29456.6	1.251780
31598.2	1.709820
33547.9	2.105260
35529.7	1.820770
37543.4	1.533430
39557.1	0.967283
41538.8	0.793741

Table G.2 Forcing factor for short-lived ozone

Altitude	forcing factor
16000.0	0.469417
17502.3	0.469417
19484.0	0.557610
21497.7	0.620199
23479.5	0.711238
25525.1	0.711238
27506.8	0.813656
29520.5	0.930299
31502.3	1.009960
33484.0	1.132290
35561.6	1.428160
37575.3	1.624470
39589.0	1.803700
41538.8	1.931720

Table G.3 Forcing factor for long-lived ozone and methane

Altitude	forcing factor
16000.0	0.867710
17470.3	0.867710
19484.0	0.924609
21497.7	0.955903
23543.4	0.961593
25525.1	0.944523
27538.8	0.927454
29520.5	0.927454
31534.2	0.941679
33516.0	0.975818
35561.6	1.140830
37543.4	1.214790
39589.0	1.203410
41570.8	1.203410

Appendix H – Inflight Magazine Article

Fly responsibly

Aircraft, especially the latest generation of modern commercial airliners, are often advertised with claims about their environmental advantages. However, most of these claims cannot be verified due to a lack of standards or scientific backup. This phenomenon is called 'greenwashing'. In order to counter this trend of greenwashing, an ecolabel for passenger aircraft was developed. This label aims to collect objective and standardized environmental information in one document, also called 'ecolabel'.

The last couple of years were characterized by the ever-growing environmental awareness of humankind. With the growing focus on environmental change, there has never been this much attention on our carbon footprint. Environmental activists have changed our attitude towards flying. In Sweden, the home country of Greta Thunberg, flight shame - Flygskam in Swedish - caused the passenger numbers at the ten busiest airports to drop by more than 5% in 2019. In Germany, the number of people flying domestically even dropped by 12% in November 2019 compared to November 2018 (Farmbrough 2019).

In 2016, aviation was accountable for 3.6% of the total European Union greenhouse gas emissions and for 13.4% of the emissions from transport. Greenhouse gas emissions from aviation in the European Union are increasing and have more than doubled since 1990. However, the account of aviation in the global carbon emission is relatively low compared to the carbon emissions of the fashion and the food industry. Although commercial aviation has, compared to other industries, a relatively low share in global carbon emission, there is no denying that the climate is changing. Anything that can be done should be applauded.

Ecolabel

New commercial aircraft are often advertised with many claims about their environmental advantages over reference and competitor models. Unfortunately, these advertisement claims are often not verifiable, not based on any reporting standards (often due to a lack of such standards), and generally not backed up by reviewed scientific publications.

To help the traveling public make more sustainable choices when choosing to fly, an ecolabel for aircraft was designed by students at the Hamburg University of Applied Sciences. The idea is to provide a single source of easily accessible, easy-to-understand data and enable the traveling passengers to make an educated choice among different airline offers (a specific aircraft with a particular seating arrangement) such that the selected flight is the least environmentally damaging. In the end, the main objective is to help the passengers to understand that they should select a flight on the shortest possible route and select the best combination of aircraft and airline based on the ecolabel.

The use of ecolabels is not new. In 1994, the European Union introduced the EU Energy Labels. These Energy Labels are often applied to household products, like lightbulbs, fridges, or washing machines and provide information about the environmental impact and the energy efficiency of specific products at the point of purchase. This makes it easier for consumers to save money on their household energy bills and contribute to reducing greenhouse gas emissions. In an EU-wide survey in 2019, 93% of consumers confirmed that they recognized the label and 79% confirmed that it had influenced their decision on what product to buy (European Commission 2021). The design of the ecolabel for aircraft is therefore based on the EU Energy Label.

The Ecolabel for Passenger Aircraft

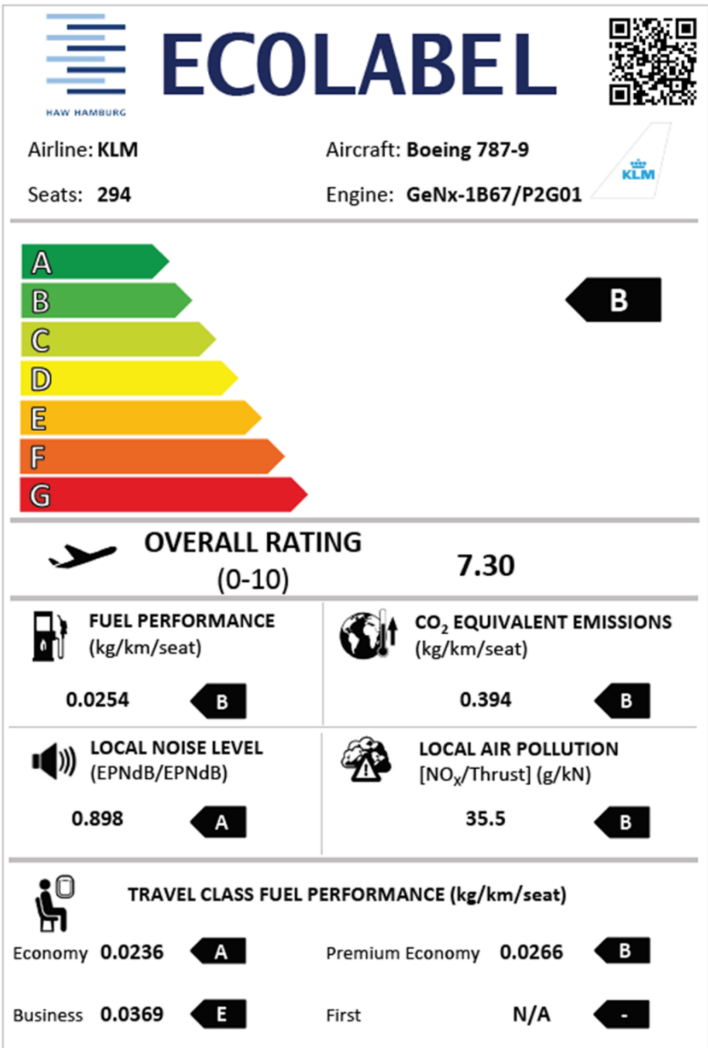

Figure H.1 Example of an Ecolabel for Passenger Aircraft

The ecolabel consists of several components, each with its own score. Each score is valid for a specific aircraft of a given airline with a particular type of engine and a given cabin layout. The lower this score, the better. The score is also represented by a scale from A to G. An A score is very good, while a G score is relatively weak.

The **fuel performance rating** represents the amount of fuel (in kilograms) an aircraft burns per traveled kilometer and per available seat. This rating can be expressed as an A to G score.

The **carbon dioxide (CO_2) equivalent** is used to compare the emissions from various greenhouse gases based on their global warming potential (GWP). This global warming potential is the amount of heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that the same mass of CO_2 would absorb. In short, the CO_2 equivalent emission is the amount of emitted CO_2 plus the amount of other emitted gases like nitrogen oxides (NO_X) and water vapor converted to the equivalent amount of carbon dioxide with the same global warming potential.

The **local noise level** is a metric that describes the average noise level produced by a specific aircraft during 3 phases of a flight in the vicinity of airports.

Aircraft engines form pollutants in the air. Besides carbon dioxide (CO_2), water (H_2O) and sulfur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), unburned hydrocarbons (HC), and soot are generated. The amount of emitted nitrogen oxides is defined as the key indicator to rate the local air quality. Therefore, the **local air pollution** is a measure of the amount of emitted NO_X in the vicinity of airports.

The **travel class fuel performance** is the same as the standard fuel performance. However, it does consider the travel classes that are available on the specific aircraft. The more comfort and, therefore, the more space per seat is desired, the larger the fuel consumption per seat will be. This is reflected in a rating per travel class.

Keep on flying

In today's world, aviation is still essential. Not only does it link up families, friends, and employment, but very often, flying demonstrates a time when people are happy, sharing time with their loved ones on hard-earned holidays. Furthermore, travel can be the best education many of us can have. Learning about different religions, countries, and history. Learning about ourselves, tolerating others, and celebrating differences