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Carbon footprint method for combined passenger freight operations

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Abstract

This deliverable concerns a proposed methodology for emission allocation in belly freighters. It builds on the existing IATA RP1678 methodology, proposing an alternative approach to overcome the unintended side effects of the current emission allocation method. With the proposed methodology, a split between marginal emissions and empty aircraft emissions is suggested. This distinction allows to estimate the proportion of emissions that is attributed to cargo and the proportion that is attributed to passengers, obtaining thus one allocation value for passengers and one for cargo. In this way, a fairer comparison is done between cargo emissions allocation in a full freighter and in a belly freighter. Applying the proposed methodology, cargo emissions allocation values are always lower in a belly freighter compared to a full freighter. The positive consequence is that the cargo capacity of belly freighters is fully utilised, enabling the distribution of cargo into available belly freighter capacity, reducing the number of flights and ultimately the amount of GHG emissions.

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VI. LIST OF ACRONYMS

Acronym	Meaning
BF	Belly Freight
C	Cost
CO_2	Carbon Dioxide
DOW	Dry Operating Weight
ec.eq	Economy-equivalent
FF	Full Freighter
GCD	Great Circle Distance
GHG	Greenhouse Gas
LF	Load Factor
OD	Origin-Destination
Pax	Passenger
RP	Recommended Practice
W	Weight
WP	Work Package
ZFW	Zero Fuel Weight

1 Executive Summary

This document is the first deliverable of the TULIPS project task 8.6. The TULIPS consortium accelerates the implementation of innovative and sustainable technologies towards lower emissions at airports, aiming to zero-emissions and zero-waste airports by 2030 and climate neutral aviation by 2050. To reach this goal, Amsterdam Schiphol Airport (lighthouse airport) and its fellow airport partners Avinor in Oslo, Hermes at Cyprus and SAGAT in Torino will be the proving ground for demonstrator projects. The project is developed in 12 work packages, focusing on specific aspects of the green airport solutions. In specific, task 8.6 is part of the project's performance monitoring and economic data collection and analysis (WP8), and is linked to the carbon footprinting of transport chains. This deliverable explores the current methodologies for Greenhouse Gas (GHG) emission allocation for combined passenger freight operations, showing their potential unintended side effects and proposing adaptations to allow for an allocation method that assigns emissions in a way that resembles reality as much as possible.

The motivation to work on this topic lies on the observation that while full freighters and belly freighters have different payload capacity, the emission allocation method is the same for both configurations. This leads to a potential unbalanced allocation, in which 1 tonne of cargo gets allocated more emissions when transported in a belly freighter compared to when transported in a full freighter. In the contingency that shipping decision are based on sustainability, this would lead to the preference of using full freighters, with the consequence of underutilised belly cargo capacity and potentially the creation of unnecessary flights (and therefore the creation of more GHG emissions).

With the allocation methodology proposed in this deliverable, emissions are allocated in a way that 1 tonne cargo gets allocated less emissions than if transported in a full freighter. This is realised by estimating the empty-aircraft emissions (i.e., system emissions generated by the aircraft weight and fuel weight) and the marginal emissions (i.e., operating emissions generated by the payload weight), and assigning them to passengers and cargo based in a way that cargo distribution is achieved.

The knowledge developed in TULIPS task 8.6 and described in this deliverable will be further applied in the following deliverable to the EU commission (TULIPS D8.2), in which the proposed emissions allocation methodology is used for the carbon footprint evaluation of a selected transport chain.

2 Introduction

2.1 General description

The TULIPS project unites a consortium of 29 partners, supported by an external advisory board, that will engage over a duration of 48 months to facilitate the transition to low-carbon mobility and enhanced sustainability at European airports. The goal is to accelerate the implementation of innovative and sustainable technologies towards lower emissions at airports, aiming at zero-emissions and zero-waste airports by 2030 and climate neutral aviation by 2050.

Schiphol Airport in Amsterdam, as the lighthouse airport and its fellow airport partners Avinor in Oslo, Hermes at Cyprus and SAGAT in Torino will be the proving ground for 17 demonstrator projects that result from the collaboration. Topics covered by the demonstrators include:

- improved multi-modal shift for passengers and freight, to reduce traffic congestion and offer seamless green travel options
- improved airside infrastructure for future electric/hybrid aircraft infrastructure
- smart energy solutions to manage airport operations
- integration of hydrogen fuel cell technology into current ground support equipment (e.g., testing of facilities for recharging aircraft with electricity and hydrogen)
- enablement of large-scale supply of Sustainable Aviation Fuel (SAF) fuel along with the preparation of an EU clearing house
- circular economy
- Ultrafine Particles (UFP) mitigation

The TULIPS project started in January 2022 and lasts until December 2025. The dedicated goal for Schiphol Airport, is to realise an estimated 800kT/year CO_2 savings based on the sum of the expected benefits of the 17 demonstrations by 2025, with further savings scaled with technology roll out.

The project is divided into 12 Work Packages (WPs), each with different Tasks focusing on specific topics. The following deliverable is linked to the carbon footprinting of transport chains (T8.6) as part of the project’s performance monitoring and economic data collection and analysis (WP8). In this task, the current methodologies for Greenhouse Gas (GHG) emission allocation for combined passenger freight operations are explored, showing their potential unintended side effects. Subsequently, a new methodology is proposed, which aims to establish a fair allocation of emissions between passenger and freight for the passenger-freight combined service (i.e., belly freight aircraft), with the potential consequence of optimising the fleet service and reduce emissions.

2.2 Methodology for GHG emission allocation of air cargo

The focus of Task 8.6 is the current standards and methodologies for emission allocation in air transport, with respect to potential unintended side effects of their application. Current methodologies are based on the IATA RP1678[1], and are described in the ISO 14083 standard. Emissions are allocated based on the weight proportion of revenue load (cargo, mail, and/or passengers). Although there is a significant difference in weight capacity between a full freighter and a belly freighter version of the same aircraft, the current methodology does not distinguish between these two configurations, and the same methodology should be followed in both cases. This allocation procedure might lead to a biased preference towards full freighters, with the consequence that the cargo capacity of belly freighters are underutilised and more (full freighter) aircraft movements may be incentivised.

In line with the overall goals of the TULIPS project, the goal of Task 8.6 is to reduce air transport emissions as much as possible, allowing for an optimised utilisation of belly freighters and avoiding unnecessary (full freighter) flights. We do so by developing a new (extended) methodology for transport chain emissions assessment, which builds on the existing methodologies (IATA RP1678 and ISO 14083) and extends them where methodology gaps are evident. The proposed methodology should specifically provide an emission allocation procedure that assigns the most accurate amount of emissions to passengers and freight for the passenger-freight combined air service, based on their weight and on their contribution to total emissions, in a way that resembles reality as much as possible.

To assess the policy implications of the proposed methodology, meetings were conducted with IATA experts. Operational implications were discussed with KLM and Smart Freight Centre members. After these conversations, no immediate objections were expressed. Nonetheless, the validity of the proposed methodology still needs to be checked, once primary data are made available.

2.3 Reader

The document is organised as follows: Section 3 elaborates on the motivations for carbon footprinting and explains the context in which this project is carried out. Section 4 provides a description of how carbon emissions are reported in air transport, with reference to the ISO 14083 Standard and the current IATA RP1678 emission methodology. In this Section, the fuel burn model that was developed at TNO for modelling fuel tankage data is also explained. Section 5 presents the unintended side effect of the current IATA RP1678, further elaborating on the motivations for carrying out the project. An example is presented, to show the consequences of these unintended side effects. Section 6 introduces the proposed methodology, with the steps to follow in case of

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[1] RP stands for Recommended Practice, meaning that the emission allocation methodology is currently based on recommended rules

primary data and in case of modelled data. The same use case of the previous section is presented, now applying the proposed methodology, to show the effects of the new methodology on the allocated emissions. Section 7 shows a further application of the proposed methodology, in which a *seat factor* and passenger emissions are used to identify the emissions that should be allocated to passengers of different seat categories. Section 8 provides a discussion of the results and Section 9 concludes the report together with recommendations for further research and applications.

3 Motivation for carbon footprinting

3.1 Why carbon footprinting matters

Carbon footprinting refers to the measuring and quantification of the amount of greenhouse gas emissions (primarily carbon dioxide (CO_2)) and other related gases that are released into the atmosphere as a result of human activities, products, or services. It is an important tool for assessing and managing the environmental impact of various activities in industries, transportation and aviation.

Focusing on carbon footprinting in academia, research and practice aim to raise awareness about the environmental impact of human activities. It aims to let individuals, businesses, and governments understand the extent of their contribution to climate change and helps to take necessary actions to reduce emissions. Governments and international organizations use carbon footprint data to formulate policies, regulations and agreements aimed at mitigating climate change. Accurate data is crucial for setting emission reduction targets and implementing effective strategies.

Businesses can use carbon footprinting to identify emission hotspots within their operations and supply chains. This enables them to implement sustainable practices and meet consumer demands for environmentally friendly products and services.

Carbon footprint information empowers consumers to make informed choices about the products and services they use. This can drive demand for low-carbon alternatives and incentivize industries to adopt greener practices.

3.1.1 Impact of aviation on the global greenhouse emissions

The aviation industry is a significant contributor to global greenhouse gas emissions, primarily due to jet fuel combustion. According to the International Energy Agency (IEA), aviation accounts for around 2% of global energy-related CO_2 emissions in the year 2022, a sector that in the previous decade has grown faster than other modalities such as rail, road, or shipping [1]. Moreover, the demand for flying internationally recovered following the Covid-19 pandemic. The global aviation emissions in 2022 reached almost 800 Mt CO_2, about 80% of the pre-pandemic level [1].

Other academic sources put the aviation emission at 2.5% of global CO_2 emissions, but 3.5% of global emissions when we take non-CO_2 (e.g., soot, sulphur, and nitrogen compounds) impacts on climate into account [2]. According to the EU commission, direct emissions from aviation accounted for 3.8% of total CO_2 emissions in the EU in 2017. Furthermore, the aviation sector is responsible for 13.9% of the emissions from transport, making it the second biggest source of transport GHG emissions after road transport [3].

Figure 1 shows the figures of global CO_2 emissions from aviation (including passenger air travel, freight, and military operations). It shows how CO_2 emissions have more than quadrupled in the last 50 years, reaching 1.04 billion tonnes in 2018 [4].

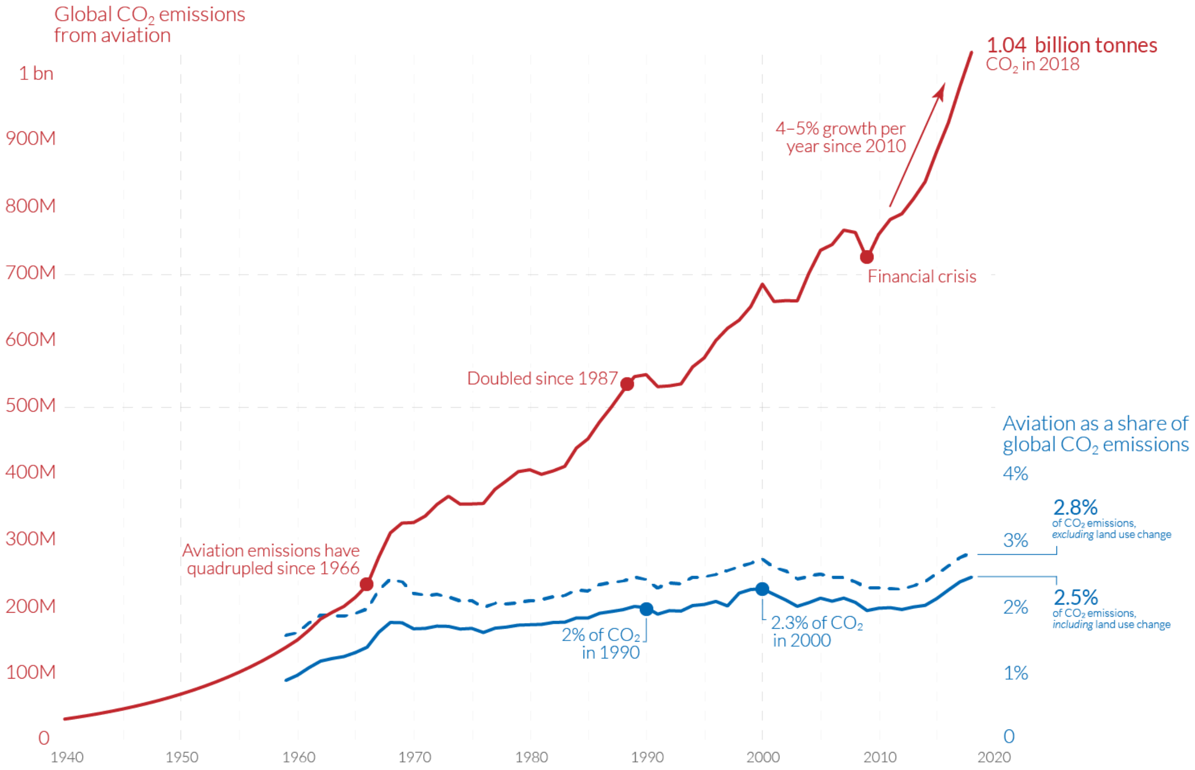

Figure 1 – Global CO_2 emissions from aviation, including passenger air travel, freight, and military operations. Retrieved from [4]

One should note that unlike CO_2 (which is the most common greenhouse gas) other emissions from aviation sector such as methane or nitrogen oxides (i.e., non-CO_2 emission) *are not included* in the Paris Agreement, which may be overlooked. This is particularly true since international aviation is not counted within any country's emissions inventories or targets [4].

3.1.2 Carbon footprinting and connection with future cleaner aviation

Carbon footprinting is vital for the aviation sector to set emission reduction goals in line with international climate agreements, such as the Paris Agreement. Carbon footprint data helps identify areas within aviation that require innovation and technological advancement to reduce emissions. It encourages research and development of cleaner aviation technologies, such as more fuel-efficient engines, lightweight materials, and alternative fuels.

Airlines operating with passengers and cargo can use carbon footprinting to optimize flight routes, improve operational efficiency, and reduce fuel consumption. This not only lowers emissions but may also cut operational costs. Carbon footprinting provides necessary data for compliance with (inter)national agreements on emission reductions and helps the aviation industry transition to more sustainable practices.

Furthermore, carbon footprinting provides transparent information that can influence investment decisions, such as investing on fully fledged cargo flights or optimising the belly freight so that the cargo can be distributed over already scheduled passenger flights.

In summary, carbon footprinting is crucial for understanding, addressing, and mitigating the environmental impact of human activities, including aviation. It plays a key role in shaping the future of cleaner aviation by driving technological innovation, regulatory compliance and sustainable practices within the industry.

3.2 Recent trends in the belly freight as part of the air cargo sector

Belly freight is widely utilised in the aviation industry. According to the International Air Transport Association (IATA), belly freight accounted for approximately 50% of the world's air cargo volume in 2019. This indicates that a significant portion of the world's air cargo is transported in the cargo holds of passenger aircraft [5].

The utilization of belly freight has also increased in recent years due to the growth of e-commerce and the increasing demand for fast and reliable delivery of goods. As more people purchase products online, the need for efficient transportation of goods has become increasingly important and belly freight has become an important mode of transportation for e-commerce packages.

Overall, belly freight is a critical component of the global supply. It can be expected that sustainability will become more and more important in the aviation industry and will likely be an important factor in logistics decisions. To keep up with the sustainability trend, a promising avenue for overall emission reductions could be the optimisation of cargo capacity use to minimise extra cargo full freighter flights and distributing the existing freight in belly freight.

As new markets and regions open up for trade and economic development, belly freight can help facilitate the movement of goods to and from these areas, since the passenger routes are already existing for many of such areas. It can play a role in globally connecting producers with consumers.

4 Reporting on GHG emissions for air transport

According to the ISO 14083 Standard, reports on carbon footprinting of transport operations should include details on the following information:

- operations covered by the reporting activities (operational boundaries)
- corresponding total emissions
- corresponding emission intensity values (e.g., emissions allocated to one tonne payload transported)

With respect to air transport, the IATA RP1678 states that the operations covered by the reporting activities should be limited to the fuel consumption linked to vehicle operational processes, excluding upstream emissions, handling processes, administrative processes or overhead, and all the non-CO2 emissions. Therefore, emission calculation refers only to the fuel used for flying the aircraft, from taxiing at the departure airport to taxiing at the arrival airport (see Figure 2) and only includes CO_2 emissions.

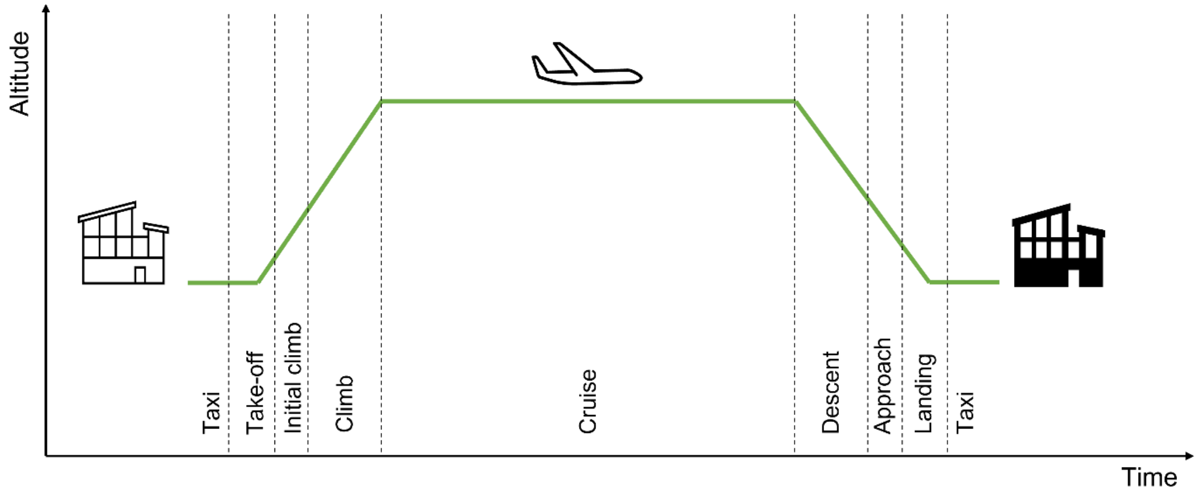

Figure 2 – Flight phases. Adapted from [6]

Figure 2 is purely illustrative, to show the flight phases as described in the ISO 14083 Standard. This report focuses on the cruising phase, averaging and balancing out the other flight phases for full freighters and belly freighters. The assumption of averaging and balancing out the flight phases prior to and following after the cruising phase is based on the fact that the emissions comparison between full freighters and belly freighters is done for the same origin-destination (OD) pair, and thus the preceding parts (i.e., taxi, take-off, initial climb, and climb) and the following parts (i.e., descent, approach, landing, and taxi) take approximately the same time, allowing for an averaging of the fuel burnt.

The following sections describe the methodology currently in use for the emission calculation and emission allocation, according to the ISO 14083 Standard and the IATA RP1678.

4.1 Emissions calculation

In the IATA RP1678, the recommended practice for measuring the CO_2 emissions for both air cargo and combined passenger cargo generated by air transport are defined. The CO_2 emissions are calculated based on the fuel consumption linked to the operational processes (i.e., only the emissions generated by flying the aircraft). Non-CO_2 emissions and other non-aircraft emissions are not included in the calculation methodology. Moreover, upstream emissions, handling processes and administrative processes are not included in the calculation method.

In the IATA RP1678 it is stated that for one flight, the CO_2 emissions are calculated by multiplying the fuel burnt during the flight by the default emission factor for aviation fuel[2]:

Equation 1 $CO_2\ emissions\ = fuel\ burnt * default\ emission\ factor$

Fuel burnt can be either retrieved from fuel tankage data (i.e., primary data), or modelled based on the distance flown (and/or the flight duration, based on the type of model used), and the weight transported (including the weight of the aircraft itself). For the calculation of the distance flown, the IATA RP1678 states that Great Circle Distance (GCD[3]) should be used.

4.1.1 Data requirement for emissions calculation

According to equation 1, the data required to calculate the CO_2 emissions are the amount of fuel burnt during the flight, which depends on the weight transported (including the weight of the aircraft itself and the total payload, as a sum of passenger weight and cargo weight) and the flight time.

The quantification and reporting of GHG emissions for all transport modes are regulated by the ISO 14983 Standard. The baseline for the aviation section in the ISO 14083 Standard is the recommended methodology of the IATA RP1678. On a general note, for all transport modes, the ISO 14983 Standard prescribes that primary data should be used as much as possible. In case of unavailability of primary data, one can rely on modelled data or default data. Within the TULIPS project, reasonable effort was made to acquire primary data from airline companies. Establishing such a collaboration, however, proved to be challenging due to the time constraints and the data sensitivity in the aviation industry. Therefore, a hybrid approach was selected, by which emission data is estimated by using a fuel burn model, developed at TNO in 2019 [7]. This fuel burn model estimates the fuel tankage data (i.e., the fuel burnt during the flight) based on empty aircraft weight data from aircraft manuals, the payload weight and the flight time from commercially available calculation tools. Primary data on transported cargo and number of passengers for specific OD pairs are then combined with the modelled fuel tankage data to evaluate different use cases.

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[2] The default emission factor for aviation fuel is equal to 3.15, which represents the CO_2 (in tonnes) produced by burning one tonne of aviation fuel [9].
[3] GCD is distance determined as the shortest distance between any two points measured along the surface of a sphere [ISO 14083 Standard Section 3.1.27.2]

In case that primary data can be retrieved at a later stage, the project will then run the modelled results against primary data if acquired successfully to validate the model's accuracy against the actual fuel consumption data.

4.1.2 Fuel burn model

Should fuel data from real flights not be available, modelled data can be used. The fuel burn model developed at TNO estimates the amount of fuel burnt for a given plane on a given route. The value of the fuel burnt during flight time is then used in equation 1 to calculate the total CO_2 emissions for the particular flight.

The inputs needed for the fuel burn model are as follows:

- aircraft empty weight (dry operating weight (DOW))
- total payload (the sum of cargo weight and passenger weight)
- fuel reserve[4]
- weight/fuel factor[5], specific to the aircraft type that is used
- flight duration

The assumptions behind the fuel burn model are based on previous research and are as follows:

- the amount of fuel burnt during a flight is linearly dependent on the flight duration [8]
- the fuel burnt depends on the aircraft weight, which in turn depends on the weight of the fuel necessary for the flight

Due to many uncertainties and factors that influence the fuel burnt during a flight[6], the amount of fuel burnt is averaged per hour of flight, without the distinction of the flight phases described in Figure 2. The assumption of a linear estimation of this non-linear process is justified by the fact that the methodology development is based on the comparison between flights carried out between the same origin-destination pair, for which averaging out taxiing, climb and descent would not bring substantial errors. Due to the unavailability of primary data, the model was verified using the ICAO CORSIA CO_2 Estimation & Reporting Tool (CERT)[7].

The following paragraph explains how the fuel burn model works. Variables with their symbols, units and description are presented in Table 1.

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[4] Fuel reserve, also known as contingency fuel, is the mandatory "extra" fuel that should be planned in a trip in order to account for unforeseen circumstances (e.g., adverse weather conditions and changes of planned route). In this project, it is assumed to be 5% of the sum of aircraft empty weight and total payload

[5] The weight/fuel factor shows the fuel consumption rate of a specific aircraft, based on its weight and flying at optimal altitude

[6] Examples of factors that influence the fuel burnt during a flight are the flight phase, the speed of the aircraft, and the air drag.

[7] The specification of the ICAO CORSIA CO_2 Estimation and Reporting Tool can be found in the ICAO website: ICAO CORSIA CO_2 Estimation and Reporting Tool (CERT)

Table 1 – Description of variables used in the fuel burn model

Variable	Symbol	Unit	Description
Time	t	hour	
Total weight at each hour of flight	$w(t)_{landing-n}$ With: $n = [0, \dots, flight\ hours]$	tonne	n refers to the flight hour and is reversely enumerated, with the landing weight $w(t_{landing})$ at $n = 0$, $n = 1$ being the flight time 1 hour prior to landing $w(t_{landing-1})$ and $n = flight\ hours$ being the take-off weight
Fuel burnt during each hour of flight	fb_m With: $m = [1, \dots, flight\ hours]$	tonne	m refers to the flight hour and it is reversely enumerated, with fb_1 being the fuel burnt during the last hour before landing, fb_2 the fuel burnt the second-to-last hour before landing and $fb_{flight\ hours}$ the fuel burnt in the first hour

To account for the circular dependency between fuel burnt and total aircraft weight, the fuel burn model works with reverse hour calculation. Starting from the landing weight $w(t)_{landing-n}$, the model estimates the quantity (in tonnes) of fuel burnt during the last hour of the flight fb_1, using the $weight/fuel$ factor specific to the aircraft type[8]. The fuel burnt during the last hour fb_1 is then added to the landing weight $w(t)_{landing-n}$, to calculate the weight of the aircraft one hour prior to landing: $w(t_{landing-1}) = fb_1 + w(t_{landing})$. Then using weight of the aircraft one hour prior to landing $w(t_{landing-1})$, the model is used to estimate the quantity (in tonnes) of fuel burnt in the second-to-last hour of the flight fb_2, which is added to the previous weight $w(t_{landing-1})$ to calculate the weight of the aircraft two hours prior to landing $w(t_{landing-2}) = w(t_{landing-1}) + fb_2$. This is repeated, until the total flight duration is reached. The outcome is the amount of fuel burnt (in tonnes) and the initial weight of the aircraft, as a sum of empty weight, payload, and total fuel. A visual representation of the reverse hourly calculation is shown in Figure 3.

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[8] Ratio between the empty weight of the aircraft and the fuel factor. The fuel factor, also referred sometimes as burn factor, represents the fuel efficiency of a specific aircraft and it is expressed in tonne weight over tonne fuel

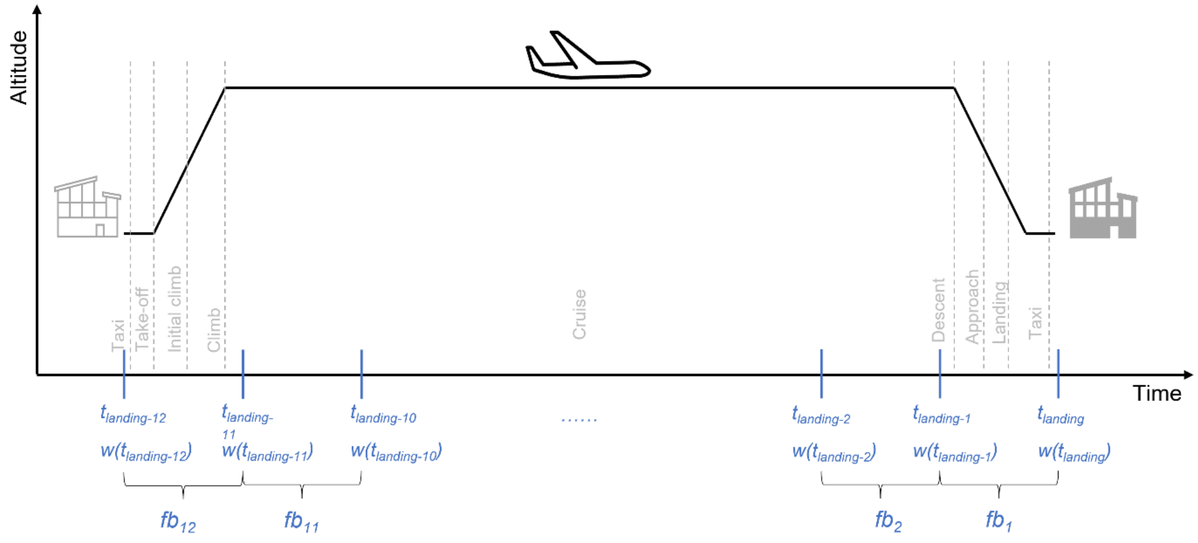

Figure 3 – Representation of reverse hour calculation of the fuel burn model, assuming a flight time of 12 hours

As previously explained, different flight phases (see Figure 2) have different fuel requirements, as the aircraft has to produce different levels of thrust. In the fuel burn model, these differences are not taken into account, and it is assumed that the fuel burnt decreases with time, because the weight of the fuel transported decreases with time, which makes the aircraft lighter and therefore less fuel is needed. The simplification of not considering different flight phases is justified by the fact that the comparison is made between flights having the same origin and destination, for which the taxi, take-off, climbing, descent, and landing are fairly similar. A visual representation of the fuel burn model is shown in Figure 4.

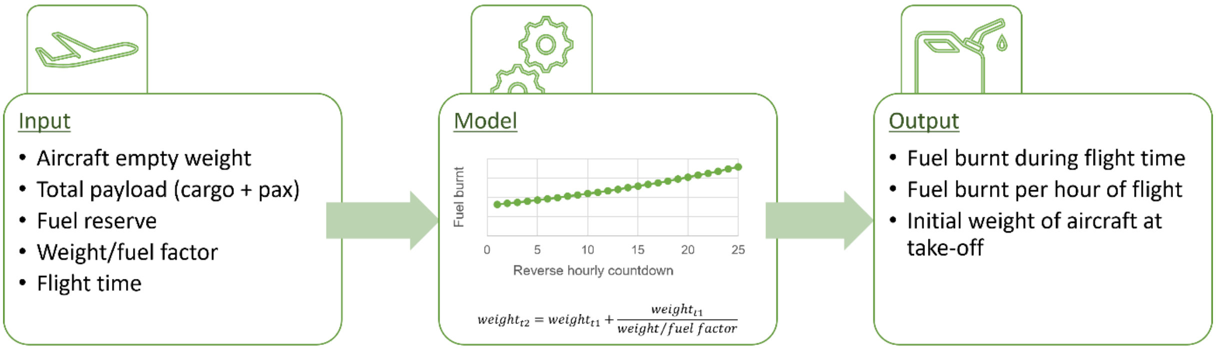

Figure 4 – Representation of the fuel burn model

4.2 Emissions allocation

The output of the emissions calculation is the amount of CO_2 emitted over the total trip. Emissions allocation refers to the procedure of assigning a proportion of the total CO_2 to the corresponding revenue load, such as passengers, cargo, and mail. The current methodology described in the IATA RP1678 allocates emissions to freight and passengers proportionally to their weight, computing the CO_2 emissions per tonne payload transported.

For cargo load, weight allocation values refer to the weight of the cargo transported. In case that primary data cannot be retrieved, the cargo weight can be estimated by multiplying an average load factor (e.g., 80%) to the maximum amount of cargo weight that can be transported by the specific aircraft type. Passenger weight should refer to the actual mass for passenger and checked baggage. In case that primary data are not available, passenger weight can be estimated by multiplying a standard weight value of a passenger by the number of passengers, considering a standard load factor (e.g., 90%). The IATA RP1726 provides a standard value of 100 kg for each passenger and their checked baggage.

When allocating emissions for belly freighters, to compensate for gallery and luggage provision, the infrastructure associated with passengers should be taken into account (e.g., the seats weight). For this purpose, a standard allocation weight per seat can be considered, equal to 50 kg for each available seat [9]. For the total allocation weight of passengers in case of weight estimations due to lack of primary data, it is important to sum the weight of each passenger and the weight of each seat. As an example, in the case of a Boeing 777-200ER with a passenger capacity of 320 seats and load factor of 90% (equal to 288 passengers), the total allocation weight for passengers is equal to 320 times 50 kg (the structural weight) plus 288 times 100 kg (the passenger plus baggage weight), resulting in a total of 188.8 tonnes total weight attributed to passengers.

4.2.1 Data requirements for emissions allocation

The data needed to allocate emissions in belly freighters according to IATA RP1678 are:

- total CO_2 emissions
- passenger weight
- cargo weight

In case that emissions should be calculated per kilometre flown, data should also include the distance flown.

As explained in Section 4.1.1, the ISO 14082 Standard prescribes the use of primary data whenever possible and to resort to modelled or default data only in case that primary data are not available. Within the TULIPS project, reasonable effort is made to acquire primary data from airline companies. Similar to the emissions calculation step, it was not possible to establish such collaboration, due to the time constraint and the data sensitivity. Therefore, modelled and standard values were used. The value of the distance flown is the same as was used for the emissions calculation in the fuel burn model, approximated by the Great Circle Distance. Passenger and cargo weights are estimated based on the passenger and cargo capacity and on the load factor. For passenger weight, the standard value of 100 kg for each passenger and checked baggage is used, as well as the standard value of 50 kg per seat available [9].

5 Unintended side effects of current allocation method

The current IATA RP1678, as described in Section 4.2 of this document, is used to allocate emissions to freight and passengers proportionally to their weight, and to compute the CO_2 emissions per tonne payload transported based on the total weight capacity of the aircraft. As described in [7], this approach might lead to fewer CO_2 emissions per tonne freight when cargo is transported by a full freighter compared to a belly freighter of the same aircraft type, for the most common cargo load factors. This unbalanced allocation is due to the fact that the weight capacity of a full freighter is much higher than the weight capacity of its belly freighter version (an example is provided in the next section 5.1). Moreover, the current IATA RP1678 allocation method might favour a passenger in a larger belly freighter over a passenger-only aircraft. In a belly freighter, emissions are spread over both passengers and cargo, and passengers have a relatively low weight/volume ratio compared to cargo; consequently, less CO_2 is attributed to the passengers of a belly freighter compared to a low-cost aircraft that transports only passengers.

The calculation reported in [7] is an example of a B747-400 dedicated freighter with 112 tonne weight capacity compared to a B747-400 passenger aircraft with 54 tonne weight capacity (passengers and freight combined). Under the assumption of a 100% load factor, 1 tonne of payload in the dedicated freighter configuration gets allocated 0.9% of the weight capacity (1/112 of the total emissions) whereas 1 tonne of payload in the passenger configuration gets allocated 1.9% of the weight capacity (1/54 of the total emissions). It can be safely assumed that over time, sustainability will gain more and more importance in the fleet decision process, especially in case that a carbon tax is implemented. In this scenario, an allocation process that favours full freighters rather than belly freighters, would lead companies to opt for full freighters when deciding on their shipment strategies. This decision would contribute to the creation of additional aircraft movements (and therefore, additional CO_2 emissions), while keeping the belly capacity of passenger aircraft underutilized.

The following paragraph elaborates on an example to show the unintended side effects of the current emissions allocation methodology, by comparing the emissions per tonne payload of a belly freighter with the ones of a full freighter.

5.1 Example of current emissions allocation method

To showcase how the current emissions allocation method works, the example proposed in [7] is reported. The first step is to estimate the emissions generated by the flight of an aircraft from its origin airport to its destination airport. The inputs for the emissions calculation, as described in Section 4.1.1, relate to the aircraft type and the OD pair.

Aircraft type inputs

In the proposed example, a B747-400 and a B777-200 aircraft types are considered, in their two configurations of full freighter and belly freighter. For the B747-400 two variants are modelled, the KLM model and the British Airways model. The first model (KLM) has more economy seats, whereas the second model (British Airways) has a large number of business class seats, and hence, a smaller total number of seats. This distinction for the B747-400 is done to show the impact of the passenger seat capacity on the emission allocation. The aircraft type inputs for the emissions calculation are the empty weight and the aircraft capacity (in terms of passenger capacity and freight capacity). All the aircraft type inputs are taken from aircraft manuals available online[9].

Table 2 – Input values for the two aircraft B747-400 and B777-200 in their full freighter (FF) and belly freighter (BF) configurations. For the B747-400, a KLM model and a British Airways (BA) models are used

Inputs		B747-400		B777-200	
Configuration	**BF (KLM)**	**BF (BA)**	**Generic FF**	**Generic BF**	**Generic FF**
Pax Max [nr]	408	275	-	320	-
Cargo Max [tonne]	12.5	12.5	112	13	102
Aircraft empty weight [tonne]	186	186	164	145	144

OD pair inputs

The current emissions allocation method is showcased by taking these routes as example:

1. from New York (JFK) to Amsterdam (AMS);
2. from Shanghai (PVG) to Amsterdam (AMS).

The two routes are of particular interest due to the distance flown, the direction of the trip (and consequent prevailing wind direction) and the different average load factors that have been recorded during previous flights. For what concerns the distance, the route New York to Amsterdam is a relatively short long-haul segment, which is flown in the Eastern direction (with tailwinds) with an average flight duration of 6 hours and 23 minutes. This relatively short flight duration means that the amount of fuel needed is relatively small. On the other hand, an average flight from Shanghai to Amsterdam takes 11 hours and 20 minutes, for which the general accuracy of the model might be hampered by the unmodelled influences during cruising (due to e.g., the uncertainties in speed, wind, and altitude during the cruise phase).

For what concerns the average load factors, figures from 2019 [10] show that the passenger load factor across the long-haul network was 89% on average, and its variation across regions was small. Therefore, the passenger load factor is assumed to be 89% in both of the example cases. On the other hand, average load factors for cargo operations varied significantly depending on the

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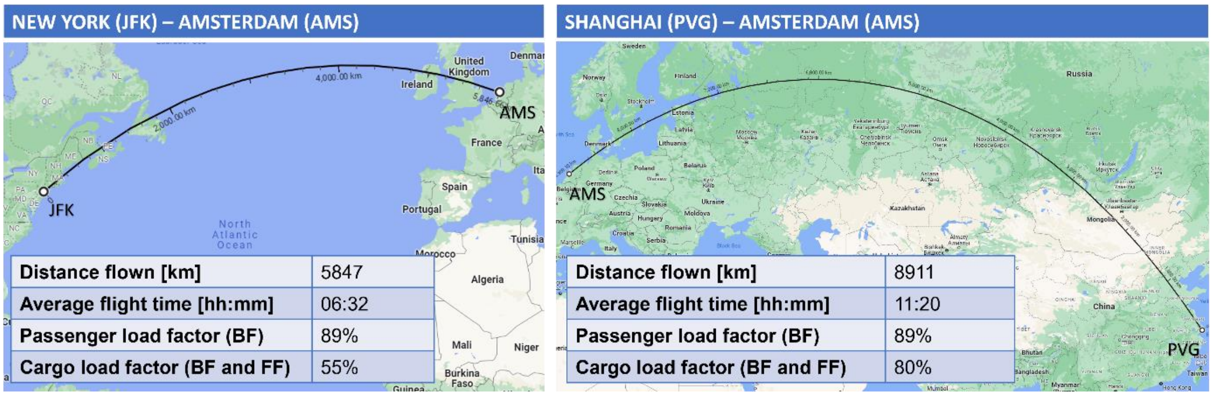
[9] Generally speaking, less seats available should mean also less aircraft weight. Since a first class seat weights substantially more than an economy seat, the weight difference between the two aircraft configuration (498 pax capacity vs 275 pax capacity) would not be relevant for emissions estimation. For what concerns the cargo weight allowed, a configuration with less passengers there could potentially increase its cargo payload. The same argument can be stated for the configuration with more passengers, in case that less passengers are flying to the destination. For simplicity reasons, it was decided to use the same weights and capacities for both configurations.

part of the network, with a global value of 64,5%. Based on the average values reported in [7], a cargo load factor of 80% is assumed for the Shanghai – Amsterdam use case, and a cargo load factor of 55% is assumed for the New York – Amsterdam use case.



NEW YORK (JFK) – AMSTERDAM (AMS)

Distance flown [km]	5847
Average flight time [hh:mm]	06:32
Passenger load factor (BF)	89%
Cargo load factor (BF and FF)	55%

SHANGHAI (PVG) – AMSTERDAM (AMS)

Distance flown [km]	8911
Average flight time [hh:mm]	11:20
Passenger load factor (BF)	89%
Cargo load factor (BF and FF)	80%

Figure 5 – OD pair information for the two use cases New York – Amsterdam and Shanghai – Amsterdam

Under the assumption that the aircraft lands with only its fuel reserve and no additional fuel, the landing weight (zero fuel weight, ZFW) and the fuel reserve are estimated. The fuel reserve is assumed to be 5% of the ZFW (see footnote 4).

Using these parameters as input for the fuel burn model of Section 4.1.2, it is possible to estimate the fuel consumption and the CO_2 emissions. Subsequently, these emissions are allocated to passengers and freight according to the IATA RP1678 principles.

Figure 6 shows the results of the Shanghai – Amsterdam use case in terms of CO_2 per tonne payload (left-hand side) and in terms of relative CO_2 per tonne payload with full freighter benchmark (right-hand side).

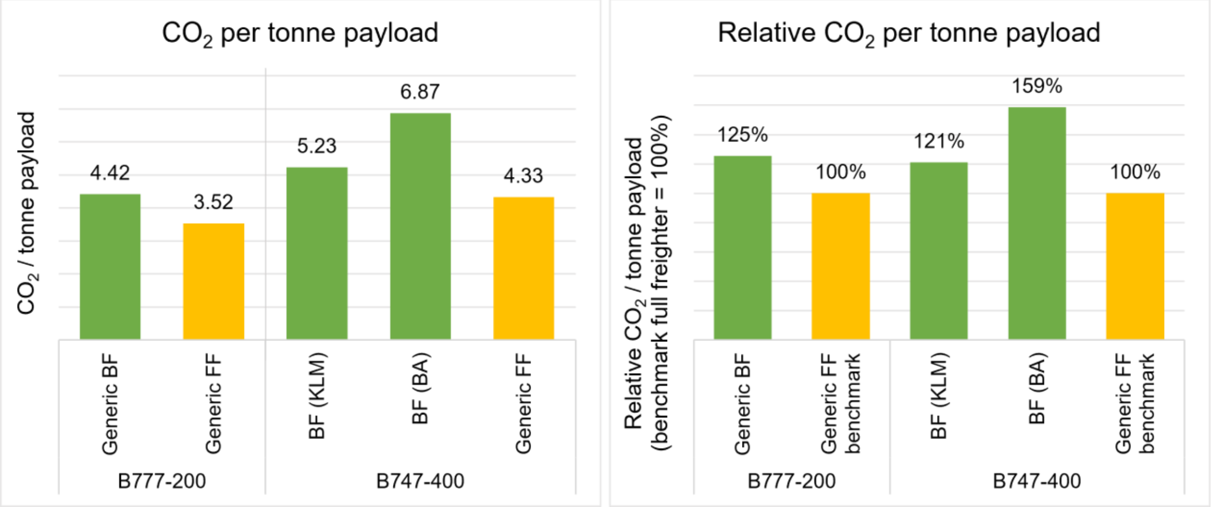


Figure 6 – Application of IATA RP1678: difference between full freighter (FF) and belly freighter (BF) for the Shanghai – Amsterdam use case, with aircraft types B777-200 and B747-400 (KLM and BA models)

The results show that, for the specific route considered, a tonne payload in a B777-200 belly freighter gets allocated 25% more emissions compared to the same aircraft in its full freighter configuration. For a B777-200, the difference is similar for the KLM model (21% more) and substantially greater for the British Airways model (59%). This difference is due to the different passenger capacities of the two models: the higher the passenger capacity, the lower the relative difference between belly freighter and full freighter, because the total payload capacity increases.

Figure 7 shows the results of the New York – Amsterdam use case in terms of CO_2 per tonne payload (left-hand side) and in terms of relative CO_2 per tonne payload with full freighter benchmark (right-hand side).

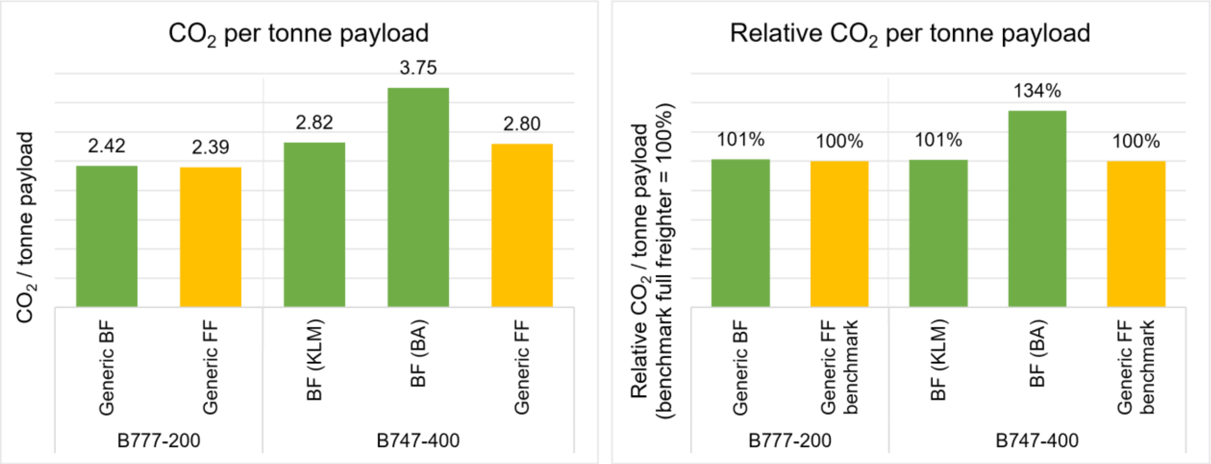


Figure 7 – Application of IATA RP1678: difference between full freighter (FF) and belly freighter (BF) for the New York – Amsterdam use case, with aircraft types B777-200 and B747-400 (KLM and BA models)

In the New York – Amsterdam use case, the relative difference between full freighter and belly freighter is less marked, only 1% for the B777-200 and B747-400 in the KLM model and 34% for the B747-400 in the British Airways model. As for the previous use case, the difference between the KLM and the BA models are to be attributed to the different passenger capacities. The lower relative differences, on the other hand, for the flight from New York compared to the flight from Shanghai, show how the emissions allocated to a tonne of payload are sensitive to the load factor used (55% in the first use case and 80% in the second) and the flight duration (6 hours and 32 minutes in the first and 11 hours and 20 minutes in the second).

To show the effects of the load factors of cargo and passengers on the CO_2 per tonne payload, Figure 8 shows the CO_2 emissions per tonne allocation payload in a full freighter (FF) on the left-hand side and the CO_2 emissions per tonne allocation payload in a belly freighter (BF) on the right-hand side, linked to the cargo load factor and the passenger load factor. Numbers are obtained from the Shanghai – Amsterdam use case previously explained, with the B777-200 aircraft, but the trend can be extended to other OD-pairs, aircraft and flight times.

Emissions are allocated to revenue load in the IATA RP1678. This means that in a full freighter, CO_2 emissions can only be allocated to the cargo weight, whereas in a belly freighter, CO2 emissions are spread over both cargo and passengers.

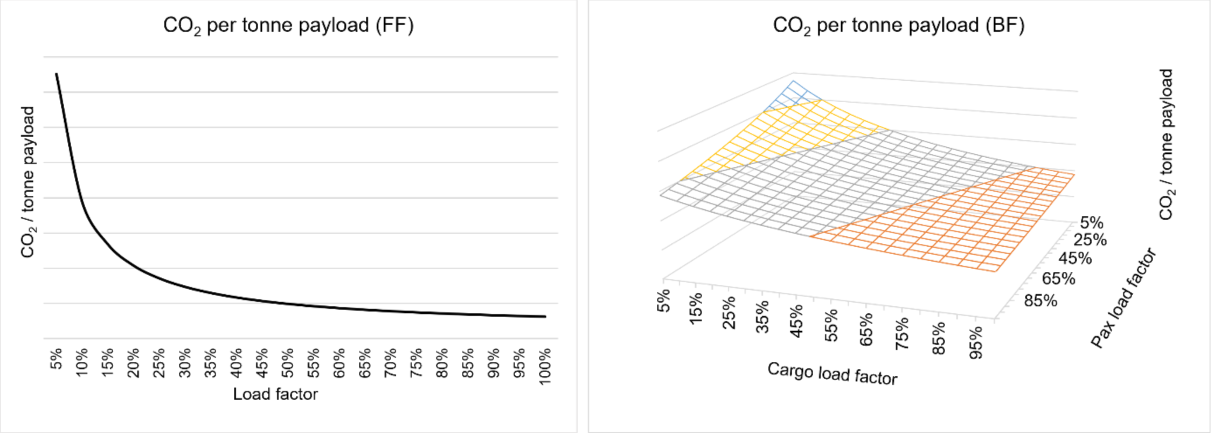


Figure 8 – Dependency of CO_2 per tonne payload on cargo load factor for full freighters (FF) configuration (left-hand side); and dependency of CO_2 per tonne payload on passenger and cargo load factors for a belly freighter (BF) configuration (right-hand side)

Intuitively speaking, increasing the load factor(s) decreases the CO2 emissions allocated to a tonne of payload, because the total emissions can be spread over a higher amount of revenue load. The total emissions are not only due to the load, but also due to the empty aircraft weight. The latter can be spread over more payload with a higher load factor, resulting in lower CO2 emissions per tonne payload.

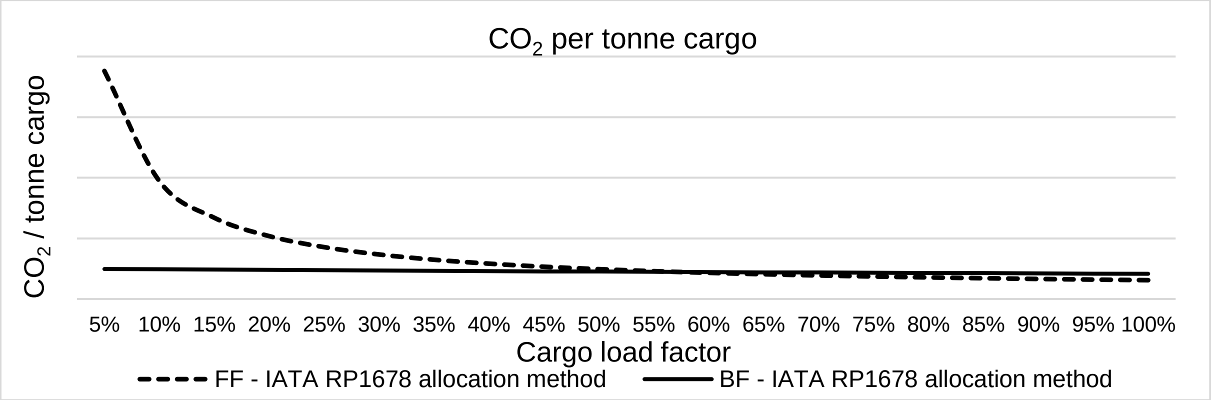


Figure 9 shows the comparison of the allocated CO_2 emissions per tonne cargo in a full freighter (dotted line) and the allocated CO_2 per tonne cargo in a belly freighter, with a fixed passenger load factor (solid line). The line corresponding to the belly freighter (solid line) does not show a significant decrease with higher load factors, as happens with the full freighter. This slow and slight decrease in CO_2/tonne cargo is attributed to the low share of cargo weight in the total payload capacity. Therefore, with the passenger load factor constant, a change in the cargo load factor is only slightly visible in the CO_2/tonne cargo figures.

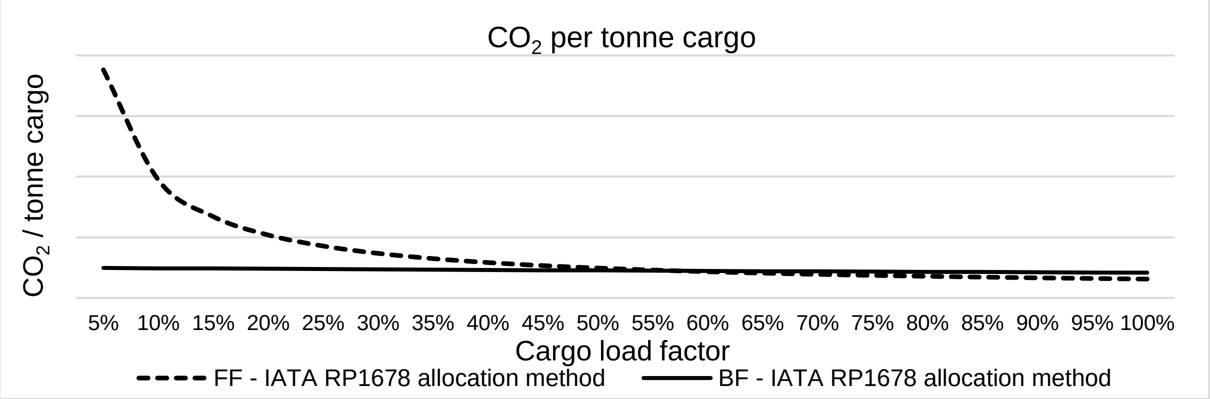


Figure 9 – Comparison of allocated CO2 per tonne cargo in a full freighter (FF) and in a belly freighter (BF), based on cargo load factor and fixed passenger load factor

From this figure, it can be noticed how for the most common cargo load factors (i.e., values higher than 55%), it is more beneficial to transport one tonne of cargo in a full freighter rather than in a belly freighter, in terms of CO_2 emissions.

6 Proposed emissions allocation methodology

The goal of task 8.6, is to propose a carbon footprinting method that if applied can lead to the reduction of GHG emissions. This method incentivise the distribution of cargo into belly freighters, instead of using dedicated full freighters, thus potentially avoid unnecessary flights and therefore reduce fleet emissions.

The starting point for the methodology development is the findings from [7], which shows how the current allocation method based on weight proportions could lead to an unintended side effect of one tonne of freight getting allocated more emissions when transported in a belly freighter compared to a full freighter. This has been further discussed in Section 5.

To elaborate on the proposed methodology, we started by identifying the issues that could lead to this unbalanced allocation. The current IATA RP1678 approach calculates the emissions based on the total fuel used and allocates these emissions to the total revenue load, without taking the different sources of emissions into account. The proposed methodology looks at the different drivers of fuel used (i.e., aircraft weight, cargo weight and/or passengers' weight) and allocates the emissions to the corresponding weight source. Therefore, the concepts of empty-aircraft emissions and marginal emissions are suggested.

Empty-aircraft emissions are generated by the fuel burnt to fly to the destination with an empty aircraft, without payload (i.e., empty-aircraft fuel). The empty-aircraft fuel needed for a specific flight is constant, since it depends only on the empty weight of the aircraft and on the flight duration. Marginal emissions are the emissions generated by the fuel burnt to fly to the destination that are attributed to the payload (i.e., marginal fuel). The marginal fuel consumption depends on the number of passengers and/or the amount of cargo transported (i.e., the payload). The sum of empty-aircraft emissions and marginal emissions gives the total emissions generated during the flight (equation 2).

Equation 2 $$total\ emissions = empty\ aircraft\ emissions + marginal\ emissions$$

Emissions are linearly dependent on fuel (1 tonne of fuel emits 3.15 tonne of CO_2 – see footnote 2), and fuel linearly influences costs. Therefore, equation 2 can be rewritten in terms of costs:

Equation 3 $$cost_{fuel,total} = cost_{fuel,\ empty\ aircraft} + cost_{fuel,marginal}$$

Figure 10 shows on the left-hand side the total fuel cost (C) as a function of the payload weight (W), with a distinction between empty-aircraft and marginal fuel costs; and on the right-hand side the relative fuel cost per unit payload weight (C/W) as a function of the payload weight (W). Figure 10 (right-hand side) shows that when the total payload weight is increased, the fuel cost per unit payload weight declines.

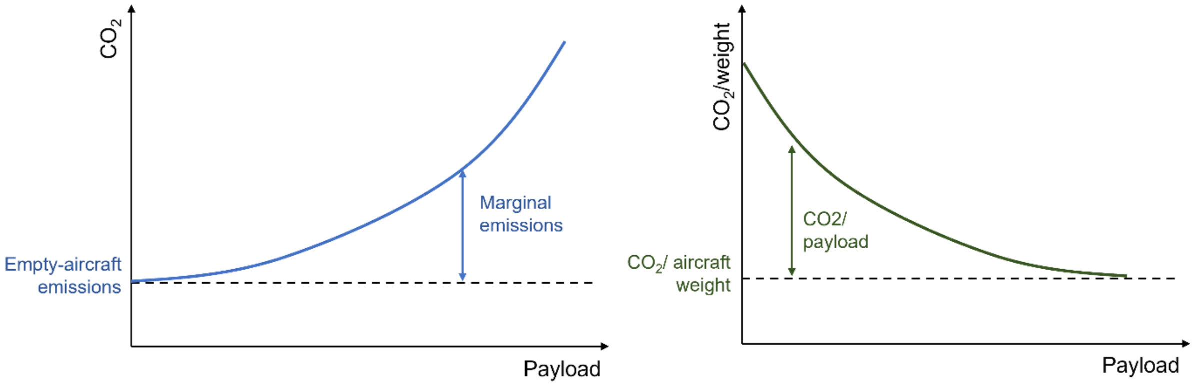


Figure 10 – Total fuel costs as a function of the payload weight (left-hand side); Relative fuel cost per payload weight as a function of the payload weight (right-hand side)

When looking at fleet operations, it is clear that reducing the number of flights and increasing the payload in existing flights (e.g., passenger flights) will reduce the empty-aircraft cost of fuel (due to less aircraft flying) and therefore will reduce the total cost of fuel of the fleet, reducing consequently also the total emissions of the fleet.

To showcase the need to prioritise fleet optimisations based on emissions reduction, two scenarios are identified:

- scenario A: “Business as usual”. In this scenario, cargo and passengers have to reach the same destination. The entire cargo load is shipped using a full freighter, whereas belly freighters are only used to transport passengers
- scenario B: “Fleet optimisation based on sustainability”. In this scenario, only belly freighters are used, and the cargo is fit in the already existing passenger flights.

In the scenarios, the same aircraft type as defined in Table 2 are used. in both scenarios, a passenger load factor of 90%, and a flight time of 10 hours are used. For scenario A, a cargo load factor of 0% for belly freighters and 100% for full freighters is used. For scenario B, a cargo load factor of 100% for belly freighters is used. To estimate emissions, the fuel burn model defined in Section 4.1.2 is used.

For the B777-200 aircraft, there is a cargo capacity of 13 tonne in the belly freight configuration and a cargo capacity of 102 tonne in the full freighter configuration. This means that in order to carry the same amount of cargo, 1 full freighter has to be replaced by 8 belly freighters. For this reason, in scenario A, 1 full freighter and 8 belly freighters are used; in scenario B, 8 belly freighters are used. Figure 11 shows the differences in emissions for scenario A and scenario B for a B777-200 in the Shanghai – Amsterdam route. For the B747-400 aircraft, there is a cargo capacity of 12.5 tonne in the belly freight configuration and a cargo capacity of 112 tonne in the full freighter configuration. In this case, to carry the same amount of cargo, 1 full freighter has to be replaced by 9 belly freighters. Therefore, in scenario A there are 1 full freighter and 9 belly freighters, and in scenario B there are only 9 belly freighters.

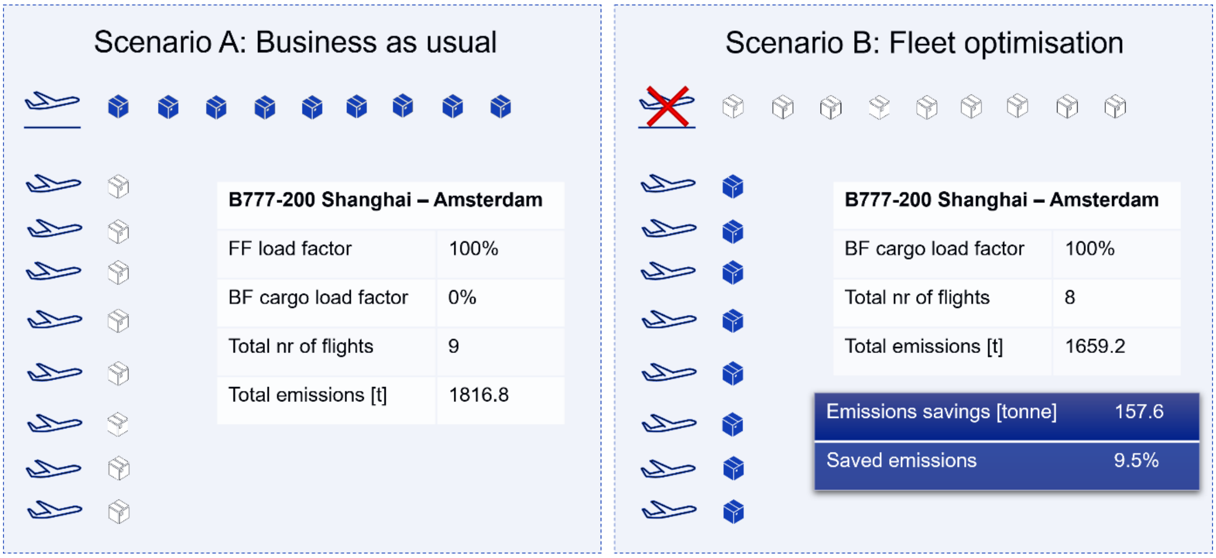


Figure 11 – Effects on fleet emissions of cargo distribution over available belly freight capacity. Example of a B777-200 in the route Shanghai Amsterdam

Table 3 shows the total emissions in each scenario, for the two aircraft types used, as well as the potential emissions savings that can be achieved implementing a fleet optimisation based on sustainability (scenario B). Emissions savings are calculated by subtracting the total emissions of scenario B from the total emissions of scenario A. The average emissions per flight are estimated by diving the emissions savings by the total number of flights of scenario B.

Table 3 – Total emissions for scenario A and scenario B with a B777-200 and a B747-400, and potential emissions savings achievable with scenario B

		B777-200	**B747-400**
Scenario A: **Business as usual**	Total number of flights	9	10
	Total emissions [tonne CO_2]	1816.80	2532.66
Scenario B: **Fleet optimisation based on sustainability**	Total number of flights	8	9
	Total emissions [tonne CO_2]	1659.20	2350.80
Emission savings with fleet optimisation [tonne CO2]		157.60	181.86
Average emissions savings per flight [tonne CO_2]		19.70	20.21
% of saved emissions per flight		9.5%	7.8%

The results shown in Table 3 represent a situation in which a 90% load factor applies. Running the same model with different passengers' load factors did not lead to different results, making the percentage of saved emissions per flight independent from the passenger load factor.

6.1 Steps for the proposed methodology

In the proposed methodology, emissions are allocated based on the distinction between empty-aircraft emissions and marginal emissions.

In a full freighter, the marginal emissions are solely generated by the cargo payload (being cargo the only payload transported), and both emissions components are allocated to it.

In a belly freighter, the marginal emissions are generated by both passenger payload and cargo payload and are assigned to them based on their total weight (as described in the IATA RP1678). To estimate the proportion of empty-aircraft emissions that should be allocated to cargo, the decision was based on the aim to incentivise the distribution of cargo into the available belly freight capacity. We looked at the percentage of saved emissions per flight from Table 3, and set similar percentages as target for CO_2 allocation savings. To reach the target of 9.5% savings in CO_2 per tonne cargo in a B777-200, empty-aircraft emissions should be allocated with a split of 11% to cargo and 89% to passengers[10]. In this way, the most accurate amount of emissions is assigned to passengers and freight for the passenger-freight combined air service, based on their weight and on their contribution to total emissions, in a way that mostly resembles reality.

Assigning the correct amount of emissions to freight means that when sustainability will have a much larger impact on the decision making, shipping cargo in a belly freighter will become more advantageous compared to a full freighter. Consequently, cargo capacity of belly freighters can be fully utilised and no unnecessary full freighter flights needs to be planned.

The steps to apply the new methodology depend on whether primary data or modelled data are used. In case that primary data are used, refer to Section 6.1.2; in case that modelled data are used, refer to Section 6.1.1.

6.1.1 In case of modelled data

When primary data are not available, fuel burnt can be estimated with a model (in this project, the fuel burn model developed in TNO and described in Section 4.1.2 was used). In this case, the split between marginal and empty-aircraft emissions can be made when estimating the fuel burnt during the flight. The steps to follow, shown in Figure 12, are:

1. **model the fuel consumption of the aircraft**, distinguishing between empty-aircraft and marginal fuel consumption

2. **calculate the empty-aircraft emissions**, i.e., the CO_2 emissions generated by the aircraft flying empty. This value is constant for a given aircraft model and for a given flight, since it only depends on the empty weight of the aircraft

   Equation 4 $$empty\ aircraft\ CO_2 = empty\ aircraft\ fuel\ *\ emission\ factor$$

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[10] Extending the model to a wider range of passenger load factors and different aircraft types did not lead to substantially different results, therefore the proposed share is not unique to the selected use case.

3. **calculate the marginal emissions**, i.e., the CO_2 emissions generated by the payload. This value depends on the weight of passengers and/or cargo, or, if not available, on the load factors for passengers and/or cargo

   Equation 5 $$marginal\ CO_2(FF) = marginal\ fuel * emission\ factor$$

   Equation 6 $$marginal\ CO_2(BF, pax) = marginal\ fuel * emission\ factor * \frac{pax\ weight}{payload}$$

   Equation 7 $$marginal\ CO_2(BF, cargo) = marginal\ fuel * emission\ factor * \frac{cargo\ weight}{payload}$$

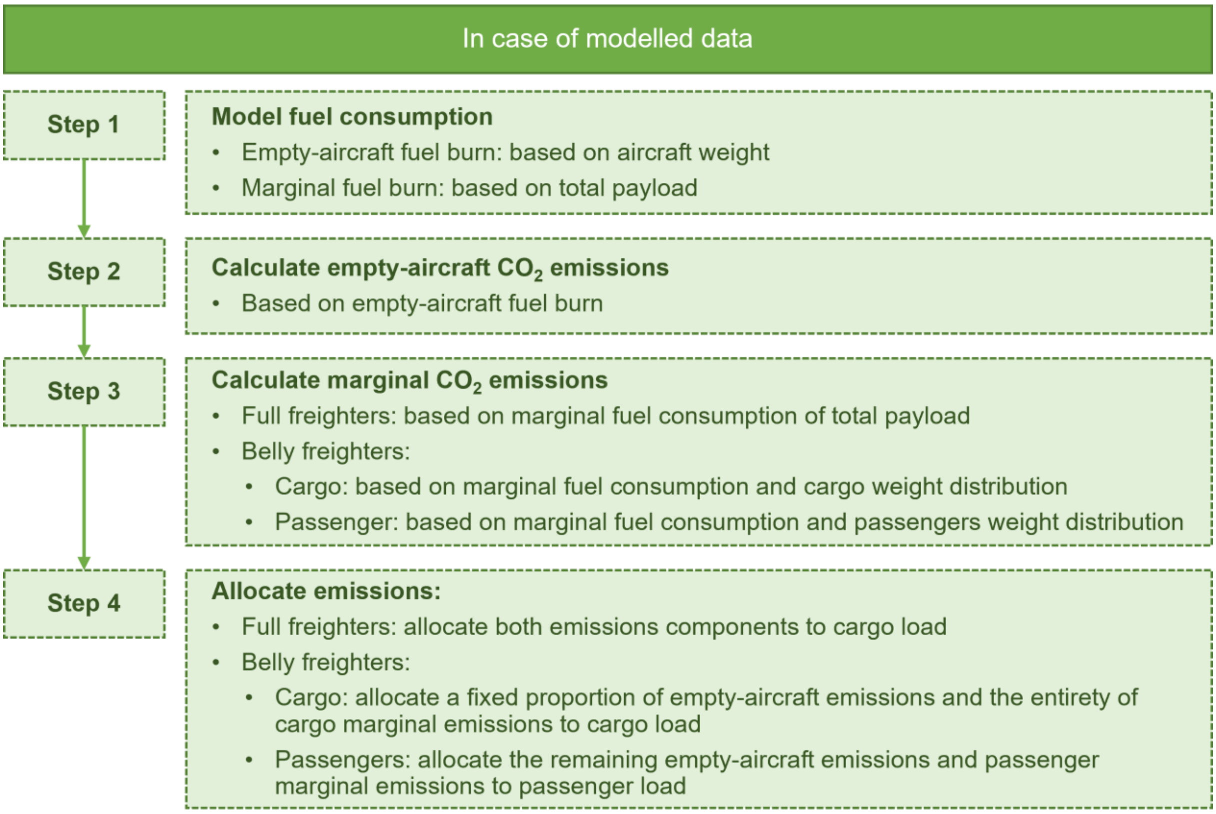
4. **allocate emissions**
   1. for full freighters, both emissions components (empty-aircraft and marginal emissions) are allocated to the transported weight

      Equation 8 $$cargo\ allocation(FF) = \frac{empty\ aircraft\ CO_2(FF) + marginal\ CO_2(FF)}{cargo\ weight}$$

   2. for belly freighters, empty-aircraft emissions are allocated partially to passengers and partially to cargo, with a higher proportion being allocated to passengers, to incentivise the distribution of cargo into the available belly freight capacity. The chosen percentage is based on the results of Table 3

      Equation 9 $$cargo\ allocation\ (BF) = \frac{empty\ aircraft\ CO_2(BF)*0.11+marginal\ CO_2(BF,cargo)}{cargo\ weight}$$

      Equation 10 $$pax\ allocation\ (BF) = \frac{empty\ aircraft\ CO_2(BF)*0.89 + marginal\ CO_2(BF, pax)}{pax\ allocation\ weight}$$



In case of modelled data

Step 1

Model fuel consumption
- Empty-aircraft fuel burn: based on aircraft weight
- Marginal fuel burn: based on total payload

Step 2

Calculate empty-aircraft CO_2 emissions
- Based on empty-aircraft fuel burn

Step 3

Calculate marginal CO_2 emissions
- Full freighters: based on marginal fuel consumption of total payload
- Belly freighters:
  - Cargo: based on marginal fuel consumption and cargo weight distribution
  - Passenger: based on marginal fuel consumption and passengers weight distribution

Step 4

Allocate emissions:
- Full freighters: allocate both emissions components to cargo load
- Belly freighters:
  - Cargo: allocate a fixed proportion of empty-aircraft emissions and the entirety of cargo marginal emissions to cargo load
  - Passengers: allocate the remaining empty-aircraft emissions and passenger marginal emissions to passenger load

Figure 12 – Steps of proposed allocation method in case of modelled fuel burn data

6.1.2 In case of primary data

In case that fuel tankage data is available, the total amount of fuel burnt during the flight is known, and the split between marginal fuel burnt and empty-aircraft fuel burnt cannot be made. To allow for an estimation of the fuel proportion due to aircraft weight (i.e., empty-aircraft fuel burnt) an equation is estimated. Using the inputs from the modelled data, it is possible to estimate the influence of aircraft weight and flight time on the empty-aircraft fuel burn, using a regression model. The equation returns the amount of empty-aircraft fuel burnt (y), for a given aircraft empty weight (x_1) and a given flight time (x_2). The steps to obtain the equation are described in Appendix A.

The steps to follow, shown in Figure 13, are:

1. **estimate the amount of empty-aircraft fuel burn** from the tankage data

   Equation 11 $$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$$

   With: $\begin{cases} x_1 = aircraft\ empty\ weight[ton] \\ x_2 = flight\ duration\ [hours] \\ y = empty\ aircraft\ fuel\ burn[ton] \end{cases}$ and $\begin{cases} \beta_0 = 0 \\ \beta_1 = -0.07 \\ \beta_2 = 0 \\ \beta_3 = -0.0449 \end{cases}$

2. **derive the amount of marginal fuel burn** based on the total tankage data

   Equation 12 $$marginal\ fuel\ burnt = total\ tankage\ data - empty\ aircraft\ fuel\ burnt$$

3. **calculate the empty-aircraft emissions**, as done in equation 4

4. **calculate the marginal emissions**, as done in equation 5, equation 6 and equation 7

5. **allocate emissions** as in equation 8 for full freighters and in equation 9 and equation 10 for belly freighters

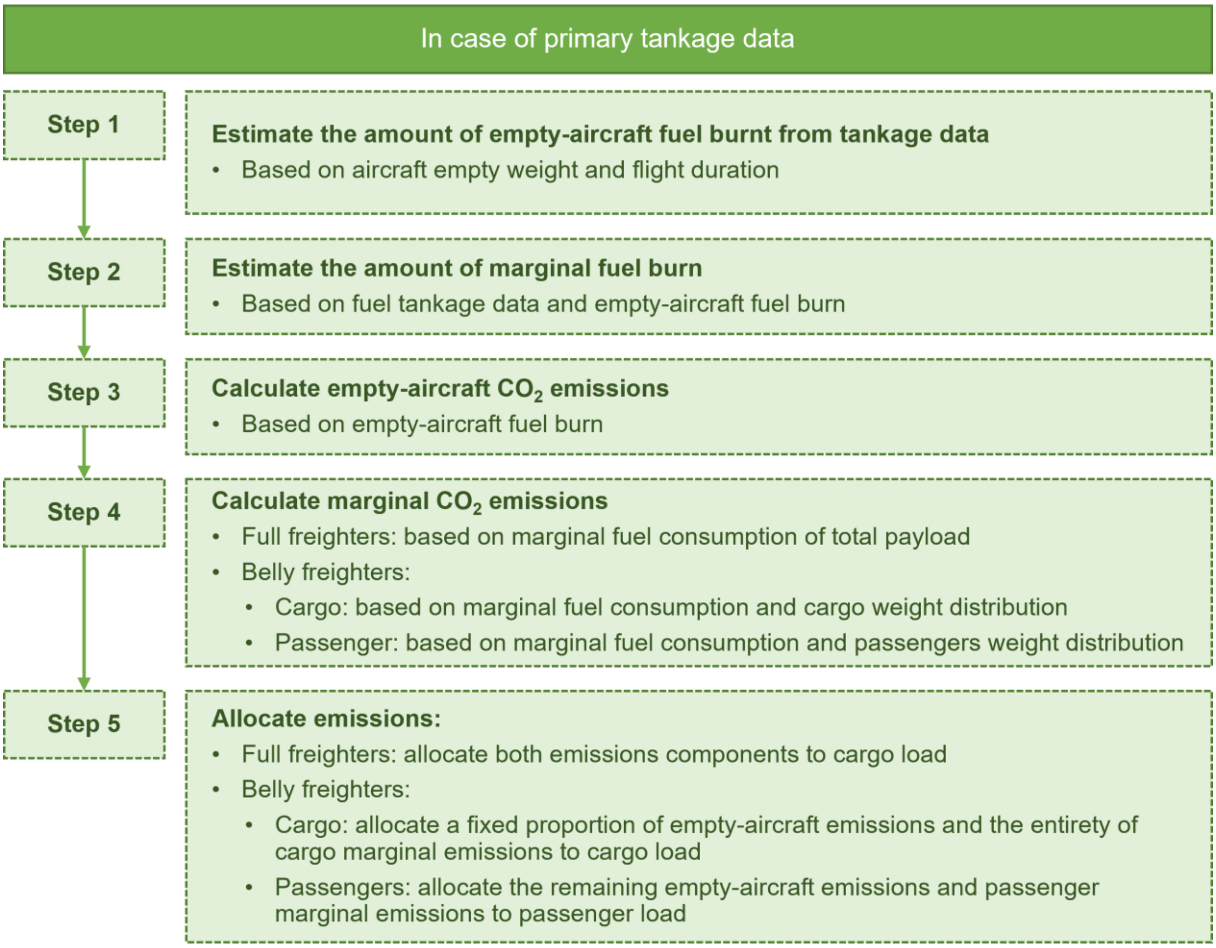


Figure 13 – Steps of proposed allocation method in case of primary tankage data

6.2 Example of the proposed emissions allocation method

To show the effect of using the proposed methodology, the 5 steps of Figure 13 are applied to the example of Section 5.1. Based on the empty aircraft weight, payload weight and flight duration, fuel tankage data are modelled. This is done using the previously explained fuel burn model. This model is applied to the flight of an empty aircraft and the flight of the aircraft with its payload, allowing for a distinction between marginal and empty-aircraft fuel burn, and hence, emissions. Emissions are then allocated based on the steps of Figure 13.

Results of the Shanghai – Amsterdam use case are shown in Figure 14, whereas Figure 15 shows the results for the New York – Amsterdam use case.

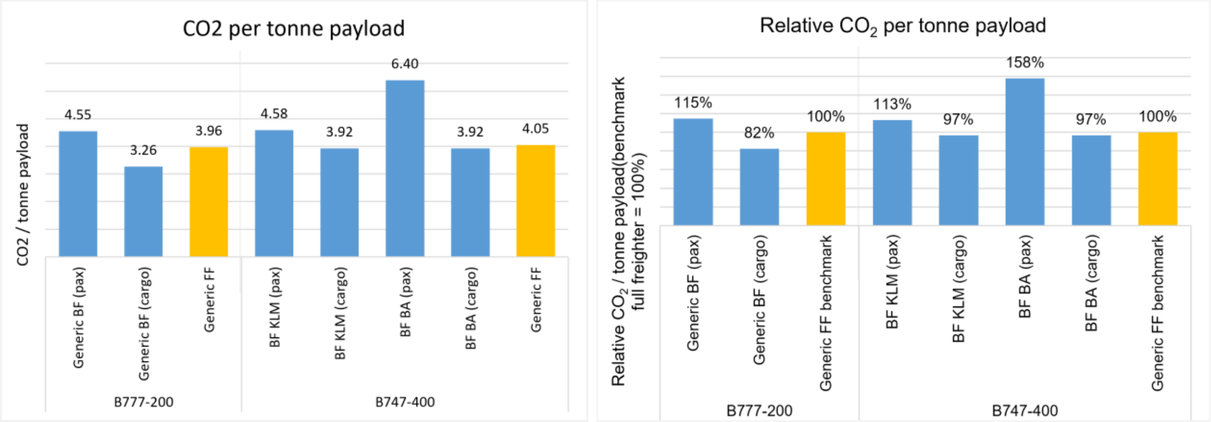


Figure 14 – Application of the proposed methodology: difference between full freighter (FF) and belly freighter (BF) for the Shanghai – Amsterdam use case, with aircraft types B777-200 and B747-400 (KLM and BA models)

With the new allocation methodology, belly freighters have two values for emissions allocation: one showing the tonne of CO_2 produced to transport 1 tonne of passengers and another one showing the tonne of CO_2 produced to transport 1 tonne of cargo. In the Shanghai use case, cargo emissions per tonne transported are up to 18% lower in a belly freighter compared to a full freighter. Since the amount of emissions did not change compared to the IATA RP1678 method, the remaining emissions of a belly freighter are now allocated to passengers. As a result, cargo gets less emissions allocated, at the expenses of passengers, who get allocated comparatively more emissions per tonne transported. In the British Airways models, the CO_2 per tonne passenger is higher due to the lower passenger capacity of the aircraft.

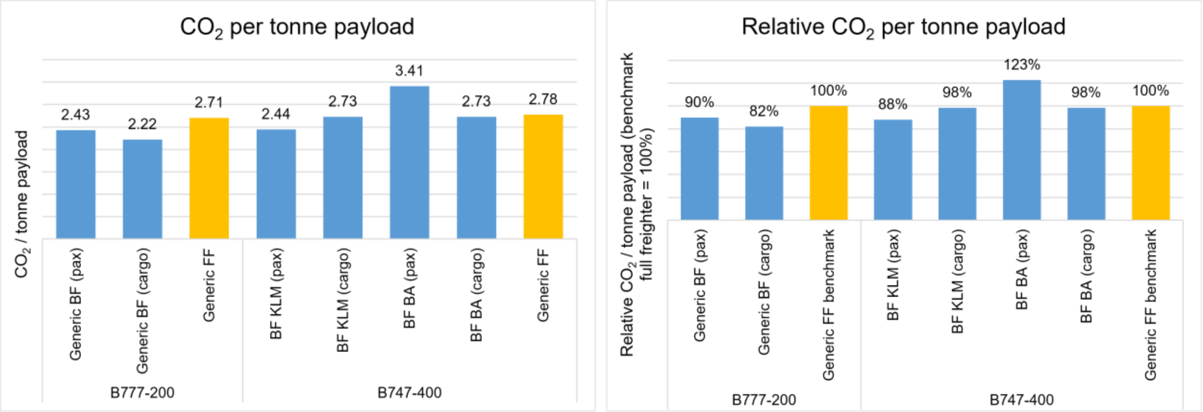


Figure 15 – Application of the proposed methodology: difference between full freighter (FF) and belly freighter (BF) for the New York – Amsterdam use case, with aircraft types B777-200 and B747-400 (KLM and BA models)

Similarly, in the New York use case, cargo emissions are up to 18% lower in a belly freighter compared to a full freighter.

Using the proposed methodology, the cargo transported in the BF gets allocated less emissions per tonne transported compared to a FF. To evaluate the effect of the proposed methodology on a larger scale, the CO_2 per tonne payload (distinguished between CO_2 per tonne passenger and CO_2 per tonne cargo) was plotted in dependency with the cargo load factor and the passenger load factor. From equation 7 and equation 8, one can see that the CO_2 per tonne passenger depends only on the passenger load factor, since the empty-aircraft emissions and marginal passenger emissions do not depend on the cargo load factor. With the increase of the passenger load factor, the CO_2 per tonne passenger decreases, because the empty-aircraft emissions are "spread" over more passengers, and therefore over more tonnes transported. Similarly, the CO_2 per tonne cargo depends only on cargo load factor, and their values are inversely proportional (the empty-aircraft emissions are "spread" over more cargo transported).

The goal of this project is to provide a methodology that allow for full utilisation of the belly freight cargo capacity, so to minimise the number of flights and therefore emissions. The way to do that, is to propose an allocation method that favours belly freighters for cargo shipment. Figure 16 shows how the proposed methodology promotes this decision, by allocating a lower proportion of emissions to cargo transported in a belly freighter.

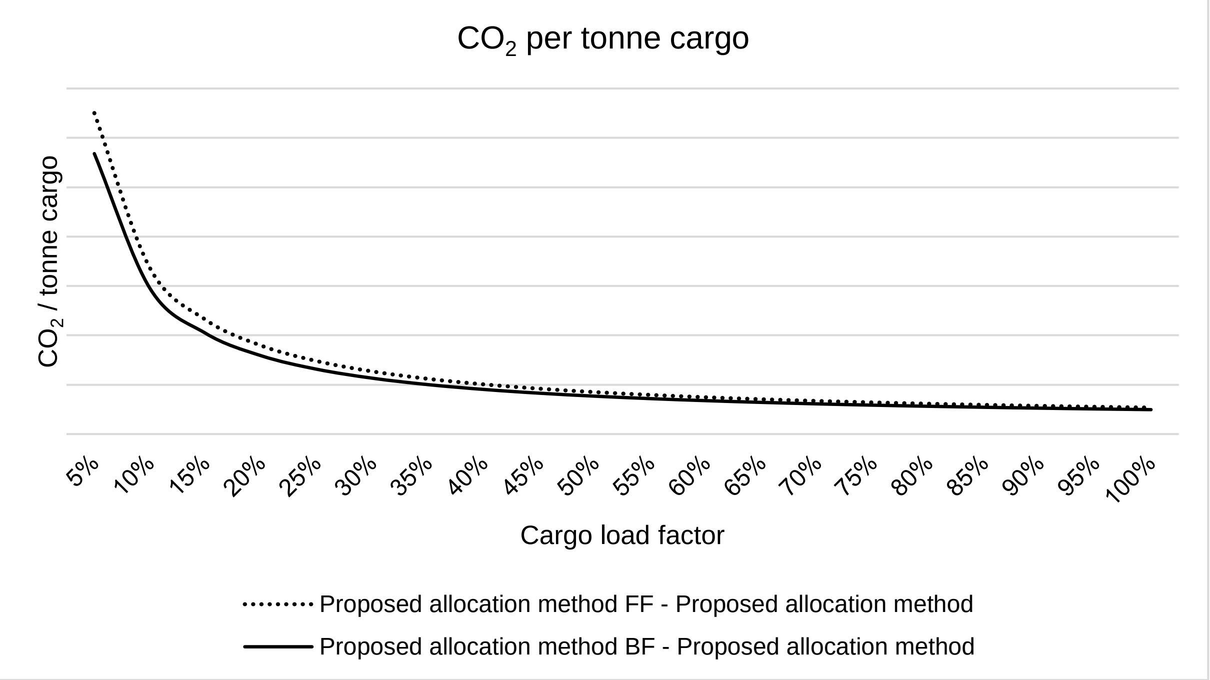


Figure 16 – CO_2 per tonne cargo in a full freighter and in a belly freighter configuration, in relation to cargo load factor. Based on proposed allocation methodology

6.3 Comparison of proposed method with current IATA RP1678

The proposed methodology suggests an alternative way of allocating emissions, based on a split between empty-aircraft and marginal emissions in the calculation phase.

Figure 17 shows a visual comparison between the IATA RP1678 method and the proposed method. The left-hand side shows a representation of the current IATA RP1678 method, whereas the right-hand side shows the proposed methodology. Dotted arrows and rectangles indicate the inputs needed. In the IATA method, payload refers to the cargo weight in case of a full freighter, and to the sum of cargo and passenger weight in case of a belly freighter.

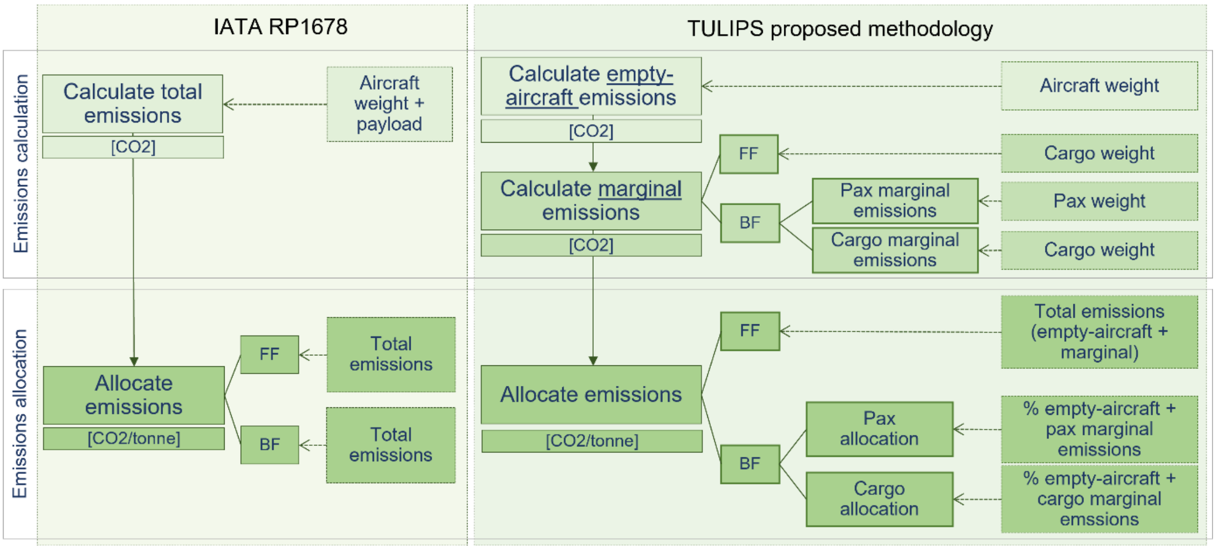


Figure 17 – Visual comparison of IATA RP1678 method and proposed method

The main distinctions between the current IATA RP1678 method and the proposed method are to be found in the following three aspects:

- Emission calculation. In the proposed methodology, emissions are split between empty-aircraft emissions and marginal emissions, and for belly freighters, the marginal emissions are further distinguished between marginal passenger emissions and marginal cargo emissions, based on their weight proportion. The current IATA method, on the other hand, does not make this distinction and provides the total emissions generated by the flight, based on the sum of the aircraft weight and the payload transported.
- Weight and payload used in the emission calculation step. In the proposed methodology, marginal emissions are calculated separately for cargo and for passengers based on the fuel used to carry their respective weights, in order to allow for proper allocation. Since the current IATA method does not separate between marginal and empty-aircraft emissions, this distinction is not made. The resulting emissions are therefore calculated based on the fuel used to carry the whole payload.
- Emission allocation. In the current IATA method, the total emissions are allocated to the total payload transported, without distinction between cargo and passengers. In the proposed method, empty-aircraft emissions are allocated to cargo and passengers based on a fixed share. Full freighters fly because of the cargo load; therefore, empty-aircraft and marginal emissions are both allocated to cargo. Belly freighters, instead, fly mainly due to passenger demand, therefore, empty-aircraft emissions are allocated with a higher share to passengers, in reference to the potential savings of implementing a fleet optimisation system based on sustainability, together with marginal passenger emissions, while cargo gets allocated a lower share of empty-aircraft emissions plus the marginal cargo emissions.

The examples reported in Section 5.1 and Section 6.2 show that in the current IATA RP1678 allocation methodology, shipping cargo in a belly freighter is only beneficial (in terms of emissions per tonne) for small load factors. In the proposed methodology it is always beneficial to ship cargo in an existing belly freighter flight, provided that there is still capacity left. (Figure 18).

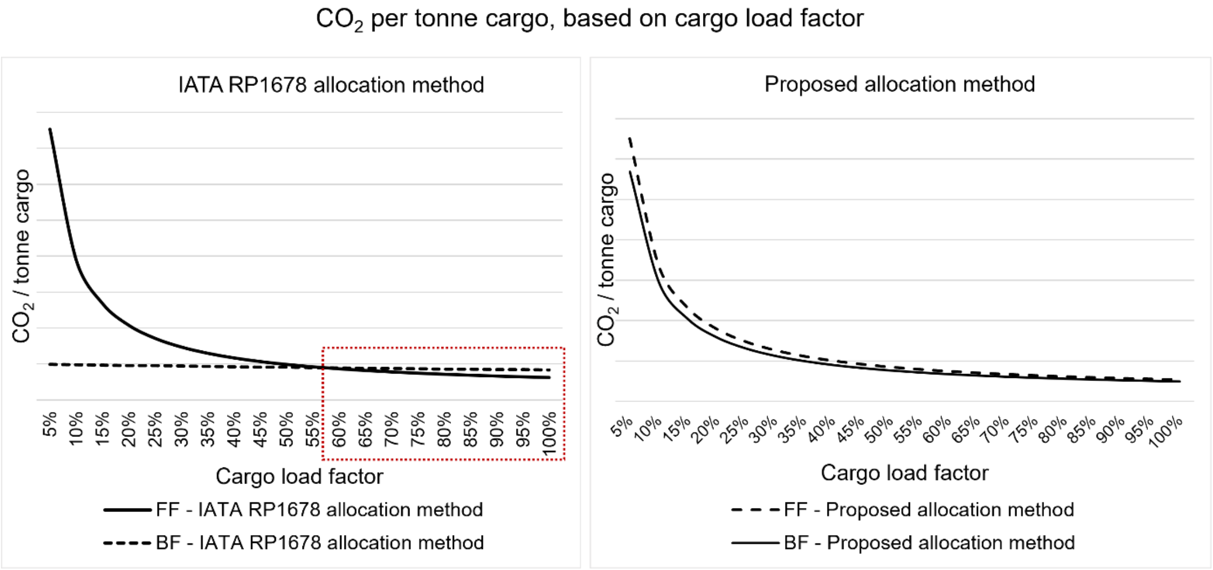


Figure 18 – Comparison of IATA RP1678 allocation method and proposed allocation method in terms of CO_2 per tonne cargo transported in a full freighter (FF) and in a belly freighter (BF)

Moreover, the distinction between empty-aircraft and marginal fuel usage allows for a comparison of the performances of different aircraft models. Measuring the empty-aircraft fuel usage of different aircraft types can be seen as a baseline for understanding the efficiency of the flight: lower empty-aircraft values will correspond to lower total values (for the same amount of payload transported) and consequently lower total emissions.

7 Passenger class allocation

This section provides an example of how to include passenger seat category in the proposed emissions allocation methodology. It is a preparatory exercise that will be used in the second part of task 8.6 of TULIPS, in which the proposed methodology is applied to transport chains that go via Schiphol. It is therefore not pertaining to the elaboration of the methodology, but it is more a further application of the methodology that will be used in the next steps of the project.

The IATA RP1678 already provides a methodology to distinguish the emissions allocation per passenger seat class. In this section, the proposed methodology based on marginal and empty-aircraft emissions is applied to this class categorisation according to a volume-based approach, in which the passenger emissions are allocated to each passenger based on the volume occupied by their seat.

This volume-based approach considers the volume occupied by an economy seat and the volume occupied by the other seat categories (in the example of Figure 19, the other categories are the world business and economy comfort). The output is a so-called *seat factor*, that estimates the number of economy-equivalent seats that could replace another seat class (e.g., number of economy seats that could replace one business seat or one first class seat). The *seat factor* is then used to calculate the economy-equivalent allocation weight and therefore the economy-equivalent allocation weight per tonne passenger, to, ultimately, calculate the proportion of the passenger emissions per seat category.

It is very difficult to define a standard aircraft configuration, since it varies not only between aircraft types, but also between airline companies. For this reason, it is not possible to define a standard *seat factor*.

In the following paragraph, we provide an example using a Boeing 777-200ER from the airline company KLM, in its V2 configuration. The seat configuration of Figure 19 is taken from an available online source [11], and it relates to 240 economy (E) seats, 40 economy comfort (EC) seats and 34 world business (WB) seats. To calculate emissions to use for this example, the fuel burn model described in Section 4.1.2 is used, for a given OD pair. Numbers regarding emissions do not resemble the actual emissions of a specific flight but are instead only used as an example to explain the methodology steps. For simplicity reasons, a 100% load factor for passengers and an 85% load factors for cargo are assumed.

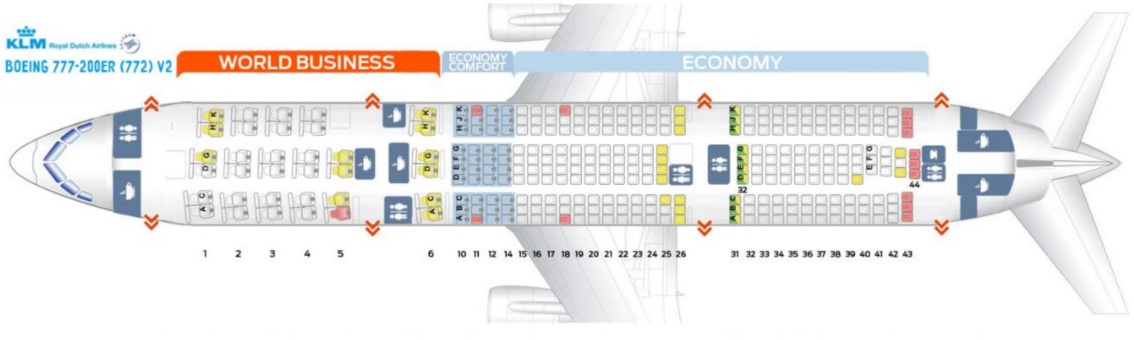


Figure 19 – Seat configuration of a KLM Boeing 777-200ER version 2. From [11]

The steps to follow to allocate emissions based on passenger seat class, shown in Figure 20, are as follows:

1. **calculate total emissions.** Using the methodology proposed in this document, calculate the total emissions distinguished in empty-aircraft emissions, cargo-related emissions and passenger-related emissions, as explained in equation 4, equation 6, and equation 7:

   Equation 13 $empty\ aircraft\ emissions = 186.58\ tonne$

   Equation 14 $cargo\ emissions = 14.22\ tonne$

   Equation 15 $pax\ emissions = 40.66\ tonne$

2. **calculate the economy seat equivalent.** Based on the ratio between the volume occupied and the number of seats, calculate the economy seat equivalent. In the example of Figure 19, assuming a total usable space of 400 m^2, we can derive the information provided in Table 4. The f_x-value shows the economy-equivalent of the Economy Comfort class (f_{EC}) and the economy-equivalent of the World Business class (f_{WB}), obtained by dividing the respective volume/seat ratio by the volume/seat ratio of the Economy class

   Table 4 – Volume, seats and economy seat equivalent for B777-200ER V2 from KLM[11]. E = Economy class, EC = Economy Comfort class, WB = World Business class.

	Number of seats	Volume [m^2]	Volume/Seats	Economy-equivalent (f_x)
E	242	240	1	1
EC	40	40	1	1
WB	34	120	3.5	3.5

3. **calculate the economy-equivalent number of passengers and their allocation weight.** The economy-equivalent (*ec.eq.*) number of passengers is calculated by multiplying the number of passengers of each seat category by their economy-equivalent factor f_x

   Equation 16 $ec.eq.\ pax = Pax_E \cdot f_E + Pax_{EC} \cdot f_{EC} + Pax_{WB} \cdot f_{WB} = 401$

   Assuming an allocation weight of 150 kg per passenger [9], the economy equivalent allocation weight is:

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[11] Volume is not based on actual value, but it is estimated via assumption. Values are reported just for the purpose of showing the application of the proposed methodology to seat class emission allocation.

Equation 17 $ec.eq.\ allocation\,weight = 401 \cdot 0.15 = 60.15\ tonne$

4. **allocate the economy-equivalent weight.** The total passengers' emissions are then allocated to the economy-equivalent allocation weight (based on equation 10), to find the CO_2 per tonne economy-equivalent passengers:

   Equation 18 $emissions\ allocated\ to\ pax = 206.72\ tonne$

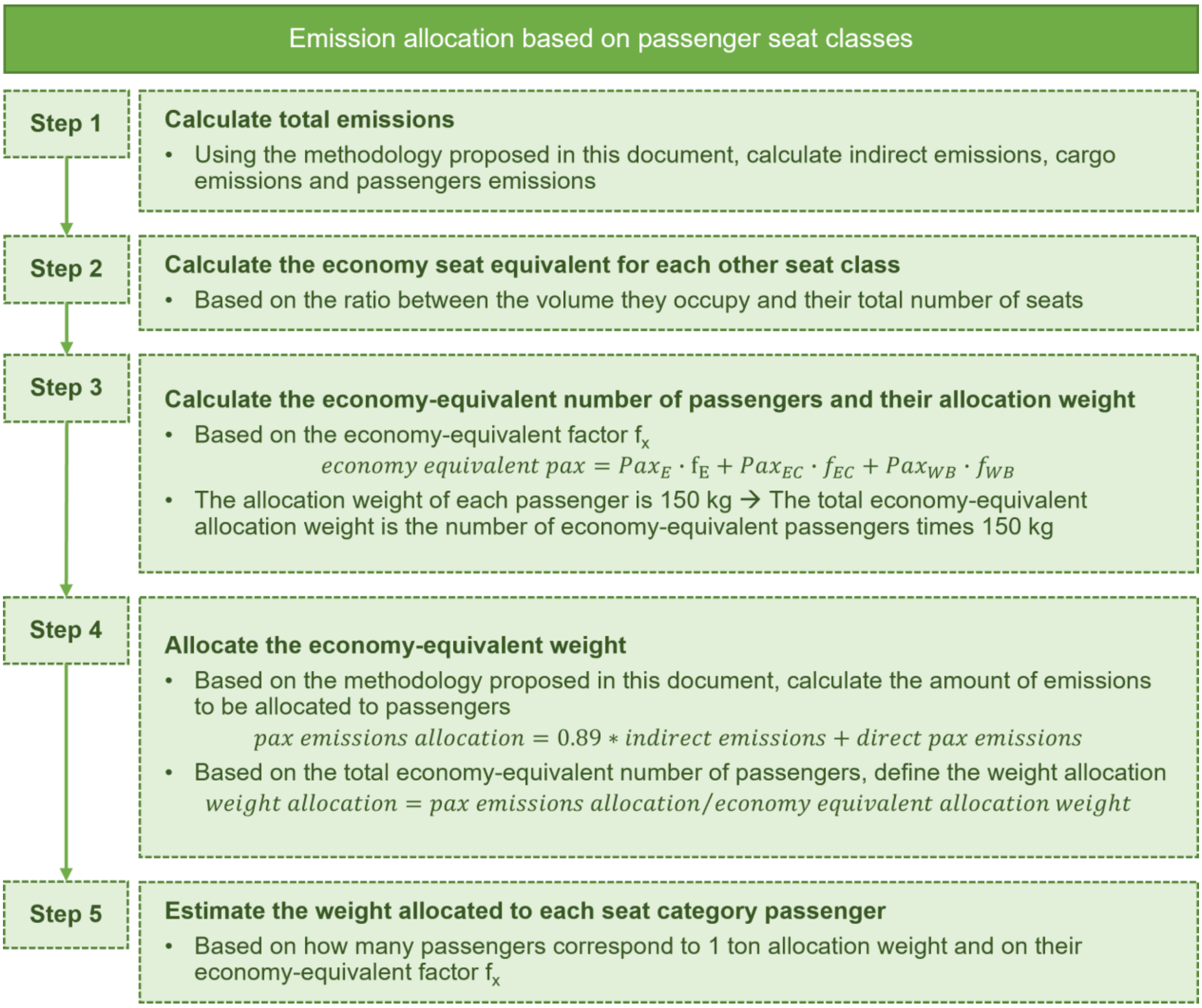
   Equation 19 $weight\ allocation = 206.72/60.15 = 3.44\ tonneCO_2/tonne\ ec.eq.pax$

5. **estimate the weight allocated to each seat category passenger.** With the IATA recommendation of using the allocation weight value of 150 kg per passenger, 1 tonne allocation weight corresponds to 6.67 passengers. Using the economy-equivalent factor, we can define how many passengers correspond to 1 tonne allocation weight for each of the passenger classes:

   Equation 20
   $$\begin{cases} 1\ tonne\ allocation\ weight = 6.67\ pax_E \\ 1\ tonne\ allocation\ weight = 6.67/1\ pax_{EC} = 6.67\ pax_{EC} \\ 1\ tonne\ allocation\ weight = 6.67/3.5\ pax_{WB} = 1.9\ pax_{WB} \end{cases}$$

   Ultimately, we can calculate the amount of CO_2 to be allocated to each passenger based on their seat class, using the weight allocation value of equation 19 and the number of passengers per tonne allocation weight of equation 20:

   Equation 21
   $$\begin{cases} 1\ pax_E = 3.44/6.67 = 0.52\ tonne \\ 1\ pax_{EC} = 3.44/6.67 = 0.52\ tonne \\ 1\ pax_{WB} = 3.44/1.9 = 1.81\ tonne \end{cases}$$



Emission allocation based on passenger seat classes

Step 1

Calculate total emissions

- Using the methodology proposed in this document, calculate indirect emissions, cargo emissions and passengers emissions

Step 2

Calculate the economy seat equivalent for each other seat class

- Based on the ratio between the volume they occupy and their total number of seats

Step 3

Calculate the economy-equivalent number of passengers and their allocation weight

- Based on the economy-equivalent factor f_x

$$economy\ equivalent\ pax = Pax_E \cdot \mathrm{f}_E + Pax_{EC} \cdot f_{EC} + Pax_{WB} \cdot f_{WB}$$

- The allocation weight of each passenger is 150 kg → The total economy-equivalent allocation weight is the number of economy-equivalent passengers times 150 kg

Step 4

Allocate the economy-equivalent weight

- Based on the methodology proposed in this document, calculate the amount of emissions to be allocated to passengers

$$pax\ emissions\ allocation = 0.89 * indirect\ emissions + direct\ pax\ emissions$$

- Based on the total economy-equivalent number of passengers, define the weight allocation

$$weight\ allocation = pax\ emissions\ allocation / economy\ equivalent\ allocation\ weight$$

Step 5

Estimate the weight allocated to each seat category passenger

- Based on how many passengers correspond to 1 ton allocation weight and on their economy-equivalent factor f_x

Figure 20 – Steps to follow to allocate emissions based on passenger seat class

8 Discussion

Emission reductions can be achieved through technology improvements (e.g., deploying better-performing aircraft or using sustainable aviation fuels), but also with a reduction of the total number of flights. To reduce the number of flights, air travel demand has to decrease (e.g., with a modal shift, especially for short-distance trips) or airline companies can consolidate the cargo transported utilising the available cargo capacity.

Many aspects contribute to the strategic and operational decisions of logistics companies, with costs, capacity availability and time constraints being the most important ones. With the current concerns on climate change and the growing interest in sustainability, it is expected that CO_2 emission reductions will also play an important role in the logistics decisions of shippers. It is therefore important that the methodologies used to calculate and allocate emissions are resembling reality as much as possible.

In previous studies, it has been highlighted how the current methodologies used for emissions allocation might lead to undesired results, with cargo payload getting lower emissions intensities (i.e., CO_2 / tonne transported) assigned when transported in a full freighter compared to when it is being transported in a belly freighter. If sustainability becomes the deciding factor for logistics decisions, this undesired result might lead to companies opting for shipping their cargo in full, creating new flight demand and disregarding of already existing belly cargo capacity. Moreover, even in current practices, the emission allocation method should indicate which option resembles reality the most, in terms of CO_2 emissions.

In this deliverable, a methodology for emissions allocation is elaborated upon, looking specifically at the emissions allocation between passengers and cargo in belly freighters. Contrarily to the current IATA RP1678, the proposed methodology favours the use of belly freighters to ship cargo, instead of dedicated freighters. This preference is obtained because one tonne of cargo gets allocated a lower value of CO_2 when transported in a belly freighter, compared to the CO_2 allocated to one tonne of cargo shipped in the full freighter configuration. In the proposed methodology, emissions are categorised into empty-aircraft emissions (from the fuel burnt to fly the aircraft without any payload) and marginal emissions (from the fuel burnt to transport the payload weight). In this way, it is possible to distinguish the single weight components of the payload and attribute them their specific emissions values.

For full freighters, marginal emissions refer only to cargo marginal emissions, with cargo being the only revenue load transported. The marginal emissions in belly freighters are further split into passengers' marginal emissions, which are related to the total passenger weight, and cargo marginal emissions, related to the total cargo weight. This distinction allows for two different allocation values for the belly freighter configuration: the CO_2 per tonne passenger transported and the CO_2 per tonne cargo transported. Consequently, a more accurate estimation of the emission allocation is possible.

The case studies show how the proposed methodology increases the accuracy of emissions calculation and emissions allocation, which may lead to the distribution of cargo into available belly freighter capacity and therefore to reduce emissions. However, implementing the proposed methodology will result in a reduction of number of flights only if logistics companies choose the least polluting option to transport their cargo, as indicated by the proposed methodology. The importance of sustainability in the logistics decisions is the first assumption made in this document. It is indeed assumed that emissions reduction will gain more and more importance, due to the concerns around climate change and to the carbon tax. Consequently, other factors like costs, availability, time constraints and priorities will have less importance in the logistics decisions. However, even if sustainability will not be the decisive factor when airlines allocate cargo to either belly freighters or full freighters, it is important that the emissions allocation method resembles reality as much as possible.

This document has only taken CO_2 emissions into account, excluding any other GHG emissions, in line with the IATA RP1678. While this decision was not within the scope of this document, it is important to mention that other pollutant are also part climate impact of the aviation sector. If correct measurements can be obtained for other pollutants (e.g., NO_x and PM_x), the proposed allocation methodology can also be extended to those pollutants.

Moreover, the fuel burn model that is used as replacement for primary fuel burn data (unavailable due to time constraints and data sensitivity) also has the assumption that only specific flight phases are considered. While the reasons for this assumption are discussed, it is noteworthy to mention that an in-depth knowledge of the emissions for each flight phase would result in a more precise fuel burn estimation.

9 Conclusions

The goal of the TULIPS consortium is to accelerate the implementation of innovative and sustainable technologies towards lower emissions at airports, aiming at zero-emissions and zero-waste airports by 2030 and climate neutral aviation by 2050. Within WP 8, the monitoring of the project's performance is described, together with the economic data collection and analysis. This deliverable concerns task 6 of WP 8, aiming to defining an appropriate method to allocate emissions in a combined passenger-freight (belly freight) aircraft.

Throughout the document, the proposed methodology is thoroughly explained, starting from the motivation to this research (i.e., the unintended side effects of the current IATA RP1678 emissions allocation methodology), followed by the step by step explanation of the proposed approach and concluded with use case examples to show the potential benefits and differences obtained when applying the new method, in comparison with the IATA recommended practice.

The proposed methodology allocates emissions differently, based on their source. The total flight emissions are separated into empty-aircraft emissions (generated by the flying the aircraft without payload) and marginal emissions (generated by transporting the payload). With this separation, it is possible to obtain two different emissions intensity values for the belly freighter configuration: the CO_2 per tonne freight transported and the CO_2 per tonne passenger transported. Results show that the proposed methodology leads to assigning less CO_2 to cargo transported in a belly freighter compared to cargo transported in a full freighter, which is, for the most common load factors, directionally opposite to the current IATA RP1678 methodology.

The purpose of the proposed methodology is to calculate the right amount of CO_2 per tonne transported (separated for passengers and freight), where the term *"right"* refers to *"as close to reality as possible*". By favouring belly freighters over full freighters, it is possible to maximise the capacity of the first ones and avoid creating unnecessary flights with the second ones. While we are aware that currently CO_2 emissions are not the deciding factor in the logistics decisions, we believe that when sustainability will have a high impact in the decision process, an allocation method that prefers belly freighters over full freighters, will make it possible to obtain an emissions reduction as a result of a more optimal fleet allocation. Moreover, even if CO_2 allocation is not the decisive factor, it is important for the methodology to lead to results as close to reality as possible.

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Appendix A: EQUATION TO ESTIMATE THE EMPTY-AIRCRAFT FUEL BURN IN CASE OF PRIMARY DATA

In this section, we will discuss the method for estimating the empty-aircraft fuel burn (which is equal to the fuel burn of an empty aircraft) by using flight duration and empty aircraft weight as independent variables. We base this estimation on the data that is derived from the fuel burn model as discussed in Section 4.1.2. Creating a model to estimate the empty-aircraft fuel burn based only on empty aircraft weight and flight duration makes allocation of emissions to both passengers and freight possible for real world data on fuel burnt when there is no split in empty-aircraft and marginal emissions available.

The most basic model is of the form $\mathrm{y} = \beta_1 x_1 + \beta_2 x_2$, with y denoting the empty-aircraft fuel burn, x_1 denoting empty aircraft weight and x_2 denoting flight duration. This model does not include an intercept, because empty-aircraft fuel burn is equal to zero in case of a flight of zero minutes (or in case the aircraft has no weight, which is not possible in reality, but should not lead to non-zero values in case it would be possible). Table 5 contains the results of the linear model, showing the coefficient for the aircraft weight (β_1) and the flight duration (β_2) and their 95% confidence interval; furthermore, the table shows the R-squared, the condition number and the Akaike Information Criterion of the linear model. A large condition number indicates a high sensitivity of the model parameters to small changes in the input data. The Akaike Information Criterion (AIC) is an information criterion that takes both overfitting and goodness of fit into account. The lower the AIC, the better.

Table 5 – Results of the linear model

	Coefficient	95% confidence interval		R^2	0.873
Aircraft weight [tonne]	0.1872	[0.139, 0235]		**Condition Number**	36.9
Flight duration [min]	8.9434	[7.886,10.001]		**Akaike Information Criterion**	2560

We have also estimated non-linear models, in order to compare the differences and get insight in the goodness of fit of the linear model. The first model in this category is of the form $\mathrm{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$,which means that this model incorporates interaction effects through the $(x_1 x_2)$-term. If we look at the model results (see Table 6), we see that the intercept and flight duration coefficients are estimated to be zero. Moreover, the coefficient for aircraft weight is negative. However, we have to combine the parameter coefficients with the interaction term: the coefficient for increasing aircraft weight by 1 tonne, while keeping flight duration the same, would be $0 + 0.0449 = 0.0449$.

While the R-squared value is higher for this model, the condition number is high compared to the first model we have estimated. Moreover, adding parameters to a model will always result in an equal or higher R^2-value, because more information is included. This means that we should be careful of overfitting. While we want to prevent overfitting, it is good to take the fact that we want to estimate values within the bounds of the estimation data into account. This means that we will not extrapolate values and overfitting is, to a certain extent, allowed.

Table 6 – Results of the interaction model

	Coefficient	**95% confidence interval**		**R^2**	0.994
Intercept	-4.364e-14	[-6.813, 6.813]		**Condition Number**	2.54e+04
Aircraft weight [tonne]	-0.0701	[-0.091, -0.049]		**Akaike Information Criterion**	1676
Flight duration [min]	-1.729e-14	[-0.458, 0.458]			
Interaction term	0.0449	[0.044, 0.046]			

Adding powers to the model (e.g., x_1^2) leads to even higher values for the condition number, while the R^2-value rises to 0.999. The increase in R^2-value is only minor compared to the raise in condition number. Taking these model results into account and also keeping in mind that the model should be easy to use in order to make it accessible for users to apply for emission allocations, we recommend using the model with interaction terms.