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SOFTWARE

AeroMAPS: a framework for performing multidisciplinary assessment of prospective scenarios for air transport

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Abstract

AeroMAPS is an open-source software, also available as a web application, for performing multidisciplinary assessment of prospective scenarios for air transport. Such investigations are a significant challenge for aviation stakeholders but are required to explore and evaluate different transition strategies for the sector. The framework presented in this paper aims to provide these stakeholders with a standardised methodology for simulating prospective scenarios. Developed using the Python programming language and easy to use via Jupyter Notebooks or graphical user interfaces, it enables the rapid exploration of various decarbonisation strategies for research or decision-making audiences. Several scientific computing packages are used to facilitate the modular assembly of models and solve complex numerical problems. The framework is structured around various models derived from the academic literature and newly developed ones. In particular, it can be used to model various components of the air transport system (air traffic, aircraft fleet, energy carriers), assess its environmental (climate and energy resources) and cost impacts, and perform environmental sustainability analyses. An application is proposed in this paper in order to understand the capabilities, interests and limits of the software. Future developments are planned to improve existing models, complete environmental analyses and continue extending to other disciplinary fields (economics, regulation, sociology), in order to make AeroMAPS a systemic and holistic aviation integrated assessment model.

Keywords: Air transport; Prospective scenarios; Sustainable aviation; Multidisciplinary

1. Statement of need

Air transport is currently responsible for various climate impacts [1], including CO_2 emissions and non-CO_2 effects such as contrails. Several commitments have therefore been made to reduce these impacts, including the recent goal of achieving "carbon neutrality" by 2050, for example, at the level of the International Civil Aviation Organization (ICAO) or industry stakeholders such as the Air Transport Action Group (ATAG). As a result, environmental roadmaps, and more specifically, decarbonisation roadmaps, have emerged in recent years. These issues have also been at the heart of numerous academic publications in recent years as explained in [2]. Indeed, the study of prospective scenarios for air transport makes it possible to assess the effectiveness of various levers of action (new aircraft architectures, alternative fuels...) to reduce the sector's impacts. Most publications focus on estimating the future climate impacts of air transport. While first papers were limited to CO_2 emissions alone [3, 4], more recent ones also include non-CO_2 effects [5, 6, 7, 8, 9, 10].

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Due to methodological differences, it is relatively complex to compare these different prospective scenarios. Moreover, their reproducibility is either impossible due to the use of private models, or often based on the use of non-modular spreadsheets. Finally, as the environmental transition is a central issue for all air transport stakeholders, it is crucial to have adequate tools that enable a diverse audience to conduct prospective analyses. Consequently, a reference methodological framework and an associated open-source tool would help to overcome this problem.

Initiatives in this direction are relatively limited in academic literature. The AIM2015 tool [11, 12] is currently one of the only open-source solutions. Nevertheless, it does not include exhaustive analyses of environmental impacts, requires significant calculation times (between 40 minutes and 2 hours on a typical scientific laptop [13]) due to the very detailed modelling of the air transport system, and lacks a user-friendly interface. Other academic tools, such as FLEET [14], AirClim [15] and APMT-IC [16, 17], can partially help perform these studies (e.g. some are limited to climate models which require to be linked to air transport system models) but are private. Software from institutional or industrial stakeholders, such as Boeing's Cascade [18], also exist but are either private or only available for basic use, via an interface, without access to the models. Finally, the common shortcoming of all these solutions is that they only allow an analysis of gross environmental impacts, but do not include an assessment of the environmental sustainability of the scenarios, for instance via comparisons with the temperature objectives of the Paris Agreement.

These various observations help define the different requirements for developing dedicated software to perform detailed analyses of transition scenarios for air transport. First, it must be open-source and relatively easy to use, so that it can be distributed to the academic community as well as to institutional and industrial decision-makers involved in these issues. Then, the models developed must be able to represent various prospective scenarios for the aviation sector and their impacts, covering multiple disciplinary fields to make the analysis more exhaustive, in order to enable the evaluation of transition strategies. In particular, the framework must enable environmental sustainability assessments to be performed at the sectoral level. Finally, a modular code is needed to facilitate the integration of models from different disciplinary fields and to implement a multi-fidelity approach for faster or more accurate simulations. It also requires the implementation of dedicated solutions for solving numerical couplings and optimisation problems.

This paper presents AeroMAPS, a Python open-source framework for performing simulation and assessment of aviation prospective scenarios taking into account the different requirements highlighted previously. In the following, Section 2 provides a general overview of AeroMAPS. Then, an application of AeroMAPS is proposed in Section 3 to demonstrate uses and results. Lastly, Section 4 highlights the contributions and limits of the framework and outlines a roadmap of future developments for enabling systemic and holistic analyses of the air transport transition.

2. Software overview

This section provides an overview of AeroMAPS. After a description of previous works related to AeroMAPS, the main elements concerning the development of the software and the methods and models used are detailed. A discussion about the validation of the framework is finally offered.

2.1 Previous works

Initially, the software was published in 2021 under the name CAST (for *Climate and Aviation - Sustainable Trajectories*) [19]. It allowed performing analyses on the future climate impact of air transport for various prospective scenarios, similarly to the first studies detailed in the bibliography previously. It included simplified models of the main levers of action for mitigating the climate impacts of aviation, as well as a methodology for assessing the climate sustainability of a scenario via comparisons with the climate targets.

New developments were then carried out. Indeed, more detailed models of the various levers of action were developed, as well as dedicated models for estimating energy resources consumption [20]. Work focused in particular on the development of fleet renewal models to facilitate interactions between the results of aircraft design studies and their integration into prospective scenarios [21]. Moreover, cost models were published [22, 23], extending the disciplinary fields covered by the framework.

Finally, all these models were structured into a single code and were published in 2023 under the name AeroMAPS (for *Multidisciplinary Assessment of Prospective Scenarios for air transport*). This framework is intended to be broader, integrating for instance other environmental impacts than climate change or new disciplinary fields such as cost evaluation. Unlike CAST, whose models were not directly available, AeroMAPS is open-source.

2.2 Software development

Licensed under the GPL-3.0 license, AeroMAPS relies on the Python programming language. The software architecture is provided in Figure 1. The main folders are written in bold and the simulation process is detailed in the central rectangle, with the main functions. The various models are grouped together in a single folder, and the user can add them in a dedicated file in the core of the program. Connections between models are generated automatically via variable names, making it easy to add or substitute models. The various basic functions are also defined in the core folder. Simulation execution relies on a resource folder to use inputs and store outputs, while results display is facilitated by the integration of basic plots. Finally, two additional folders, indicated with dotted arrows, allow simplifying the use of AeroMAPS, as described in the following.

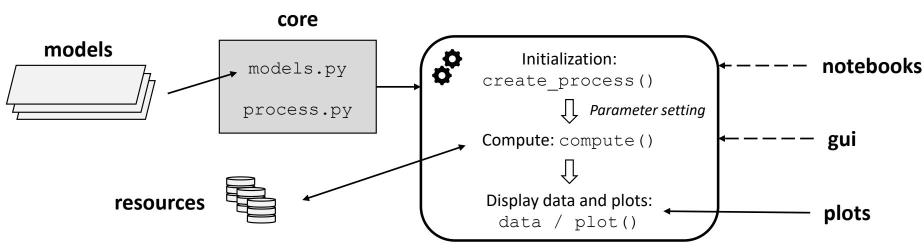


Figure 1. AeroMAPS software architecture.

For an extensive use of AeroMAPS, the use of Jupyter Notebooks is preferred, and several examples are available. These provide examples to help understand basic features such as model loading, parameter setting and results display. Moreover, to reach a broader audience, graphical user interfaces are also available. A simplified one is available in open-source, whereas an improved one, developed within an academic chair with a digital services and software development company, is available in open access to disseminate the tool to decision-makers.

To facilitate the software use and ensure scientific consistency, a documentation based on the use of Jupyter Book is provided. It includes in particular a changelog file, an installation procedure, a complete scientific documentation, and some examples via Jupyter Notebooks. Improvements regarding test coverage and DevOps are planned in future developments. The scientific documentation details the architecture of AeroMAPS, the different models with associated references and a tutorial on the use of the graphical user interface. In addition to their usefulness in demonstrating basic functions, as mentioned previously, the examples also show possible applications.

Concerning the data, most inputs are of type float, while most outputs are of type time serie for obtaining outputs over the years. AeroMAPS data are based on public data from academic literature or organisations such as the International Air Transport Association (IATA) and the International Energy Agency (IEA). All the references corresponding to the default input data are shown in a CSV file, which is available in the resources tab or can be downloaded directly after a simulation run.

Finally, various packages are used to operate AeroMAPS. Solving the numerical problem, and in particular the connections between the different models, is based on GEMSEO [24], a scientific software for engineers and researchers used to explore design spaces and find optimal solutions for multidisciplinary systems. Other scientific packages are used, such as *Pandas* [25] for manipulating, rendering and exporting data, and *SciPy* [26] to solve implicit models. The open-source graphical user interface is based on *ipywidgets* (Jupyter Widgets) [27] for the widgets and *ipympl* (Matplotlib Jupyter Integration) [28] for the figures. It is deployed as a web application thanks to *Voilà* [29].

2.3 Methods and models

Even if the AeroMAPS global structure and the associated methods and models are not in the direct scope of this software paper, they are briefly described in the following in order to make it easier to understand the framework. Detailed information is available in the main references [19, 20, 21, 22, 23] summarised in Section 2.1 and in the software documentation.

Figure 2 provides a simplified architecture of the current version of AeroMAPS. The objective is to represent the future air transport system, to estimate its induced impacts, and to assess the environmental sustainability. The main models for these three parts are described below. In this current state, most of the AeroMAPS models require the use of exogenous variables derived from assumptions about various fields: socio-economic and technological developments, evolutions in other business sectors, political choices… It is important to note that several limitations of the modelling remain, such as the lack of cost-demand coupling and a comprehensive Life Cycle Assessment (LCA) approach, and are discussed in Section 4.

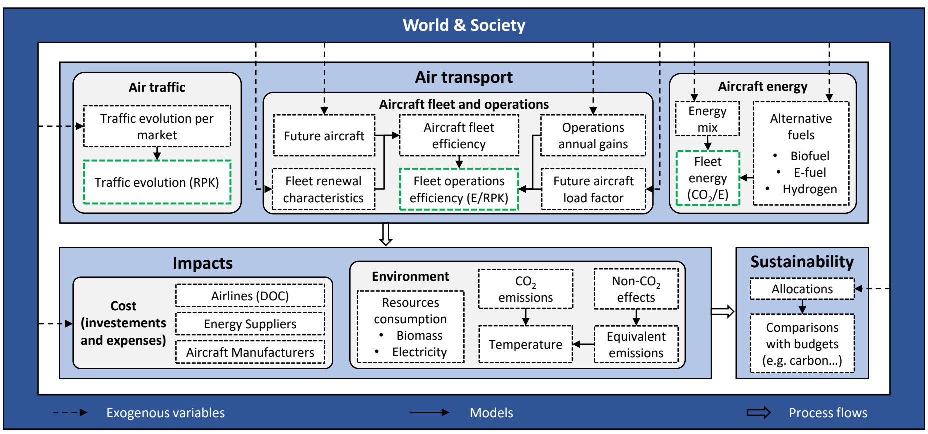


Figure 2. AeroMAPS models architecture.

In a first step, air transport modelling is based on the representation of the air traffic, aircraft fleet and energy carriers needed to power it. Only commercial aviation is considered, excluding military and private aviation using [30]. The initial construction is based on an adaptation of the Kaya identity [31] to aviation, given in Equation (1). This decomposition highlights the three characteristics introduced previously.

$$CO_2 = RPK \times \frac{E}{RPK} \times \frac{CO_2}{E} \tag{1}$$

with CO_2 the aviation CO_2 emissions, RPK the Revenue Passenger Kilometre and E the energy consumed by aviation.

Air traffic is divided into four main markets (passenger short/medium/long-range and freight). The corresponding historical fleet was calibrated using mean fuel consumption per market and representative aircraft. The evolution of air traffic per market is then calculated using annual growth rates per period. The future aircraft fleet can be modelled using two solutions: a top-down approach based on annual efficiency gains, and a bottom-up approach in which aircraft data (performance, entry-into-service...) are coupled with fleet renewal models. The latter are based on dedicated logistic functions to model the aircraft architecture distribution within the fleet over time. Equation (2) provides for instance the calculation of the share of an aircraft in the fleet in a simple case. Concerning operational and load factor improvements, they are estimated using similar logistic functions and regressions from historical data, respectively. Finally, the energy carrier modelling is based on a statistical analysis of public data, in particular concerning CO_2 emissions over the whole life cycle. More than ten fuels and associated pathways are considered, including biofuel, electrofuel and hydrogen. The deployment of these energy carriers into the fleet is then based on incorporation rates to obtain an annual energy mix.

$$S_{i_0}(t) = \frac{A}{1 + e^{-k\,(t - t_{0,i_0})}} - \sum_{i > i_0} \frac{A}{1 + e^{-k\,(t - t_{0,i})}} \text{ with } k = \frac{\ln\left(\frac{100}{l} - 1\right)}{D/2} \text{ and } t_{0,i} = t_{a,i} + D/2 \tag{2}$$

with $S_{i_0}(t)$ the share of the aircraft i_0 in the fleet for the year t, depending on the aircraft i that will enter service after the aircraft i_0, A a parameter representing the final share of aircraft in the fleet (value of 100% if there is no aircraft sub-category), k a parameter adjusting the rate of fleet renewal, and $t_{0,i}$ a parameter defining the introduction timing of aircraft i; D is the duration for replacing $(100 - l)$ % of the fleet and $t_{a,i}$ the entry-into-service year of aircraft i.

In a second step, the impacts induced by the scenario are evaluated. Currently, two impact categories are considered: environment and costs. On the one hand, environmental impacts are estimated, focusing on climate and energy issues as they are predominant for air transport [20]. The scope is limited to fuel production and combustion, which account for most of the impacts [32]. Concerning climate impacts, estimations are focused in particular on CO_2 emissions and non-CO_2 effects. These emissions are calculated using the aircraft fleet energy consumption and the characteristics of the different energy carriers. The climate modelling then relies on the use of climate sensitivity to emissions from [1] to estimate the induced Effective Radiative Forcing (ERF). The estimation of the induced temperature evolution ΔT is thus obtained using Equation (3), based on the use of the climate metric GWP* which is relevant for Short-Lived Climate Pollutants (SLCP) such as aviation non-CO_2 effects [1, 33, 34]. Concerning energy resources consumption, the estimation directly relies on the models developed for the different energy carriers pathways. Only biomass and electricity consumption are considered. On the other hand, several cost models are available. The cost of using alternative energy sources is estimated by calculating their Minimal Fuel Selling Price (MFSP), at which their producers reach the economic equilibrium [35]. This energy cost is combined with other costs incurred by aircraft operations by using a Direct Operating Cost (DOC) model. The model is adapted from [36] and recalibrated using operational data. Aircraft production recurring and non-recurring costs are also modelled. Finally, it is possible to implement an exogenous carbon tax and to monitor its effects on the various costs.

$$\Delta T = TCRE \left(\sum_t E_{CO_2} + \sum_{t,i} E_{CO_2\text{-we},i} \right) \text{ with } E_{CO_2\text{-we},i} = \frac{(1-\alpha_i)\,H}{AGWP_H} \frac{\Delta ERF_i}{\Delta t_i} + \frac{\alpha_i}{AGWP_H} ERF_i \quad (3)$$

with $TCRE$ the Transient Climate Response to cumulative CO_2 Emissions, E_{CO_2} the annual CO_2 emissions, $E_{CO_2\text{-we},i}$ the annual warming-equivalent CO_2 emissions for the different aviation non-CO_2 effects, $AGWP_H$ the Absolute Global Warming Potential of CO_2 over a time horizon H of 100 years, ERF_i the Effective Radiative Forcing of the different non-CO_2 effects, and α_i and Δt_i coefficients for GWP* model quantifying in particular the impact of short-term effects.

In a last step, in order to assess the environmental sustainability, the environmental impacts are compared with objectives dedicated to the air transport sector. Sectoral objectives are set via allocations of global ones, such as temperature targets of the Paris Agreement. The allocation rules, often discussed regarding carbon budgets, can be based on several methods such as grandfathering, cost-effectiveness, or multi-criteria approaches [37]. More specifically, for climate issues, two analyses can be performed with AeroMAPS. On the one hand, the cumulative CO_2 emissions can be compared to carbon budgets. On the other hand, non-CO_2 effects can be integrated into the studies by comparing equivalent emissions with corrected carbon budgets or by directly comparing temperature estimation with temperature targets for aviation. Similarly, concerning energy resources, their consumption is compared with availability estimations obtained from literature reviews.

2.4 Software validation

As a consequence, the framework includes a wide range of models allowing simple simulations of prospective scenarios for air transport, although some modelling simplifications remain. Overall, the computation time of a simulation is around 1 second on a typical scientific laptop, which makes it possible to consider performing numerical optimisation in the future. To complete this section, the framework is validated relying on several methods as described below.

First, comparisons of methods from academic publications were performed. For instance, the Kaya identity for aviation given in Equation (1) is consistent with the scientific literature [8, 9], although other formulations are proposed [2, 38, 39]. Similarly, climate models were extracted from the literature as described above, and fleet renewal models based on logistic functions are used in [5] even if other methods more suitable for air route modelling are proposed [40]. For more comparative information on methods and models, a summary table including other publications on aviation prospective scenarios mentioned in Section 1 is provided in Appendix 1.

Then, several regression models, based on historical data, were developed, in particular to find suitable mathematical functions or to project historical trends. Error estimations were achieved to assess the models' accuracy. For instance, concerning the aircraft efficiency modelling with the top-down approach, very good coefficients of determination R^2 above 0.97 were obtained between models and historical data, for the different models considered. Similarly, concerning the aircraft load factor modelling, good coefficients of determination R^2 between 0.93 and 0.98 were obtained.

Finally, main simulation results were compared to historical datasets. For instance, CO_2 emissions from commercial aviation (only including kerosene combustion) obtained with the model in 2019 amount to 941 $MtCO_2$. For comparison, Air Transport Action Group (ATAG) and International Council on Clean Transportation (ICCT) estimates for 2019 are 914 $MtCO_2$ [41] and 920 $MtCO_2$ [42] respectively, i.e. a difference of less than 3%. Similar results were also obtained for 2013 and 2018 ICCT data. Concerning effective radiative forcing, the results were found close to data from [1] (less than 6% difference over the period 2000–2018). This quantification must be taken with caution because the scopes slightly differ (kerosene production, non-commercial aviation).

3. Application

In order to illustrate the possible uses of AeroMAPS, a simple application is provided in this section. The objective is to simulate an illustrative prospective scenario for aviation, and to analyse it from an environmental and cost point of view. This application can be found in the AeroMAPS source code via a Jupyter Notebook (see Reproducibility statement Section), and one can directly run it for obtaining the detailed input and output data.

The different assumptions of this prospective scenario are given in the following. An illustrative 2% annual air traffic growth is assumed for the different aviation markets, i.e. lower than trend estimates of around 3%. The impact of COVID-19 is modelled assuming that air traffic returns to 2019 levels in 2024. Concerning the aircraft fleet, an accelerated fleet renewal is assumed with the introduction of 20% more efficient aircraft architectures in 2035. A hydrogen-powered aircraft is more specifically considered for short-range. Operational improvements are also included for reducing fuel consumption, but operational strategies for contrail avoidance are not considered here, even though it is a promising approach [43]. Regarding the replacement of kerosene by drop-in fuels (biofuel and electrofuel here), ReFuelEU targets are considered as blending mandates [44]. Different pathways are considered for the production of biofuel and hydrogen. Electricity production is expected to decarbonise rapidly and strongly, so that CO_2 emissions from electricity-based fuels will be lower than those from kerosene by 2035. On the economic side, several assumptions are made such as median fuel costs or a constant electricity price of 80 €/MWh. Moreover, a carbon price trajectory based on [45] is implemented in the form of a tax on the emissions of fossil and alternative fuels.

Moreover, in order to carry out a sustainability assessment, some assumptions are required for setting targets for aviation. A climate target of +1.8°C with a 67% chance of success is chosen as well as a moderate use of Carbon Dioxide Removal (CDR) worldwide. Median estimations are considered for biomass and electricity availability. Finally, concerning allocation rules, a grandfathering approach is assumed for climate issues, which means that 2.6% (i.e. aviation's current share of CO_2 emissions) of the world carbon budget is allocated for aviation. For energy resources, an illustrative and arbitrary allocation of 5% is assumed.

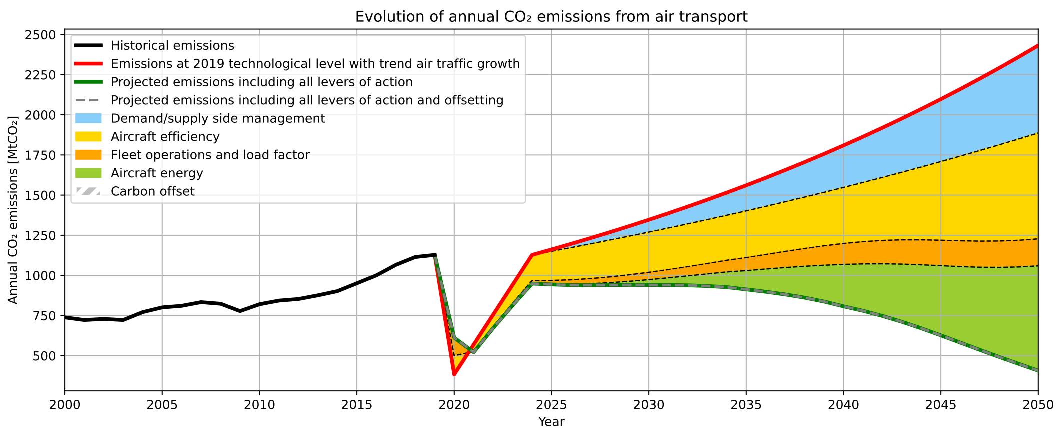
Main results obtained for this scenario are given in Table 1. For instance, this scenario allows a reduction of CO_2 emissions by 64% between 2019 and 2050. Despite the increase in air traffic, this reduction is made possible by the improvement in emissions per passenger per kilometre, with in particular a reduction of more than 60% due to the use of alternative fuels. However, aviation increases its climate impact due to its cumulative CO_2 emissions between 2020 and 2050 and the lack of specific strategies for non-CO_2 effects. Finally, the total direct operating cost per Available Seat Kilometre (ASK) is doubled due to the use of alternative fuels and the effect of the carbon tax increase.

Table 1. Main results of the illustrative scenario.

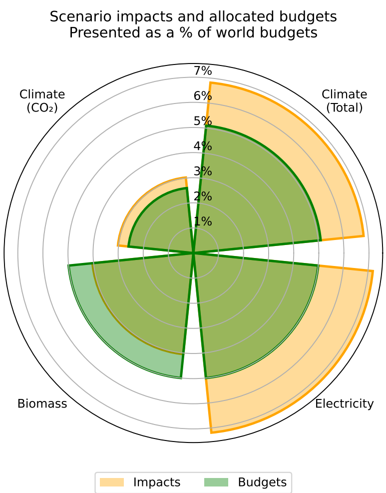
Parameter	Value in 2050	2050 vs. 2019
CO_2 emissions*	407 $MtCO_2$	-64%
CO_2 emissions per passenger per kilometre*	24 gCO_2/RPK	-79%
Temperature increase due to aviation	0.074°C	+85%
Total direct operating cost, including carbon tax	0.086 €/ASK	+99%

* *Includes other greenhouse gas emissions from fuel production and combustion, but excludes aviation non-CO_2 effects.*

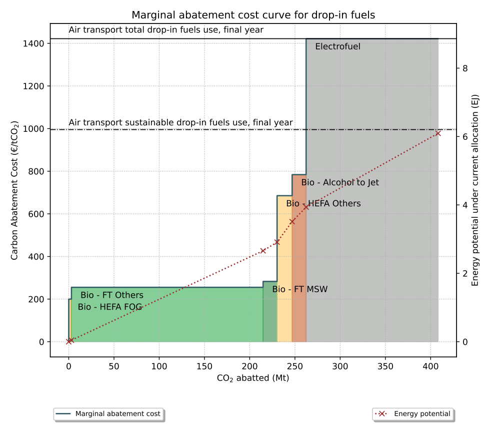
AeroMAPS also integrates interesting plots for further analyses, some of which are shown in Figure 3. For instance, Figure 3a is a typical one providing the evolution of CO_2 emissions and the influence of the different levers of action to reduce them. In this scenario, it is interesting to note that fleet renewal has a rapid effect on emissions because the replacement of old aircraft architectures is currently in progress. However, the use of alternative fuels only becomes significant after 2040 due to a later deployment. Then, Figure 3b allows assessing the environmental sustainability of the scenario on climate and energy resources issues. The environmental impacts induced by the studied scenario (in orange) and the allocated budgets for aviation (in green), which represent the targets dedicated to aviation, are expressed as percentages relative to world targets. The sustainability of a scenario is thus evaluated via the comparison between the impacts and budgets. For example, this scenario consumes more of the allocated carbon budget, but less biomass than allocated. Lastly, Figure 3 is a Marginal Abatement Cost Curve (MACC) for the drop-in alternative fuels in 2050. It shows a ranking of different fuels by carbon abatement cost, as well as their potential CO_2 emissions reduction for a given year. The carbon abatement cost estimation is based on the scenario assumption and the energy potentials depend on the energy resources allocation for aviation. It is interesting to note that biofuels are more interesting than electrofuels on this indicator in this scenario. This figure can for instance be used to redefine blending mandates.



(a) CO_2 emissions



(b) Sustainability assessment



(c) Marginal abatement cost

Figure 3. Examples of AeroMAPS results for the application.

4. Conclusions: contributions, limits and future developments

This paper presents AeroMAPS, a framework for performing multidisciplinary assessment of prospective scenarios for air transport. This software meets the various needs highlighted in Section 1 for disseminating tools dedicated to aviation prospective scenarios. Indeed, AeroMAPS allows simulating the air transport system through three major elements (air traffic, aircraft fleet, energy carriers) which also correspond to levers of action for reducing aviation environmental impacts. It is then possible to perform studies on the effectiveness of different decarbonisation strategies on various impacts such as climate, energy resources or cost, but also to perform environmental sustainability assessments of aviation scenarios at the sectoral level. Then, the software is open-source and its use relies on graphical user interfaces or Jupyter Notebooks which are relatively easy to manipulate. It also includes some examples and a documentation. Finally, the modular structure of the code makes it easy to integrate and replace models. In addition to solving the AeroMAPS numerical problem, this structure and the packages already integrated, such as GEMSEO, are designed to facilitate more advanced applications in the future (multi-fidelity, uncertainties, optimisation...).

However, some limitations to the current version of AeroMAPS have to be mentioned. First, modelling of the air transport system is still relatively simplified. For example, some stakeholders are not represented (airports, energy suppliers...). Moreover, some models are missing, such as the effect of alternative energy carriers on non-CO_2 effects and the effect of the air traffic level on the efficiency of operations. The models are also based on numerous exogenous variables, and no coupling is included, such as the influence of cost evolution on the demand (particularly due to higher cost of alternative fuels). Then, whereas one of the main objectives is to assess the environmental sustainability of scenarios, this version limits analyses to climate impacts and energy resources consumption. Lastly, the current framework covers a limited number of disciplinary fields, with an economic module currently limited to specific costs such as MFSP or DOC.

As a consequence, future developments are required in order to address these various limitations. First, work is needed to improve the representation and modelling of the air transport system. In addition to the ability to perform regional analyses, this could involve integrating new stakeholders and modelling specific mechanisms such as carbon offsetting, trading schemes and other regulation mechanisms (CORSIA, EU-ETS...). The development of multi-fidelity approaches would also be particularly relevant. For instance, the integration of various climate models would enable to compare their characteristics and specifically analyse the mitigation levers dedicated to non-CO_2 effects. Besides climate issues, the integration of prospective Life Cycle Assessment (LCA) methods could provide comprehensive analyses of environmental impacts [46]. Then, sensitivity, uncertainty and optimisation analyses could be performed in order to highlight the characteristics of different transition strategies, particularly when disciplinary couplings are integrated. Last, but not least, reaching a systemic and holistic approach in AeroMAPS could be a longer-term objective, by complementing the range of disciplinary fields considered (economics, regulation, sociology...). As a consequence, the aim would be that AeroMAPS evolves towards a sectoral Integrated Assessment Model (IAM) dedicated to air transport. This would reinforce the framework's use cases, such as global IAMs which play a major role in decision-making [47].

Appendix 1. Comparison with methods and models from other papers

Table 2 provides a comparison of methods and models in AeroMAPS with the ones from other recent papers on aviation prospective scenarios. It includes in particular a comparison of air transport and climate modelling, as well as a short description of the climate sustainability assessment in the different papers. A more complete analysis of the different papers can be found in [2].

Table 2. Main characteristics of methods and models used in recent papers on air transport prospective scenarios.

Reference	Air traffic	Aircraft fleet	Aircraft energy	Climate modelling	Other models	Sustainability assessment
AeroMAPS	Fixed annual growth rates by periods and markets	Top-down / Bottom-up	Representative and detailed low-carbon fuels	Climate sensitivity + GWP* + TCRE	Simple non-CO_2 mitigation, Cost estimates, Energy resources	Comparison with variable allocated (equivalent) carbon budget for aviation
Terrenoire *et al.* [4]	Fixed annual growth rates	Top-down	Not directly considered	Only CO_2 emissions using climate emulator (OSCAR v2.2)	/	Comparison with IPCC RCP scenario temperature
Grewe *et al.* [5]	Fixed annual growth rates by year	Top-down / Bottom-up	Representative low-carbon fuels	Dedicated climate model (AirClim)	Fuel non-CO_2	Comparison with a fixed temperature target allocated to aviation
Klöwer *et al.* [6]	Fixed annual growth rates	Included by lowering traffic growth rates	Zero-carbon fuels	Climate sensitivity + GWP* + TCRE/Climate emulator (FaIR v1.3)	Fuel non-CO_2	Comparison with remaining temperature increase & Temperature stabilisation
Brazzola *et al.* [7]	Fixed annual growth rates by year	Top-down	Zero-carbon fuels	Climate sensitivity + GWP* + Climate emulator (FaIR v1.3)	Fuel non-CO_2	Comparison with IPCC SSP1-1.9 scenario for different definitions of aviation climate neutrality
Dray *et al.* [8]	Variable annual growth rates + Cost elasticity	Bottom-up	Detailed low-carbon fuels	Dedicated climate model (APMT-IC)	Contrail avoidance, Cost/airfare estimates, Energy resources	Achievement of net-zero climate impacts for aviation
Bergero *et al.* [9]	Fixed annual growth rates	Top-down	Representative low-carbon fuels	Simple climate metrics (GWP/GTP) without temperature estimates	Cost estimates, Energy resources	Achievement of net-zero CO_2 emissions and climate impacts with CDR
Sacchi *et al.* [10]	Fixed annual growth rates (Europe)	Bottom-up	LCA low-carbon fuels	Climate sensitivity + LWE + TCRE	Fuel non-CO_2, Cost estimates, Energy resources	Achievement of flight CO_2 / warming / climate neutrality for aviation

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Author contributions

- Thomas Planès: Conceptualization, Methodology, Software, Validation, Writing–Original draft
- Scott Delbecq: Conceptualization, Software, Validation, Data Curation, Writing - Review & Editing
- Antoine Salgas: Conceptualization, Methodology, Software, Writing - Review & Editing

Open data statement

The data are available in AeroMAPS (see Reproducibility statement Section). The references associated with the public datasets used in AeroMAPS are given in the documentation.

Reproducibility statement

The source code of AeroMAPS is available on GitHub at https://github.com/AeroMAPS/AeroMAPS, including the basic graphical user interface, the documentation and some examples via Jupyter Notebooks. This software is archived at https://doi.org/10.5281/zenodo.10406487. The improved graphical user interface, developed within an academic chair between ISAE-SUPAERO and Sopra Steria, is available at https://aeromaps.eu. Finally, the source code for reproducing the application of this paper is included in AeroMAPS in the Jupyter Notebook entitled "examples_joas_application.ipynb".

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