

AIRLINE DECARBONIZATION PATHWAYS USING SYSTEM DYNAMICS: A CONCEPTUAL SIMULATION FRAMEWORK

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ABSTRACT

European airlines face increasingly ambitious climate obligations, yet whether their reported Greenhouse Gas (GHG) reduction commitments are consistent with net-zero by 2050 remains unclear. This paper presents a modeling framework for simulating European airline decarbonization pathways using a System Dynamics (SD) approach. Drawing on climate science, European Union (EU) and International Civil Aviation Organization (ICAO) regulatory instruments, and empirical sustainability reporting, the framework specifies geographic, temporal, institutional, and sectoral boundaries; core entities (airlines, fleets, fuel mix, demand, policy instruments); key processes (traffic dynamics, fleet renewal, Sustainable Aviation Fuel (SAF) deployment, and carbon pricing); and data inputs and outputs from publicly available airline and regulatory reporting. Informed by a European airline's 2024 sustainability reporting, the framework establishes causal relationships across sub-processes governing airline emissions, revealing the dynamics shaping GHG performance under policy, technical, and disruption scenarios. Results provide a replicable, software-independent foundation for simulation implementation.

1 INTRODUCTION

Global mean surface temperature is already about 1.2 °C above pre-industrial levels, and aviation contributes a non-negligible share of anthropogenic warming, estimated at around 2.5% of global CO₂ emissions from fossil fuel combustion (Larsson et al. 2019), and a higher share when non-CO₂ effects are included (Klöwer et al. 2021). The 2015 Paris Agreement established a global objective to limit temperature increase to well below 2 °C, which implies very stringent carbon budgets for all sectors, including aviation - United Nations Framework Convention on Climate Change (UN 2016). The European Union aims to become the first climate-neutral continent by 2050 (EU 2019a), tightening requirements on aviation through instruments such as the EU Emissions Trading System (EU-ETS), the ReFuelEU Aviation initiative and strengthened climate-related financial reporting (EU 2023a).

At the same time, the International Civil Aviation Organization (ICAO) has adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as a global market-based measure, while the International Air Transport Association (IATA) has committed its member airlines to net-zero CO₂ emissions by 2050 (EU 2019b; IATA 2021; Sun et al. 2025). Against this policy and industry backdrop, European airlines have published long-term climate targets and Environment, Social and Governance (ESG) reports, yet there is uncertainty as to whether current KPIs, reported actions and external drivers together form trajectories compatible with net zero by mid-century (Klöwer et al. 2021). Building on prior research that analyzed European airline sustainability reporting (Martín-Domingo et al. 2025), this paper aims to define a rigorous “system description” (Robinson 2013) applied to one European airline, as the foundation for system dynamics simulation that will evaluate the feasibility of European airline GHG reduction commitments for 2050.

Conceptual modeling is widely recognized as a critical stage of any simulation study because it determines which aspects of the real system are represented and at what level of abstraction (Robinson 2013). Robinson defines a system description as a structured representation of the problem situation and the elements of the real world that relate to that problem, distinct from the conceptual model that describes what is included in the simulation. A clear and agreed upon system description is essential in aviation decarbonization studies to avoid replicating the full complexity of the aviation system and instead focus on those elements that are conducive to evaluating GHG KPI feasibility, regulatory impacts and airline strategic responses (Robinson 2013; Efthymiou and Papatheodorou 2019).

The purpose of this paper is to provide the system description underpinning the simulation phase of a European airline decarbonization study, following Robinson's (2013) conceptual modeling framework. Specifically, the paper (i) situates the work in the literature on aviation decarbonization and conceptual modelling, (ii) explains the methodological approach to building the system description, (iii) presents the resulting description in terms of problem boundaries, entities, processes, inputs and outputs, and (iv) reflects on implications for the subsequent simulation implementation as part of the Aviation Zero Emission 2050 (AZERO) research project, a Marie Skłodowska-Curie Actions (MSCA) Postdoctoral Fellowship hosted at Dublin City University (2024–2026), in which the authors are the principal investigators.

2 LITERATURE REVIEW

2.1 Simulation Techniques

Simulation is a versatile methodology that spans a wide range of domains, from human behavior to technical systems and human-in-the-loop environments. When analyzing complex systems, three principal modelling paradigms can be distinguished: i) discrete-event simulation; ii) agent-based modelling; and iii) system dynamics (Borshchev and Filippov 2004; Law et al. 2007). Each approach presents specific advantages and limitations, depending on the objectives of the study, the nature of the system under consideration, and the level of detail required. Practitioners often assume that a single technique can be universally applied; however, this “one-size-fits-all” perspective is misguided. Instead, modelling approaches should be carefully selected to align with the problem at hand (Pidd 2004; Siebers et al. 2010). A number of considerations can be outlined, including, but not limited to, the following.

Discrete-event simulation is typically used to model sequential and interdependent processes. It is widely applied to the analysis of logistics, manufacturing, and transport systems (Tako and Robinson 2012; Tosti and Bottani 2021). The literature contains several thousands of studies across these domains employing discrete-event simulation to represent operational processes and evaluate system performance (Tosti and Bottani 2021). Its main advantages lie in its efficiency in modelling dependencies between processes, its ability to identify operational bottlenecks, and its capacity to reveal emergent dynamics (Law et al. 2007). Furthermore, it supports a wide range of abstraction levels, from high-level conceptual representations to detailed operational models (Robinson et al. 2004). Among the three principal simulation paradigms, it is probably the most flexible approach.

However, it has some limitations that should also be acknowledged. Depending on the system under study and the availability and quality of data, significant effort may be required to model the various subprocesses in sufficient detail (Tako and Robinson 2012). This can result in a time-consuming and, in some cases, inefficient modelling process.

Agent-based modelling is a simulation paradigm that has gained prominence alongside advances in computational power. It represents systems as collections of autonomous entities (agents), whose behaviors and interactions are evaluated over time, often through a clock-driven mechanism with fixed time steps (Macal and North 2010). This approach is particularly suited to systems in which the sequential structure of processes is not clearly defined, and it has proven especially effective for modelling decentralized decision-making, such as that exhibited by individual agents (e.g. human behavior).

For this reason, some practitioners regard it as one of the most advanced approaches for simulating dynamic systems. However, this perception should be treated with caution. Its limitations include

substantial computational requirements, particularly as the number of agents increases it can lead to significant performance degradation (Macal and North 2010; Abar et al. 2017). The literature nonetheless contains a wide range of applications of agent-based modelling across diverse domains (Macal and North 2010).

System dynamics (SD) is one of the most established simulation paradigms, originally developed in the 1960s (Forrester 1961). It has gained renewed relevance due to its suitability for modelling systems at a high level of aggregation, particularly where long-term dynamics are of interest. SD enables the representation of complex, interconnected systems and is effective in capturing feedback loops, dependencies, emergent behavior, and equilibrium states arising from the interaction of subprocesses (Sterman 2002). It has been widely applied to the analysis of dynamic systems across diverse domains, including working capital (Kolay 1991), manufacturing (Georgiadis and Vlachos 2004), and supply chains (Georgiadis et al. 2005; Tako and Robinson 2012).

In this study, SD is adopted because the problem under consideration spans a multi-year time horizon and requires a high level of aggregation, where micro-level interactions within airline systems, such as airport operations, have a comparatively limited impact on emissions at the scale of analysis. SD has been applied to complex environmental and energy systems where feedbacks, delays and stock-flow structures drive long-term behavior, including public transport emissions, cement production and electricity generation (Ford 2009; Ige et al. 2022; Wen and Wang 2023), and is particularly well suited to the analysis of emission evolution in the airline industry, where multiple interdependent factors evolve over time (Sgouridis et al. 2011; Csala and Sgouridis 2013). These include not only direct emissions such as CO₂, but also non-CO₂ effects, which are influenced by operational, technological, and atmospheric conditions (Klöwer et al. 2021). The SD framework allows for the explicit modelling of feedback mechanisms between airline strategies (e.g. fleet renewal, adoption of sustainable aviation fuels - SAF), regulatory interventions (e.g. emissions trading schemes like the EU-ETS, carbon pricing, and environmental standards), and demand dynamics. It also facilitates the exploration of policy scenarios and long-term transition pathways, capturing delays, rebound effects, and consequences that are difficult to represent using more reductionist approaches (Sterman 2000). As such, SD provides a coherent and flexible framework to analyze the systemic nature of emissions and the effectiveness of mitigation strategies in the aviation sector (Csala and Sgouridis 2013; Uy et al. 2025).

The framework we developed differs from the earlier SD models as it represents the EU ETS, CORSIA and the ReFuelEU SAF mandate as endogenous, interacting policy instruments rather than as a single exogenous carbon price; and it uses airline CSRD/ESG disclosures as a calibration source. For European airlines subject to EU-ETS and CORSIA, SD is particularly suitable to represent the evolution of GHG emissions as a function of traffic growth, fleet turnover, efficiency improvements, fuel switching, regulatory constraints, and other variables identified during the study (European Commission, 2021a; ICAO, 2019). A system description is therefore needed that explicitly identifies which aviation sub-systems, regulatory instruments and behavioral responses are in scope, how they interact, and which can be treated as exogenous to avoid unnecessary complexity (Robinson 2013).

2.2 Conceptual Modelling and the Role of the System Description

Robinson defines conceptual modelling as the abstraction of the simulation model from the real-world system, encompassing decisions on model objectives, inputs, outputs, content, assumptions and simplifications. Within this framework, the system description belongs to the problem domain and documents the problem situation and those aspects of reality relevant to the modelling task, while the conceptual model belongs to the model domain and specifies which parts of the system description are represented in the simulation and at what level of detail (Robinson 2013).

Failure to distinguish between system description and conceptual model often leads practitioners to attempt to “model the system description” effectively trying to replicate everything that is known about the real system, which tends to produce overly complex and inefficient models (Pidd 1996; Robinson 2013). Instead, Robinson argues that a good conceptual model should be valid, credible, feasible and useful, while

remaining as simple as possible for the stated objectives, recognizing that increasing model complexity beyond a certain point can reduce overall accuracy when data and knowledge are insufficient to support detailed structures. For a European airline decarbonization simulation, this implies starting with a structured system description of the sector, its regulatory environment and key processes, then deliberately abstracting to a focused conceptual model aligned with questions about GHG KPI feasibility, regulatory compliance and timing of emission reductions.

3 METHODOLOGY

The methodological approach follows the distinction between system description, conceptual model, model design and computer implementation as proposed by Robinson (2013) and shown in Figure 1.

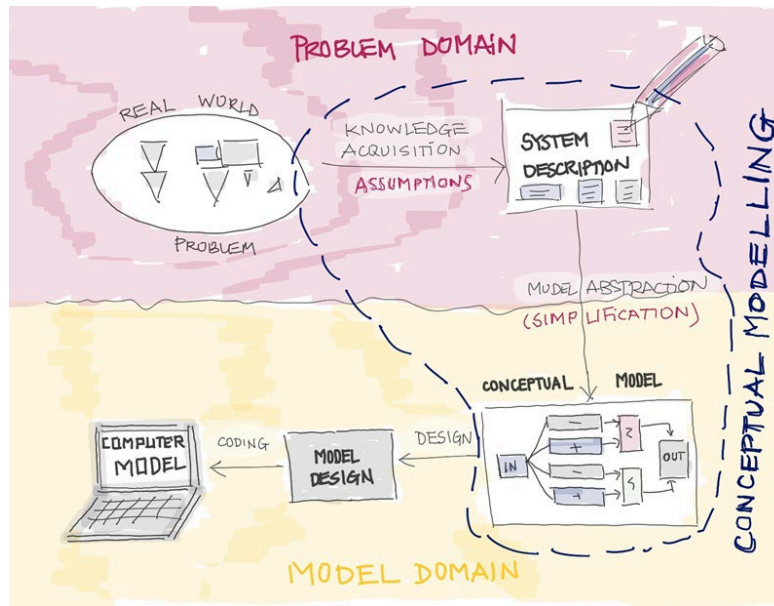


Figure 1: Artefacts of conceptual model (Robinson 2013).

First, relevant information is synthesized from climate science (Lee et al. 2021), international climate governance (UN 2016), EU climate and aviation policy documents (EU 2014; EU 2019a; EU 2020; EU 2021a; EU 2023a), ICAO and IATA sources (IATA 2021), and academic work on aviation emissions and reporting (e.g. (Cowper-Smith and de Grosbois 2011; Efthymiou and Papatheodorou 2019; Gössling and Humpe 2020; Kuok et al. 2023; Martín-Domingo et al. 2025)). This synthesis characterizes the problem situation, core entities and main causal mechanisms that influence airline GHG emissions over time (i.e. conceptual modelling).

Second, system boundaries are specified along four dimensions: geographic (EEA, UK, Switzerland), temporal (baseline year 2025 to 2030, 2040, and 2050), institutional (regulation and market-based measures such as EU-ETS, CORSIA and ReFuelEU) and sectoral (commercial passenger airlines, including low-cost and legacy carriers and excluding only air cargo carriers). Third, the main stocks, flows and feedbacks relevant to emissions are identified conceptually, including traffic and capacity dynamics, fleet evolution, fuel and SAF deployment, policy costs and strategic responses, without yet specifying equations or software constructs (Robinson 2013). Finally, the system description is documented in a structured way that is independent of any particular software package, so that it can be used as the basis for subsequent conceptual model development and stakeholder communication (Robinson 2013).

Structuring according to Robinson's artefacts: In line with Robinson (2013) and as indicated in Figure 1, this paper focuses on simulation modeling (system description and conceptual modeling). The system description is organized around five elements required before abstraction: i) Problem statement and objectives from the system perspective; ii) System boundaries and environment (geographical, temporal, institutional and sectoral); iii) Entities and attributes (e.g. airlines, fleets, routes, policies, fuel markets, demand); iv) Processes and causal mechanisms (e.g. traffic growth, fleet renewal, SAF uptake, policy compliance); and v) Observed and required data, including output variables of interest and available KPIs from airline reporting and regulatory sources (EU 2014; EU 2019c; EU 2019b; EU 2020; EU 2021a; IATA 2021; IATA 2022). By documenting these elements separately from causal loop or stock-flow diagrams, the system description remains software and even paradigm independent and traceable to external evidence, facilitating later validation and review (Robinson 2013).

Role of empirical airline reporting: Prior analysis of European airline ESG and sustainability reporting has classified the types of environmental KPIs disclosed, assessed alignment with EU reporting requirements and identified inconsistencies and gaps (Martín-Domingo et al. 2025). Earlier studies already documented substantial variation in environmental disclosure practices among airlines, and more recent work confirmed a persistent lack of standardization and the need to evaluate compliance with emerging reporting standards (Hooper and Greenall 2005; Zieba and Johansson 2022; Caraveo Gomez Llanos et al. 2023). These insights inform the system description in two ways: i) They indicate which KPIs and actions are consistently reported across airlines (e.g. total CO₂ emissions, emissions per revenue passenger-kilometer, fleet age, SAF use) and can therefore serve as empirical inputs or calibration points; and ii) They reveal how airlines frame their decarbonization strategies (e.g. reliance on offsets, SAF, operational improvements) and how this narrative maps onto the underlying physical processes and policy levers identified in the literature and policy documents. This constrains what can realistically be represented in the simulation using reported data and highlights where assumptions, external datasets or proxy indicators will be needed, for instance, for non-CO₂ effects or detailed demand segmentation (Robinson 2013; Lee et al. 2021; Forster et al. 2023). The conceptual modeling framework is applied using 2024 data, the most recent available at the time of writing.

4 MODEL FORMULATION

This section develops the system description underpinning the simulation of European airline decarbonization pathways, following Robinson's (2013) conceptual modelling framework. It defines the problem statement and objectives, system boundaries, core entities, processes, inputs and outputs that characterize the real-world system, providing a structured and transparent foundation for the subsequent conceptual model and simulation implementation.

4.1 Problem Statement and Objectives at System Level

The real-world problem is that European airlines, situated within the global Paris Agreement framework and regional policies such as the European Green Deal, EU-ETS and ReFuelEU, have adopted long-term GHG reduction targets, yet it is unclear whether the combination of reported KPIs, implemented actions and external drivers is consistent with achieving net zero by 2050 (UN 2016; EU 2019a; EU 2019b; EU 2020; EU 2021a; EU 2023a). At the system level, the objective is to understand how interactions between traffic demand, fleet and technology evolution, fuel and energy choices, and regulatory instruments drive the trajectory of sector-wide and airline-level GHG emissions over time, relative to carbon budgets and policy constraints (EU 2021b; Lee et al. 2021; Forster et al. 2023).

From the simulation perspective, the system must be described so that it allows assessment of (i) the feasibility of existing airline commitments, (ii) the timing of emission reductions and potential overshoots, and (iii) the sensitivity of outcomes to policy, technological and behavioral assumptions (Robinson 2013). This requires identifying feedback structures by which, for example, rising carbon prices under EU-ETS or

CORSIA influence airline strategies, which in turn alter future emissions, compliance costs and potentially future policy tightening.

4.2 System Boundaries

In system dynamics modelling, system boundaries define what is endogenous, explicitly represented within the model, and what is treated as exogenous or excluded entirely (Sterman 2000). Boundary selection is not merely a scoping decision; it directly determines which feedback loops, accumulations and delays are captured and therefore shapes the policy insights the model can generate (Robinson 2013). For an aviation decarbonization simulation, boundary choices must balance tractability with completeness: boundaries that are too narrow risk omitting key regulatory or demand feedbacks, while boundaries that are too broad produce the over-complexity discussed in Section 4.1. The subsections below define the geographic, temporal and sectoral boundaries adopted for this study.

4.2.1 Geographic and Institutional Boundaries

The system includes airlines headquartered in the European Economic Area (EEA: EU 27, Iceland, Liechtenstein, and Norway), the United Kingdom and Switzerland, reflecting a region with shared or closely linked regulatory frameworks for aviation emissions. The institutional environment comprises the EU ETS (Regulation (EU) 2018/2066) as revised for aviation; CORSIA for certain international flights (Regulation (EU) 2019/1603); and the ReFuelEU Aviation Regulation initiative mandating minimum SAF blending shares (Regulation (EU) 2023/2405).

4.2.2 Temporal Boundaries

The temporal horizon runs from a pre-defined baseline year (2024, chosen for data quality and comparability) to up to 2050, capturing intermediate milestones such as 2030 and 2040 that align with EU and industry climate goals (UN 2016; EU 2019d; EU 2021b; IATA 2021). The long service lifetimes of aircraft and engines necessitate modelling of capital stock accumulation and retirement over multiple decades, while acknowledging that macroeconomic shocks (such as the COVID-19 pandemic) and other crises may cause temporary deviations in traffic volume, that can be represented at a high level as capacity shocks.

4.2.3 Sectoral Boundaries and Emissions Included

The system focuses on commercial passenger airlines, including low-cost, legacy and hybrid carriers, as they dominate scheduled traffic and emissions within EU-ETS and CORSIA coverage (ICAO 2019; EU 2021b). Direct operational CO₂ emissions from jet fuel combustion are the primary focus because they are consistently reported and regulated; while non-CO₂ effects (e.g. contrails and NO_x) are recognized but are currently not systematically reflected in airline KPIs or regulatory metrics (Martín-Domingo et al. 2025). Non-CO₂ effects (contrails, NO_x, water vapor) are explicitly excluded from the system description at this stage, although Lee et al. (2021) and Klöwer et al. (2021) estimate that they roughly double aviation's total effective radiative forcing. This boundary choice reflects current regulatory and reporting practice. CO₂ is the metric on which EU ETS, CORSIA and ReFuelEU compliance is assessed and the metric most consistently disclosed in airline reporting. This is a material limitation: a CO₂-only model can evaluate compliance with these instruments but cannot, on its own, determine whether decarbonization pathways are consistent with aviation's full contribution to the 2 °C temperature targets. Subsequent versions of the model may introduce a non-CO₂ forcing multiplier informed by Lee et al. (2021) as a sensitivity layer, so that policy conclusions can be reported both on a CO₂-only basis and on a total-climate-forcing basis.

4.3 Objects

In system dynamics, entities are the conceptual objects, characterized by quantifiable attributes, whose state variables and interactions drive model behavior through feedback loops and accumulation structures (Sterman 2000; Robinson 2013). Table 1 lists the core entities retained within the system boundary defined in Section 4.2, together with their functional descriptions and the simulation parameters.

Table 1: Core simulation objectives and selected attributes.

Object Name	Description	Parameter for the simulation
Market demand	Drives passenger traffic volume (Gössling and Humpe 2020)	Revenue Passenger Kilometer [RPK], Demand Growth [RPK/Year], Load Factor – LF [%], and Available Seats Kilometer [ASK]. Note: LF = RPK / ASK.
Exogenous shocks	Sudden reductions in demand due to an external shock (e.g., the September 2001 attacks or the COVID-19 pandemic)	Shock starts year , demand reduction [RPK / year], and shock duration [years].
Operational Efficiency	Combined fleet renewal and operational efficiency improvement	Efficiency Improvement Rate [1/year]
Fuel mix	GHG emissions savings due to the use of Sustainable Aviation Fuel (SAF) (EU 2023a)	Total Jet Fuel [ton fuel/year], Target SAF Share [0,1], SAF Adoption rate [1/year], Effective SAF Share use [0,1],
Policy instrument	Regulation limiting the amount of GHG emissions. EU ETS (Domestic and European Flights) and CORSIA (International flights) (EU 2019a; ICAO 2019; EU 2021a).	ETS Free Allowances [tonCO2/Year], Total ETS emissions [tonCO2/Year], international emissions share [0,1], ETS offsetting , CORSIA offsetting , and volunteer offsetting [tonCO2/Year]
GHG emissions	Gross (Scope 1) and Net CO2 emissions reported by airlines.	Total CO2 emissions Scope 1 [tonCO2/Year], Net CO2 emissions [tonCO2/Year], Net CO2 emissions after Offsettings [tonCO2/Year]

Airlines are the central agents whose strategies (fleet renewal, operational efficiency, SAF procurement, network adjustments and pricing) mediate between exogenous drivers and emission outcomes (Cowper-Smith and de Grosbois 2011; Efthymiou and Papatheodorou 2019). Policies, fuel supply conditions and demand form the external environment, while ESG reporting serves both as a data source for modelling inputs and as a channel through which airlines articulate and may lock in decarbonization commitments vis-à-vis investors, regulators and customers (EU 2014; EU 2019b; IATA 2022)

4.4 Processes and Causal Mechanisms

Several interlinked processes govern the evolution of airline GHG emissions within the system described:

- **Traffic and capacity dynamics.** Passenger demand evolves over time as a function of economic growth, income, fares and exogenous factors, and is translated into offered capacity via airline network and fleet decisions (Gössling and Humpe 2020). Load factors (LF) and total Revenue Passenger-Kilometers (RPKs) determine the scale of fuel consumption and associated emissions for a given fleet composition and operational efficiency.

- **Fleet evolution and technology uptake.** Airlines retire older, less fuel-efficient aircraft and introduce newer types with improved fuel burn and sometimes different seating densities, subject to financial constraints and manufacturer production (Dray et al. 2018). The fleet age and technology mix determine average fuel consumption per seat-kilometer and hence CO₂ emission intensity, with long asset lifetimes creating inertia in the system.
- **Fuel and SAF deployment.** Under ReFuelEU Aviation and voluntary commitments, airlines progressively increase the share of SAF blended into jet fuel, which reduces lifecycle CO₂ emissions per unit of energy but often at higher cost (EU 2023a). The relative prices of fossil jet fuel, SAF and carbon (under EU-ETS and CORSIA) influence the economics of SAF uptake and may feed back into fares and demand.
- **Policy and market-based measures.** EU-ETS places a cap on intra-EEA aviation emissions and requires airlines to surrender allowances for covered emissions, while CORSIA obliges airlines to offset growth in international flight emissions above a baseline (EU 2023b; ICAO 2023). These instruments create explicit or implicit carbon prices that alter the cost structure of airlines and incentivize efficiency improvements, SAF use, network adjustments or, in some cases, offset purchases, while performance-based regulations (e.g. Single European Sky airspace optimization) may directly improve operational efficiency (Efthymiou and Papatheodorou 2019) .

Together, these processes form reinforcing and balancing feedback loops typical of SD models, such as a reinforcing loop where higher carbon prices make efficiency and SAF more attractive, accelerating emissions reductions, and a balancing loop where higher operating costs increase fares and dampen demand growth (Ford 2009; Robinson 2013). The system description records these mechanisms qualitatively, postponing quantitative specification to the conceptual model stage (Robinson 2013).

4.5 Inputs, Outputs and Data Considerations

From the perspective of the future simulation, the system description identifies key scenario levers, outputs and data sources:

- **Inputs (scenario levers).** Exogenous assumptions on macroeconomic growth and demand for air travel (Gössling and Humpe 2020), technology improvement rates and fleet renewal policies (Dray et al. 2018), SAF availability and cost trajectories (EU 2021a), and regulatory parameters such as EU-ETS cap trajectories, allowance prices, CORSIA phases and ReFuelEU blending mandates (EU 2023b; EU 2023a; ICAO 2023).
- **Outputs (performance measures).** Total and per-airline annual CO₂ emissions, emission intensity metrics (e.g. grams of CO₂ per ASK, RPK), compliance indicators relative to regulatory caps or offset obligations, timing of reaching specific reduction thresholds and net-zero dates, and cost measures such as carbon cost share in operating expenses (EU 2019b; EU 2021a).
- **Data sources.** Airline ESG and sustainability reports and EU Taxonomy disclosures for KPIs and planned actions (Cowper-Smith and de Grosbois 2011; EU 2014; Kuo et al. 2016; EU 2019c; EU 2020), EU-ETS and ReFuelEU legislation and guidance for regulatory parameters (EU 2019d; EU 2021b; EU 2021a), CORSIA documentation for offsetting rules (EU 2019b), and sectoral literature and technical databases for aircraft performance and SAF lifecycle emissions (Dray et al. 2018; Lee et al. 2021; Forster et al. 2023).

Empirical reporting analysis informs which KPIs can serve as robust initial conditions or time series and where data are missing or inconsistent, necessitating transparent assumptions or external proxies (Cowper-Smith and de Grosbois 2011; Kuo et al. 2016). In the subsequent conceptual model, (Robinson 2013) distinction between assumptions (reflecting uncertainty or beliefs about the real world) and simplifications (introduced to keep the model tractable and transparent) will be applied explicitly, but the system

description already identifies areas where each is likely to be required, such as representing non-CO₂ effects or segmenting demand by market.

4.6 Causal Diagrams

This subsection defines the causal structure of the system as a foundation for the System Dynamics model. The causal loop diagrams represent the feedback mechanisms governing the interaction between demand, operational capacity, and policy interventions, serving as an intermediate step between the conceptual model and its formal codification. Figure 2 presents a simple overview of the model organized by blocks, indicating the main drivers of increases and reductions in CO₂ emissions.

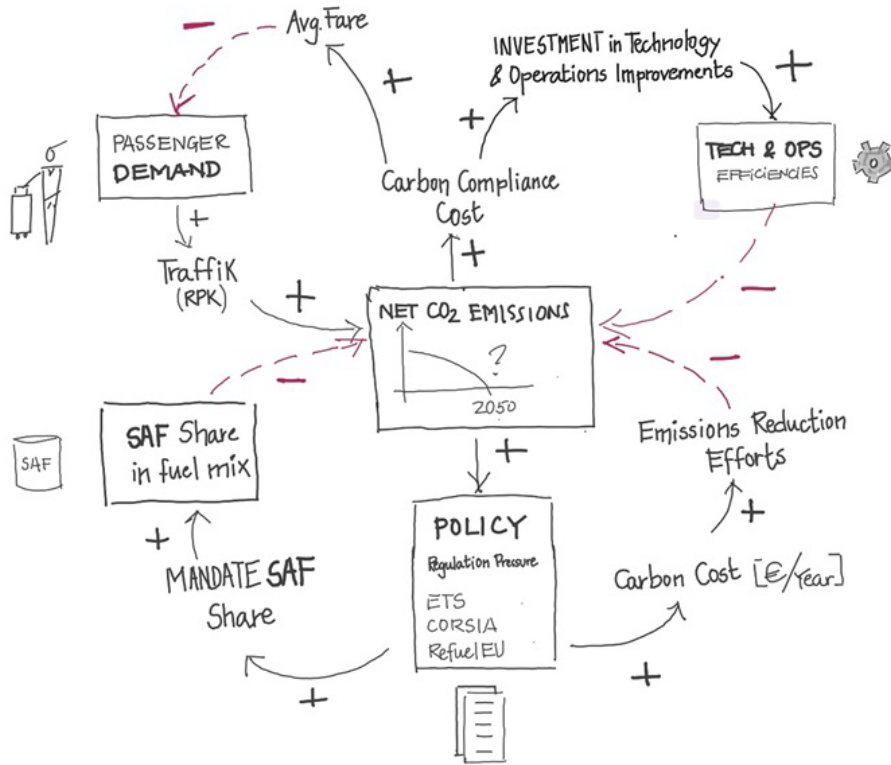


Figure 2: High-level System dynamics feedback loops of airline GHG emissions.

A more detailed diagram is available in the Zenodo repository and can be accessed via the link provided in the manuscript (<https://zenodo.org/records/20622118>).

5 CONCLUSIONS

The system description developed here offers a structured representation of European airline decarbonization that is grounded in climate science, international and EU climate policy, aviation regulation and empirical evidence on airline reporting and operations (EU 2014; EU 2019c; EU 2019b; EU 2020; EU 2021a; IATA 2021; Lee et al. 2021; Forster et al. 2023). By clearly specifying boundaries, entities, processes and data needs, it provides a solid foundation for designing a system dynamics conceptual model that remains as simple as possible while being fit for the purpose of evaluating the feasibility and timing of

airline GHG reduction commitments, in line with Robinson's (2013) criteria of validity, credibility, feasibility and usefulness.

Anchoring the system description in actual airline ESG reporting and EU disclosure frameworks increases the potential for the eventual model to generate insights that are relevant to regulators, airlines and investors, since it will be calibrated against reported KPIs and actions rather than purely hypothetical trajectories (Cowper-Smith and de Grosbois 2011; EU 2014; EU 2019c; EU 2020; Kuo et al. 2016).

At the same time, the description acknowledges significant data limitations and heterogeneity across airlines and jurisdictions, implying that the forthcoming conceptual model will need to employ aggregation, segmentation and carefully documented assumptions, particularly for non-CO₂ effects and behavioral responses. Future work will translate this system description into a formal SD conceptual model, specifying stocks, flows, feedback loops and equations in a system dynamic platform, and then proceed to calibration and scenario analysis to explore whether and under what conditions European airlines can align with net-zero pathways consistent with the Paris temperature goals.

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