Modeling Dynamic Transitions In The Global Air Transportation System

A system dynamics tool for Competitive Industry Assessment

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Abstract

The air transportation system needs to change drastically if it is to transition into a sustainable state. The stakes for the needed technology-driven change – innovation –are extremely high for the lead adopters given the high cost of R&D in manufacturing and the need to change parts of the existing infrastructure and operational procedures if a significant improvement in high energy efficiency is to be achieved. We assess different transition options, using the Global Aviation Industry Dynamics Transition (GAIDT) system dynamics model of the industry that extends a previous implementation in the ability to test how such changes will cascade through the global aviation system accounting for airline and aircraft manufacturer competition across a variety of aircraft product lines. The GAIDT model exhibits advanced features of modularity, extensibility, autocalibration and a visual user interface, some considered unique in system dynamics, such as a dynamic modular structure or compatibility with other simulation modeling techniques. We conduct a quantitative strategy assessment using a composite indicator $\bar{V}$ (normalized strategy value), that combines the economic and environmental benefits of different strategies. It has been found that the normalized strategy values will highly depend on the fuel prices. However, if the fuel prices continue to rise, any kind of innovation option is beneficial. When decoupled from fuel prices, it has been found that early transition options are preferred. In order to properly quantify the impact of technology innovation, its penetration and assess the full impact of the different transition options, further research is needed for which the GAIDT model can serve as basis.

1. Introduction

The commercial air transportation system has been consistently growing at a rate faster than the background global economic growth. This was achieved through the development of a tightly coupled ecosystem of airlines, aircraft manufacturers, airport operators, regulators and the traveling public and influenced by the exogenous but still coupled impact of fuel prices and economic growth. The endogenous dynamics of aircraft ordering rate and airline competition induced alternating periods of over- and under-capacity that would ideally be moderated at the second stage of the value chain – through the actual availability of aircraft (Sgouridis, 2007).

The primary challenge faced by the air transportation system today is the transition into a viable part of a global sustainable transportation system. The ability to do so will depend on the interplay between demand side changes driven by fuel prices, the internalization of the greenhouse gas emissions (fossil fuel peak / carbon price / biofuel premium) and the ability of airlines and aircraft manufacturers to reduce fuel consumption and by implication emissions and ticket prices through operational and technological changes (Sgouridis, Bonnefoy, & Hansmann, 2009).

Nevertheless, the yields from harvesting the low hanging fruit in the case of the air transportation system are insufficient for the scale of transition needed. Extant lean and fairly optimized operations and aircraft are a result of the high level of industry competitiveness in an environment where historically fuel prices are the major cost driver. As a consequence, drastically improving the system's efficiency requires significant changes in the technology and by implication in the existing infrastructure. The long lead times and high costs of aircraft development and the long aircraft lives (in some cases exceeding thirty years) make radical redesign a risky proposition for the manufacturer and their lead adopter customer airline.

a. Problem Definition

We develop the Global Aviation Industry Dynamic Transition (GAIDT) model as a tool to aid policy and industry decision makers for tracing the impacts of drastic transition efforts in industry behavior and competitiveness. GAIDT explores the dynamic behavior of the competitive aviation industry under transition including: existence of any first mover advantage, necessary extent and benefit of regulatory mandates for certain aviation transition options, relative impact and diffusion rate of transition options on industry financials and throughput, and the robustness of transition options under varying exogenous parameters. Assessment of the results can help develop appropriate policies and competitive strategies to facilitate the global aviation system sustainable transition.

The type of transition options that can be investigated are:

- BUINESS AS USUAL (BAU): Aircraft manufacturers carry on with their current development strategies, releasing the currently planned aircraft in the currently planned timeframe(s), under different fuel price scenarios.
- INNOVATE: One aircraft manufacturer decides to radically change the design of its offered aircraft, while the other manufacturer stays on the predefined development track, under different fuel scenarios.
- FOLLOW: All manufacturers decide to radically change the design of their offered aircraft, with a difference in introduction times and fuel benefits, under different fuel price scenarios.
- INDUSTRY REFORM: All manufacturers decide to radically change their aircraft, offering substantial fuel burn benefits and introduce it at the same predefined time in the future, under different fuel price scenarios.

In the transition option listed above, the focus has been on new technology diffusion. Other types of transitions can also be linked to the problem, such as penetration of biofuels, carbon taxes and emissions regulations, change in airport and/or air traffic control procedures regulations, etc. While the GAIDT model is prepared to handle these transitions options as well, they do not constitute the focus of the present study.

In the above description a radical change means a modification of aircraft that brings lower fuel burn (and higher potential development costs but also impacts the operationally relevant aircraft characteristics like speed and range) for future aircraft than normal aircraft redesign programs would do. At this stage of the research, only the two dominant aircraft manufacturers are considered (Morrison, Hansmann, & Sgouridis, 2010). We investigate whether it makes sense to opt for small incremental imporvements of current aircraft and “wait” for the radically new technologies to become available through other participants in the market or it is more beneficial to the competitors present in the industry, as well the industry as a whole to innovate as soon as possible. From this point forward in the study, the aircraft employing radical changes are commonly referred to as *new* aircraft, the currently available aircraft on the market are referred to as *current* aircraft and the aircraft currently in development at major aircraft manufacturers and a planned release to market in the near future are referred to as aircraft *in development*.

Initially, all new aircraft are considered to comply with the standards of the currently existing aviation infrastructure, therefore retaining their maximum wingspan, design cruise speed, balanced field length, and their design payload/range. These characteristics are collectively referred to as mission specifications. Further fuel-burn and emissions reductions of future aircraft can be obtained by modifying these mission specifications and re-optimizing the aircraft and airline operations. In this study, potential benefits offered by changes to the following mission specifications are considered:

- Design Cruise Speed Reduction (CSR)
    - Decreasing the design cruise speed of the aircraft has an impact on airline operations: while reducing the fuel-burn and thus the fuel costs of airlines, concomitantly increases the flight time, thus increasing flight-time-related costs, such as crew labor. Through the change of flight time, passenger demand is also affected.
- Wingspan Increase (WI)
    - Increasing the wingspan improves the aircraft’s aerodynamic capabilities thus reducing fuel-burn, but at the cost of limiting access to airport gates.

Changing the design range, accounting for current usage trend of aircraft operators can also yield substantial fuel burn reductions and will be investigated in the future.

To compare between different strategies, for all of the above transition options the economic and environmental impacts for all stakeholders are quantified and assessed.

b. Methodology: System dynamics approach

The aviation industry can be described as a “system of systems” or an “enterprise of enterprises” (Sgouridis, 2007). Several techniques are available to translate enterprise models into simulation models. A system dynamics approach was chosen, to best capture the global industry dynamics (Csala, 2013). To compensate for the modeling choice’s greatest disadvantage, the rigidity of the model structure, an experimental dynamic model structure has been developed, that can be expanded programmatically, during model execution and also opens the door for a seamless integration into frameworks governed by other simulation modeling methods.

c. Existing works

Several authors have studied aviation industry cost dynamics and have made causal loop diagrams or complete system dynamics models, including the works of, (Lyneis, 1988), (Lyneis, 1999), (Lyneis, 2000), (Liehr, Groessler, Klein, & Milling, 2001). However, most of these works concentrate on explaining the cyclical nature of airline profits and correlating it with the industry structure. (Sgouridis, 2007), (Pierson, 2011) and (Cronrath, 2012) present models which describe the aviation industry dynamics with great detail, including the dynamics of passenger demand, airline and manufacturer capacity management and operating economics. These works have been used as basis for the development of the GAIDT model.

2. The Global Aviation Industry Dynamic Transition (GAIDT) Model

a. Description

The Global Aviation Industry Dynamic Transition (GAIDT) model is an advanced version of the Global Aviation Industry Dynamics (GAID) model ((Sgouridis, 2007), (Sgouridis, Bonnefoy, & Hansmann, 2009)), implemented in up-to-date software (AnyLogic 6, written in JAVA language) and having a user friendly interface. The model structure has been dynamized, allowing for easy expansion in future releases, and it has been extended to accommodate for the industry transitions and mission specification changes proposed in (PARTNER, 2012). Provided that we have the right data for model input, this structure allows for greater resolution and also open the door for expansion and addition of modules, which might be based on system dynamics or other simulation modeling methods, such as Agent-Based Modeling.

b. Structure – a dynamic modular approach

The GAIDT is built upon the modular structure of the GAID model, made up from logically bound structural blocks. These modules are then integrated into classes to make up the GAIDT model. Each of the classes and modules is then replicated, depending on the model's dimensions. The model dimension types have been predefined, however, the size of each of these dimensions does no need to be preset. The size of the dimensions defines the level of insight we want to gain into the industry dynamics. The GAIDT model is built over following dimensions:

- Aircraft Type: defines the aircraft types used in the GAIDT model, e.g. [Narrow Body, Wide Body] or [A320, A330, B737, B777]
- Manufacturer Type: defines the manufacturer types used in the GAIDT model, e.g. [Airbus, Boeing]
- Airline Type: defines the airline types used in the GAIDT model, e.g. [Full Service, Low Cost] or [Delta, Lufthansa, Emirates, Southwest]
- Passenger Type: defines the passenger types used in the GAIDT model, e.g. [Leisure, Business]
- Destination Type defines the flight leg types used in the GAIDT model, e.g. [Long Haul, Short haul] or [1000 km, 2000 km, 3000 km]

At the current stage of the research, the following dimension sizes have been used, dependent upon data availability for calibration:

- Aircraft Type (2)
    - Narrow Body
    - Wide Body
- Manufacturer Type (2)
    - Boeing
    - Airbus
- Airline Type (1)
- Passenger Type (1)
- Destination Type (1)

(Airline Type, Passenger Type and Destination Type dimensions have a size of 1 and are treated as integrated entities)

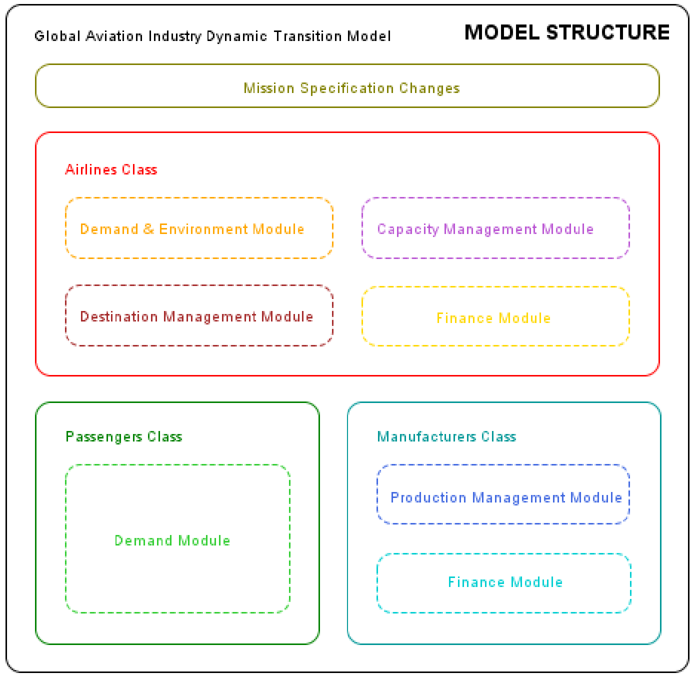

Figure 1 – GAIDT model structure

Figure 1 presents the GAIDT model's modular structure. Each of these is modules is replicated across a number of dimensions. These differentiate across the type of the data the model can handle and also define its resolution. For example, for the Airline Capacity Management Module being 2 dimensional, across the dimensions Aircraft Type and Manufacturer Type means that it is replicated *n* x *m* times, where *n* is the size of the Aircraft Type dimension and *m* is the size of the Manufacturer Type dimension. This way, the model data can be controlled individually for the Capacity Management of Aircraft Type 1, Manufacturer Type 1 until that of Aircraft Type *n*, Manufacturer Type *m*.

- Mission Specification Changes Class (2D – Aircraft Type, Manufacturer Type)
- Airlines Class (1D – Aircraft Type)
  - Forecast and Environment Module
  - Capacity Management Module (2D – Aircraft Type *(inherited)*, Manufacturer Type)
  - Destination Management Module (3D – Aircraft Type *(inherited)*, Manufacturer Type, Destination Type – currently not implemented)
  - Finance Module (2D – Aircraft Type *(inherited)*, Manufacturer Type)
- Manufacturers Class (1D – Manufacturer Type)
  - Production Management Module (2D – Manufacturer Type *(inherited)*, Aircraft Type)
  - Finance Module (2D – Manufacturer Type *(inherited)*, Aircraft Type)
- Passenger Class
  - Demand Module (1D – Aircraft Type)

Each of the GAIDT modules is composed of a parameterized system dynamics sub-model, having the capability of receiving inputs either from other modules or from historical data. A navigable, visual user interface aids model setup and operation. Figure 2 presents a snapshot of a sample module setup of the

GAIDT model and Figure 3 presents a snapshot of a sample module structure. Detailed individual modules are presented in Appendix 1 and Appendix 2.

Figure 2 – Sample GAIDT module setup

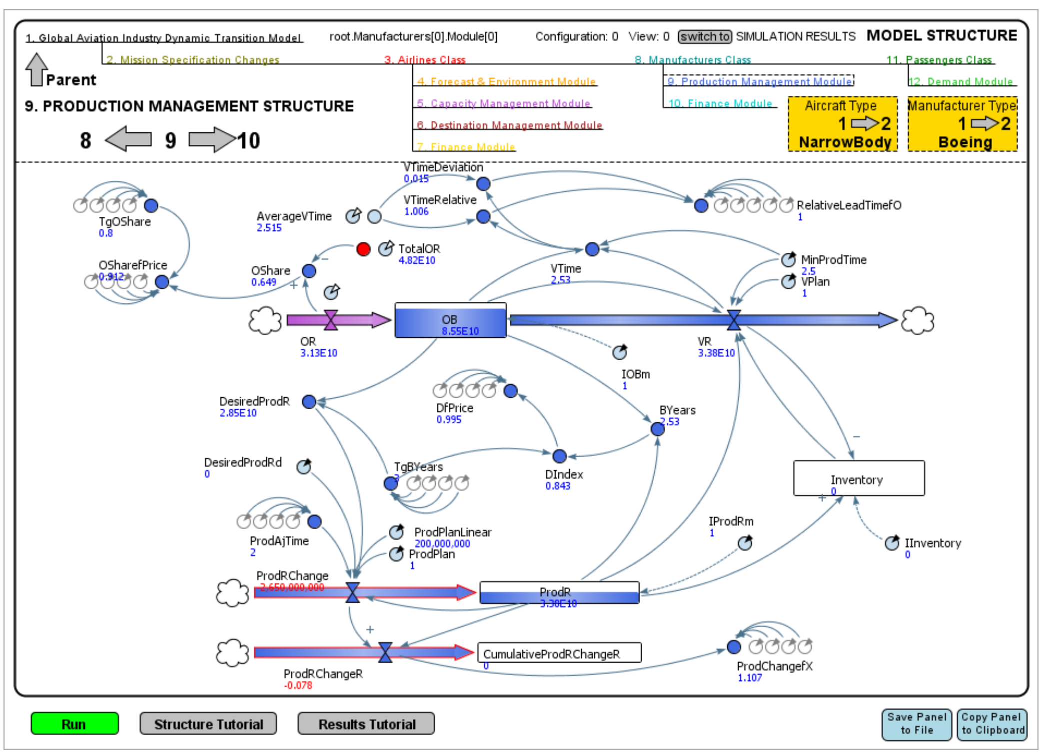

Figure 3 – Sample GAIDT module structure

c. Model calibration

Calibration of the GAIDT model has been carried out using the same principles as (Sgouridis, 2007). Since the GAIDT model is fully backwards compatible with the GAID model, using the calibration parameters deduced for the GAID model yield the same results when used in the GAIDT. This parameter set has been considered as the initial calibration setup.

Furthermore, an advanced calibration module (which we will call autocalibration) has been developed that can automatically adjust model parameters to meet a predefined output pattern for the chosen indicator variables (with weights in brackets, for establishing relative indicator hierarchy) – therefore effectively being able to deduce the form and size of unknown transfer functions between two connected variables.

- Passenger Demand (1.0)
- Airline Profit (0.5)
- Airline Profit Margin (1.2)
- Fare (0.75)
- Load Factor (1.2)
- Capacity Order Rate (4 x 0.2)
- Capacity Order Backlog (4 x 1.0)
- CO2 Emission Rate (0.5)

The following parameter types are defined (as JAVA classes) in the model and used for fitting:

- Time Parameter
    - A parameter which varies with time, unaffected by the other parameters or variables. It has the following properties:
        - Scenario – for deciding on the prediction table used
        - Multiplier – for data scaling
        - Delay – whether the data has a delayed effect in affecting the other variables of the model
        - Shift – whether the data table selected has a time shift
- Effect Parameter
    - A parameter which takes an argument and uses a transfer function to produce and effect It has the following properties:
        - Scenario – for deciding on the transfer function (table) used
        - Multiplier – for effect scaling
        - Delay – whether the data has a delayed effect in affecting the other variables of the model
        - ArgDelay – whether the argument of the transfer function has a delay before applying the function
        - ArgInitial – initial value of the argument (where applicable)

For implementation of any delay, a first order exponential smoothing is used, unless noted otherwise.

With autocalibration, GAIDT can alternate between predefined transfer functions for variable (by changing the *Scenario* parameter fields) interactions, apply weights, delays, argument delays and time shifts to them and determine which yields the smallest deviation from the predefined dataset. In further releases it should allow to devise what kind of transfer function should be used (already implemented for the simulation part, where the user can choose or construct any transfer function for the effects)

A hybrid calibration approach of per module and global calibration has been used. First, each of the classes with their respective modules were fitted separately, using different sources for their inputs – either previous simulation data or historical values. Then, an experimental global calibration was also conducted, varying every module's parameters at once. For every calibration experiment, 3 calibration scenarios were defined, based on the datasets used for fitting. These are:

0. Calibration dataset: Output of the GAID model (1984 – 2025)
1. Calibration dataset: Actual data of the GAID model (1984 – 2005)
2. Calibration dataset: Actual data from (A4A, 2012) (1984 - 2012)

Each of these scenarios was run twice, using different random seeds, 1, and 2, respectively to ensure consistency. Then the resulting parameter values were averaged (modal value was taken where necessary) and then final parameter set was created to be used in simulations, alongside the default setup from the GAID model. The Airline Profit Margin fit is presented in Figure 4. The full calibration report is presented in Appendix 3.

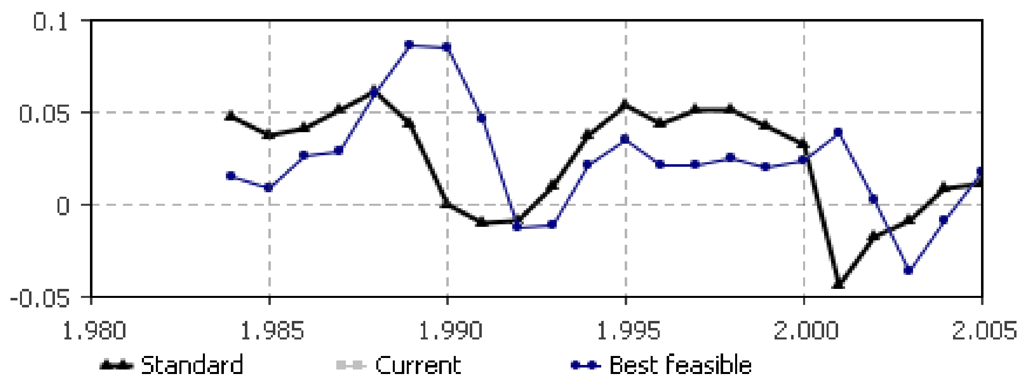

Figure 4 – Airline Profit Margin Calibration Fit

In all calibration graphs, *Standard* is the dataset against which the model gets fitted and *Current* is the model output using the current calibration parameters. *Best Feasible* corresponds to the parameter set yielding the best feasible solution. In the above graph *Current* and *Best Feasible* happen to be overlapping.

3. Dynamic transitions

a. Experiment design

Using the calibrated GAIDT model, a sensitivity analysis for strategy assessment has been carried out. Using the different preset technology scenarios identified in the International Civil Aviation Organization's Committee on Aviation Environmental Protection (ICAO/CAEP) Long-Term Fuel Burn Technology Goals (LTTG) exercise and used in (PARTNER, 2012), the manufacturers' strategies have been adjusted to apply the technology advancements and mission specification changes on their new aircraft offerings in the 2020-2030 period, complying with the transition options described in the Problem Definition section. Table 1 and Table 2 present the technology advancement options and potential mission specification changes, with their respective benefits for Narrow Body (after Boeing 737-800w) and Wide Body (after Boeing 777-200ER) aircraft (adapted from (PARTNER, 2012)).

Table 1 – Fractional fuel-burn reductions (baseline = 1.00) resulting from redesigns of new Narrow Body aircraft with different mission specifications and different levels of technology

Technology level	**Baseline**	**CSR** (0.8625)	**WI** (1.35)	**CSR + WI**
Baseline	0.9440	0.8650	0.9323	0.8542
TS1 – 2020	0.7500	0.6920	0.7413	0.6839
TS1 – 2030	0.7056	0.6527	0.6971	0.6448
TS2 – 2020	0.7056	0.6527	0.6971	0.6448
TS2 – 2030	0.6594	0.6109	0.6510	0.6031
TS3 – 2030	0.5654	0.5222	0.5606	0.5177

Table 2 – Fractional fuel-burn reductions (baseline = 1.00) resulting from redesigns of new Wide Body aircraft with different mission specifications and different levels of technology

Technology level	**Baseline**	**CSR** (0.8333)	**WI** (1.36)	**CSR + WI**
Baseline	0.9257	0.8278	0.9257	0.8278
TS1 – 2020	0.7923	0.6826	0.7674	0.6611
TS1 – 2030	0.6802	0.6033	0.6802	0.6033
TS2 – 2020	0.7084	0.6286	0.7084	0.6286
TS2 – 2030	0.6280	0.5557	0.6280	0.5557
TS3 – 2030	0.5747	0.5078	0.5747	0.5078

In the above tables, a "Baseline" technology level means re-optimization of studied aircraft (not allowing for in-family flexibility and modularity), TS1 means light redesign of current aircraft, continuation of current development trends, TS2 means a higher than average technology advancement, introduction of new technology currently under research and TS3 means significant redesign of current aircraft and introduction of new technology currently under research or beyond, potentially necessary from pressure from regulations or taxes. CSR stands for Cruise Speed Reduction and WI stands for Wingspan Increase.

It is clear that the chosen technology scenario sets the level of fuel-burn reduction, with mission specification changes only offering marginal reductions. Wingspan increase does not offer by far as much benefits in fuel-burn as cruise speed reduction would (and very small or no effect on Wide Body aircraft).

In addition to this, for comparison purposes, we need to consider the current strategy of the two considered aircraft manufacturers, Airbus and Boeing. Table 3 presents the BAU aircraft development plans for the two major aircraft manufacturers, with the timings of new aircraft introductions and their fuel benefits compared to their current models, corresponding to technology scenario TS-BAU.

The technology scenario "STATUS QUO" – TS-SQ corresponds to the theoretical strategy case when both major aircraft manufacturers stop development of new aircraft and keep their current offerings.

Table 3 – BAU aircraft development plan for the two major aircraft manufacturers

Aircraft Type	Introduction year (EIS)	Fuel-burn reduction (current model = 1.00)
Airbus A320neo	2015	0.8500
Boeing 737MAX	2017	0.8375
Airbus A350	2017	0.8266
Boeing B787	2011	0.8000

Table 4 – Strategy decisions for the two major aircraft manufacturers

Airbus \ Boeing	BAU	INNOVATE	FOLLOW
BAU	BAU	BOEING INNOVATES	–
INNOVATE	AIRBUS INNOVATES	INDUSTRY REFORM	BOEING FOLLOWS
FOLLOW	–	AIRBUS FOLLOWS	–

Taking into account the industry transition options described in the Problem Definition section, and the possible strategy decisions presented in Table 4, the possible combinations of strategy choices, technology levels and potential mission specification changes yield a very high number of possible cases. For this study, the following representative simulation scenarios were created:

Scenario 1: **BAU** (all manufacturers follow current development plan with TS-BAU parameters)

Boeing	Follows current development plan with TS-BAU parameter aircraft
Airbus	Follows current development plan with TS-BAU parameter aircraft

Scenario 2: BOEING INNOVATES SOON

Boeing	TS-SQ until 2020 then TS2-2020
Airbus	TS-BAU

Scenario 3: BOEING INNOVATES LATE

Boeing	TS-BAU until 2030 then TS2-2030
Airbus	TS-BAU

Scenario 4: AIRBUS INNOVATES SOON

Boeing	TS-BAU
Airbus	TS-SQ until 2020 then TS2-2020

Scenario 5: AIRBUS INNOVATES LATE

Boeing	TS-BAU
Airbus	TS-BAU until 2030 then TS2-2030

Scenario 6: BOEING FOLLOWS SOON

Boeing	TS-SQ until 2020 + 2 then TS2-2020 + 2
Airbus	TS-SQ until 2020 then TS2-2020

Scenario 7: BOEING FOLLOWS LATE

Boeing	TS-BAU until 2030 + 2 then TS2-2030 + 2
Airbus	TS-BAU until 2030 then TS2-2030

Scenario 8: AIRBUS FOLLOWS SOON

Boeing	TS-SQ until 2020 then TS2-2020
Airbus	TS-SQ until 2020 + 2 then TS2-2020 + 2

Scenario 9: AIRBUS FOLLOWS LATE

Boeing	TS-BAU until 2030 then TS-2030
Airbus	TS-BAU until 2030 + 2 then TS2-2030 + 2

Scenario 10: INDUSTRY REFORM SOON

Boeing	TS-SQ until 2020 then TS2-2020
Airbus	TS-SQ until 2020 then TS2-2020

Scenario 11: INDUSTRY REFORM LATE

Boeing	TS-BAU until 2030 then TS-2030
Airbus	TS-BAU until 2030 then TS-2030

In the process of designing the above scenarios, it was assumed that if new aircraft enters service in 2020, the TS-SQ scenario is followed and the aircraft in development does not get introduced (this includes the Boeing B787 entered into service in 2011, as the model starting year is set to 2010), until the introduction time of the new aircraft, 2020. However, if the innovated aircraft enters service in 2030, the TS-BAU is followed and the aircraft in development gets introduced at the planned time and the new aircraft is introduced in 2030 as a replacement. This decision was based on taking into consideration the typical duration of aircraft development programs (Morrison, Hansmann, & Sgouridis, 2010). For all scenarios technology advancement level TS2 was chosen.

Since all transitions yield fuel-burn reduction of aircraft, their operating benefit is clearly dependent on fuel price. For this reason, the simulations have been conducted for 3 different fuel-price scenarios:

- Current, high fuel price (fuel price stays at 2012 levels until 2040 – on par with Airbus' (Airbus, 2012) and FAA's (FAA, 2010) predictions)
- High fuel price (current fuel price will double by 2020 then stagnate until 2040)
- Low fuel price (current fuel price will drop by 20% by 2020 then stagnate until 2040)

After the simulation runs, the most promising manufacturer strategy scenarios for each fuel-price scenario can be chosen and mission specification changes' effects might be investigated.

The strategy decisions presented in Table 4 are taken separately for the Narrow Body and Wide Body, markets. Likewise the considered transitions are cross-dimensional and can be classified as:

- One-dimensional transition
  - Only Narrow Body
  - Only Wide Body
- Multi-dimensional transition
  - Both Narrow Body and Wide Body (all dimensions)

In order to reflect dimensional changes, the Narrow Body and Wide Body markets, respectively the combination of them, were analyzed separately and are presented as separate experiments in the results section. For multi-dimensional transitions, it is assumed that the changes get into effect at the same time across all dimensions, as having different entry times would add significant complexity to the experiment design, offering only marginal accuracy improvement (deduced empirically).

b. Simulation Results

The experiments defined and described in the Experiment design section were simulated, using the GAIDT model. This section summarizes the simulation results.

During the simulations, the cumulative airline profits, the cumulative manufacturer profits and cumulative total industry profits (all 1984 dollars), cumulative emissions (Gtons of CO2) and cumulative passenger demand (Revenue Passenger Miles – RPM) for the 2010-2040 period were taken as key comparison indicators. Cumulative per unit industry profit and cumulative per unit emissions were calculated, where the unit is RPM. Then a geometric composite indicator V was created, further referred to as *strategy value*:

$$V = \sqrt[(\alpha+\beta)]{{P_u}^{\alpha} \cdot \left(\frac{1}{E_u}\right)^{\beta}} \qquad (1)$$

where: P_u is the per unit industry profit, desired to be high
E_u is the per unit CO2 emissions, desired to be low

In this study, equal emphasis was placed on economic and environmental criteria, thus α = β = 1.

In order to aid comparison, all of the above mentioned measures have been normalized with respect to the TS-BAU scenario to give information about the relative advantage or disadvantage of a certain scenario compared to the normal industry development plan. This yields the normalized strategy value:

$$\bar{V} = \sqrt{\frac{\overline{P_u}}{\overline{E_u}}} \qquad (2)$$

where: $\overline{P_u}$ is the normalized per unit industry profit
$\overline{E_u}$ is the normalized per unit CO2 emissions

Narrow Body market

Table 5 presents scenario winners and Table 6 summarizes the results of the simulations when the transitions are only applied to the Narrow Body Market. Detailed results are to be found in Appendix 4.

Table 5 – Narrow Body market winner by scenario

Fuel	Winner by	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Current	Profits	Airbus	Boeing	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing
High	Profits	Boeing	Boeing	Boeing	Airbus	Airbus	Airbus	Boeing	Boeing	Boeing	Boeing	Boeing
	Orders	Boeing	Boeing	Boeing	Boeing	Airbus	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing
Low	Profits	Airbus	Boeing	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing	Boeing

By referring back to the simulation scenario definitions in the Experiment design section and consulting Table 5, the complex dynamics of the aviation industry are revealed. It can be seen that the innovators gain more profits, especially in the case when the competitor does not innovate. (Orders are affected by other endogenous mechanisms and no specific emphasis should be placed on them at this point) In fact, if the fuel-prices stay at current levels or go down, Boeing can only win if he chooses to innovate sooner or later (S2, S3). However, if fuel prices continues to rise, the only viable option for Airbus is to innovate (S4, S5).

Table 6 – Narrow Body transitions strategy values

Fuel	Best	->										Worst
High	P_u	S4	S5	S7	S6	S11	S9	S10	S8	S2	S3	S1
		2.086	1.539	1.319	1.285	1.257	1.255	1.22	1.213	1.124	1.114	1
	E_u	S1	S3	S5	S2	S7	S9	S8	S11	S6	S10	S4
		1	0.971	0.971	0.963	0.96	0.96	0.956	0.9555	0.952	0.949	0.942
	V	S4	S5	S7	S6	S11	S9	S10	S8	S2	S3	S1
		1.488099	1.258954	1.17216	1.161805	1.146971	1.143369	1.133827	1.126423	1.080364	1.071107	1
Current	P_u	S5	S4	S7	S9	S11	S8	S1	S6	S10	S3	S2
		1.126	1.07	1.049	1.028	1.015	1.001	1	1	0.984	0.952	0.936
	E_u	S1	S4	S5	S3	S2	S7	S9	S11	S6	S8	S10
		1	0.975	0.974	0.969	0.967	0.957	0.957	0.952	0.947	0.946	0.941
	V	S5	S4	S7	S9	S11	S8	S6	S10	S1	S3	S2
		1.075201	1.047586	1.046964	1.036431	1.032558	1.028659	1.027602	1.022593	1	0.991189	0.98384
Low	P_u	S5	S1	S4	S7	S9	S11	S8	S10	S6	S3	S2
		1.016	1	0.989	0.986	0.978	0.968	0.951	0.932	0.929	0.915	0.894
	E_u	S1	S5	S4	S3	S2	S7	S9	S11	S6	S8	S10
		1	0.979	0.976	0.968	0.966	0.958	0.957	0.952	0.947	0.944	0.94
	V	S5	S7	S9	S11	S4	S8	S1	S10	S6	S3	S2
		1.018722	1.014509	1.010912	1.008368	1.006638	1.003701	1	0.995736	0.990451	0.972239	0.962011
Average	V	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
		1	1.007453	1.010619	1.162068	1.113059	1.057459	1.075783	1.051621	1.062054	1.049054	1.060951

Table 6 presents normalized profit, emissions and strategy values. The *High, Current* and *Low* represent fuel scenarios and the color coding reflects is the value order within the table. Profits and strategies are preferred to have a high value and emissions are preferred to have a low value. The *Average* row defines the value of a certain strategy *decoupled* from the fuel price by taking the geometric average of the three studied fuel scenarios.

A dominant pattern clearly emerges from the above table: as the fuel price gets lower and lower, the technology innovations begin to lose their value. For example if the fuel price is low, the industry profits can be as much as 11% less than following the current development plan (S2). High fuel prices clearly favor the technology innovations. In scenario S4 with high fuel price, profits more than double compared to the BAU case.

It is important to remark, that, as expected, the emissions are in all innovation cases less than in the BAU case, for all fuel scenarios.

Another interesting remark is that when decoupled from fuel price and averaged, all strategy scenarios have a strategy value higher than 1. This leads to the conclusion, that all Narrow Body innovation strategies are more beneficial than following the normal development path, *regardless* of fuel prices. Clearly, the best option is for Airbus to innovate late then for Boeing either to follow or to innovate at the same time (S5, S7, S11). However, the strategy choice is not straightforward as later in time transition strategies yield the most cumulative profits, but also the least amount of emissions reductions.

Wide Body market

A similar analysis is conducted for the Wide Body market, preserving the previously introduced notations' consistency.

Table 7 presents scenario winners and Table 8 summarizes the results of the simulations when the transitions are only applied to the Wide Body market. Detailed results are to be found in Appendix 5.

Table 7 – Wide Body market winner by scenario

Fuel	Winner by	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Current	Profits	Airbus	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Airbus	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
High	Profits	Boeing	Boeing	Boeing	Airbus	Airbus	Airbus	Boeing	Airbus	Boeing	Airbus	Airbus
	Orders	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Airbus
Low	Profits	Airbus	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Airbus	Airbus	Airbus	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus

In the Wide Body market, Airbus emerges as the winner in most of the cases, with Boeing needing high fuel prices and to innovate in order to gain more profits (S2, S3, as it is the case in BAU scenario as well). Also, it can be seen that Boeing wins both of the FOLLOW LATE scenarios, no matter if he or Airbus is the first-mover. This can be largely attributed to its strong BAU development plan, as justified by the outcome of S1. In case of current of low fuel prices, Airbus always emerges as winner, except when he decides to INNOVATE SOON

Table 8 – Wide Body transitions strategy values

Fuel	Best	->										Worst
High	$\underline{P}_u$	S8	S6	S10	S2	S9	S5	S11	S4	S7	S1	S3
		1.039	1.033	1.032	1.023	1.017	1.016	1.012	1.012	1.01	1	0.982
	$\underline{E}_u$	S1	S2	S5	S4	S8	S6	S3	S10	S7	S9	S11
		1	0.995	0.991	0.989	0.987	0.986	0.985	0.983	0.98	0.98	0.979
	$\underline{V}$	S8	S10	S6	S9	S11	S7	S2	S5	S4	S1	S3
		1.026004	1.024621	1.023556	1.018703	1.016714	1.015191	1.013973	1.012535	1.011561	1	0.998476
Current	$\underline{P}_u$	S8	S6	S10	S2	S9	S11	S5	S7	S3	S1	S4
		1.015	1.014	1.013	1.011	1.011	1.007	1.005	1.005	1.001	1	0.998
	$\underline{E}_u$	S1	S2	S5	S4	S3	S8	S6	S10	S9	S11	S7
		1	0.996	0.992	0.99	0.988	0.987	0.986	0.984	0.982	0.981	0.981
	$\underline{V}$	S9	S10	S6	S8	S11	S7	S2	S3	S5	S4	S1
		1.014658	1.014629	1.014099	1.014085	1.013165	1.012159	1.007502	1.006557	1.006531	1.004032	1
Low	$\underline{P}_u$	S8	S10	S6	S2	S9	S11	S3	S7	S5	S1	S4
		1.013	1.012	1.012	1.011	1.011	1.007	1.005	1.004	1.002	1	0.995
	$\underline{E}_u$	S1	S2	S5	S4	S3	S6	S8	S10	S7	S9	S11
		1	0.996	0.992	0.991	0.988	0.987	0.987	0.984	0.982	0.982	0.981
	$\underline{V}$	S9	S10	S11	S8	S6	S7	S3	S2	S5	S4	S1
		1.014658	1.014128	1.013165	1.013086	1.012585	1.01114	1.008567	1.007502	1.005028	1.002016	1
Average	$\underline{V}$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
		1	1.009654	1.004524	1.005861	1.008026	1.016735	1.012828	1.017708	1.016005	1.017781	1.014347

The same pattern can be observed in the above Table 8, as in Table 6: as the fuel price gets lower and lower, the technology innovations begin to lose their value. However, it is important to notice that in case of Wide Body aircraft, the deviation for the BAU case is, on average, much smaller than in the case of Narrow Bodies. This clearly indicates a higher relative value for Narrow Body innovations than Wide Body ones and gives evidence of robust current development plans for Wide Body aircraft.

Profit gains can be as much as 100% less and emissions are on average 5% less than for Narrow Bodies.

When decoupled from fuel price, the INDUSTRY REFORM LATE strategy (S11) has the highest value with the FOLLOW LATE strategies closely following. This clearly indicates that the current Wide Boyd aircraft development programs are robust and new aircraft need to be introduced only in the far future.

This is in harmony with the findings in the Narrow Body market.

All dimensions

Table 9 present the market winners and Table 10 summarizes the results of the simulations when the transitions are applied across all dimensions of the model, i.e. to the entire industry. Detailed results are to be found in Appendix 6. Because of endogenous feedback mechanisms the multi-dimensional effect on the industry is more complex than just the sum of the two one-dimensional effects (due to cross-dimensional phenomena, such as brand loyalty).

Table 9 – All dimensions market winner by scenario

Fuel	Winner by	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Current	Profits	Airbus	Boeing	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Boeing	Boeing	Boeing	Boeing	Airbus	Boeing	Boeing	Airbus	Boeing	Airbus	Boeing
High	Profits	Boeing	Boeing	Boeing	Airbus	Airbus	Airbus	Boeing	Boeing	Boeing	Airbus	Boeing
	Orders	Boeing	Boeing	Boeing	Airbus	Airbus	Airbus	Boeing	Airbus	Boeing	Airbus	Boeing
Low	Profits	Airbus	Boeing	Boeing	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus	Airbus
	Orders	Boeing	Boeing	Boeing	Boeing	Airbus	Boeing	Boeing	Airbus	Boeing	Airbus	Boeing

If transitions are applied across dimensions, the true complexity of the problem emerges. In this case, there is no majority winner anymore and the individual strategy winners apparently began to depend *more* on the chosen strategy and *less* on the fuel price.

It can be seen from Table 9 that, as expected from the one-dimensional cases, if both manufacturers follow the BAU strategy (S1), high fuel prices favor Boeing and current or low fuel prices favor Airbus.

Innovators are rewarded regardless of fuel price, as both Boeing and Airbus win their INNOVATE strategies, regardless of fuel price (S2, S3 and S4, S5), and regardless of the introduction times of their new aircraft.

In the FOLLOW strategies, first-mover Airbus wins if Boeing decides to follow soon (S6), in all fuel scenarios, but Boeing can turn over the game and win if he decided to follow late (S7), if the fuel prices are conveniently high. If Boeing moves first, he can only win if the fuel prices are high, but then he does so regardless of the introduction of the new aircraft (S8, S9).

If an INDUSTRY REFORM is considered, Airbus wins if the introduction of new aircraft is soon (S10 all) and Boeing can turn it over only with late new aircraft introduction times and high fuel prices (S11 High).

Table 10 – All dimensions transitions strategy values

Fuel	Best					->						Worst
High	P_u	S4	S5	S7	S6	S10	S8	S9	S1	S11	S2	S3
		1.733	1.271	1.091	1.079	1.032	1.028	1.019	1	0.99	0.929	0.892
	E_u	S1	S3	S5	S2	S9	S8	S7	S6	S11	S10	S4
		1	0.963	0.962	0.956	0.943	0.942	0.941	0.937	0.935	0.93	0.929
	V	S4	S5	S7	S6	S10	S8	S9	S11	S1	S2	S3
		1.365814	1.149437	1.076757	1.073102	1.053412	1.044651	1.039516	1.028992	1	0.985778	0.96243
Current	P_u	S5	S4	S7	S9	S8	S10	S6	S1	S11	S3	S2
		1.136	1.083	1.06	1.021	1.017	1.014	1.013	1	0.998	0.952	0.941
	E_u	S1	S5	S4	S3	S2	S9	S7	S11	S6	S8	S10
		1	0.966	0.963	0.962	0.961	0.942	0.939	0.934	0.934	0.933	0.923
	V	S5	S7	S4	S10	S8	S6	S9	S11	S1	S3	S2
		1.084428	1.062478	1.060477	1.048137	1.044046	1.041433	1.041088	1.033694	1	0.994789	0.989539
Low	P_u	S5	S4	S7	S9	S10	S8	S11	S1	S6	S3	S2
		1.081	1.06	1.05	1.025	1.021	1.019	1.011	1	0.993	0.976	0.95
	E_u	S1	S5	S4	S3	S2	S9	S7	S11	S6	S8	S10
		1	0.971	0.965	0.962	0.96	0.942	0.941	0.934	0.933	0.931	0.922
	V	S7	S5	S10	S4	S8	S9	S11	S6	S3	S1	S2
		1.056331	1.055123	1.052319	1.048068	1.046194	1.043125	1.040404	1.031653	1.00725	1	0.994778
Average	V	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
		1	0.990025	0.987975	1.149284	1.095628	1.048581	1.065154	1.044963	1.041242	1.051287	1.034353

As expected from the previous, one-dimensional simulations, the global transition strategy values are situated between the Narrow Body and Wide Body values. It is clear, that transitions are needed and late transitions are preferred. Rooting from the benefits for the Narrow Body case for S4, this appears to bare the highest strategy value. However, for the Wide Body simulations, S4 was one of the worst strategies. So, in order to decide on the best strategy, it is preferable to account for the scale of the variations that is different across dimensions, then decide aided by Table 10. Likewise, strategy the variations have been normalized with respect to the difference between greatest and lowest strategy value in each dimension.

This way an equal comparison benchmark can be constructed. This normalization yields the following percent strategy values:

Table 11 – Normalized multi-dimensional transitions strategy values

Narrow	**Average**	$\underline{V}$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
			0.00%	54.30%	25.44%	32.96%	45.14%	94.12%	72.15%	99.59%	90.01%	100.00%	80.69%
Wide	**Average**	$\underline{V}$	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
			0.00%	4.60%	6.55%	100.00%	69.76%	35.45%	46.76%	31.85%	38.29%	30.27%	37.61%
Global	**Average**	$\underline{V}$	0	0.15802	0.129113	0.57415	0.561148	0.577661	0.580821	0.563212	0.587061	0.55016	0.550861

From Table 11 clearly emerges which are the best transition options, and the findings are on par with our predictions by consulting the previous strategy value tables and scenario winner tables.

When considered decoupled from fuel prices, FOLLOW LATE (S7, S9) strategies have the greatest value, with INDUSTRY REFORM (S10, S11) strategies closely behind. If a new technology transition is for consideration in the near future (SOON strategies), then the option for Airbus is to start the innovation with Boeing keeping his BAU (S4) scenario or following (S6).

c. Implications

Figure 5 summarizes all simulation results. The normalized strategy value is represented for all simulation cases and all fuel price scenarios.

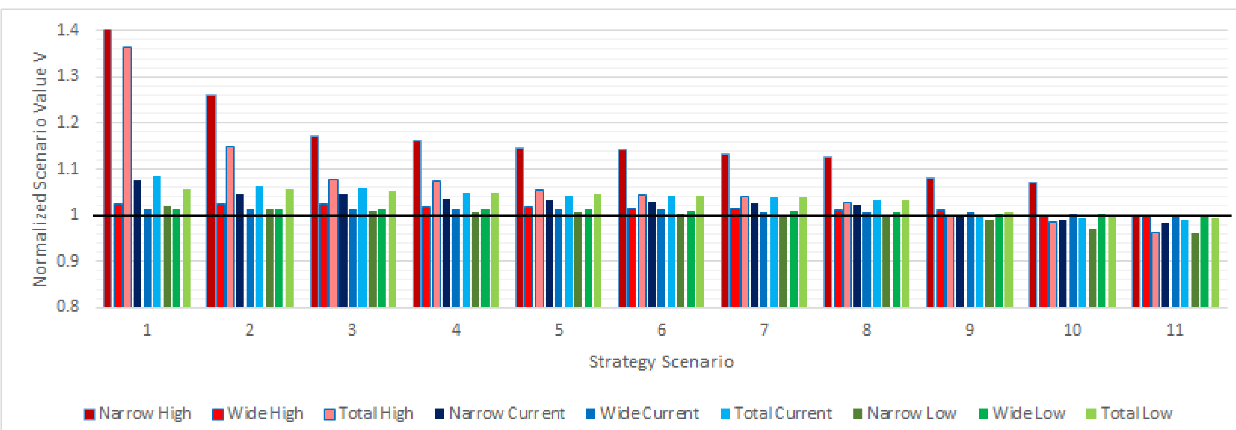

Figure 5 – Simulation results summary

It can be seen that the maximum improvement potential is in the Narrow Body market, especially for the case of high fuel prices. Also, if the fuel prices stay at today's levels or lower, the current development strategies (BAU) have a higher value than other innovating transition options.

Figure 6 presents a summary of all simulation runs, displaying the strategies by normalized cumulative profits and normalized cumulative emissions.

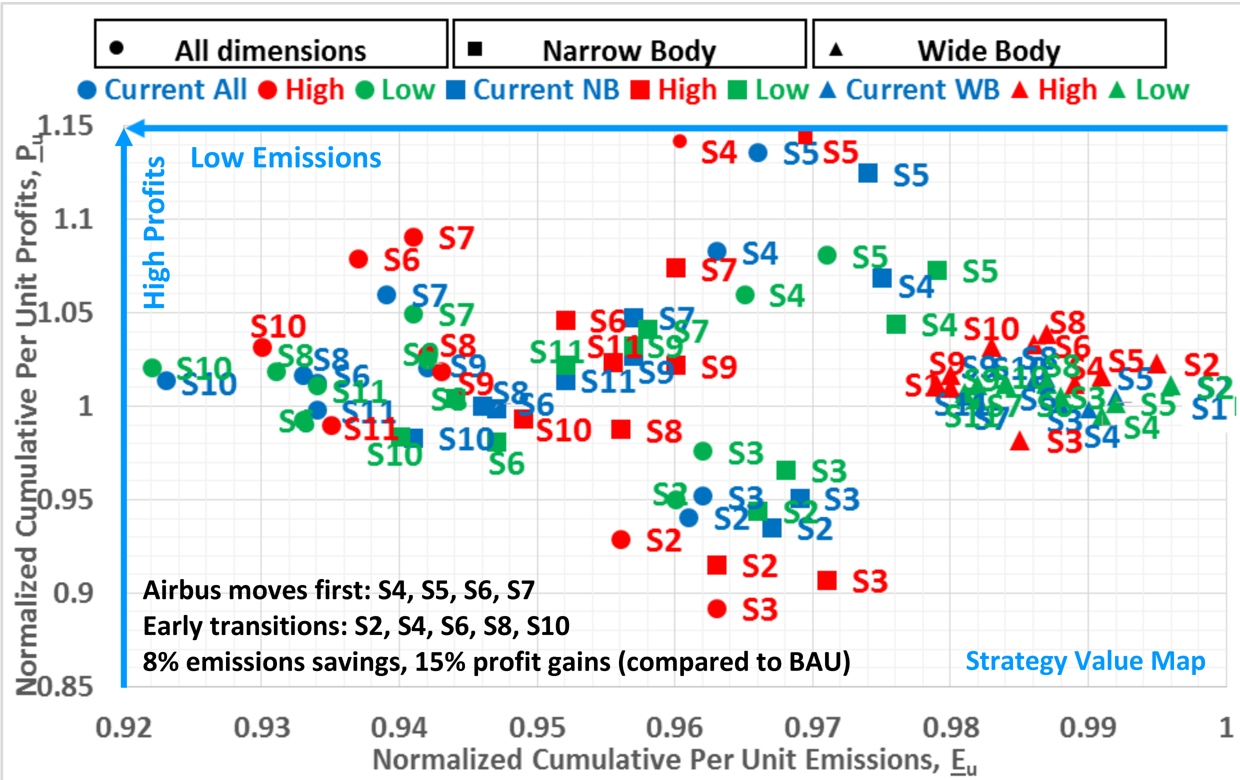

Figure 6 – Summary strategy distribution map

On Figure 6 we are looking for data points in the top left corner of the map, featuring high-profit – low-emission strategies. We can observe that the strategies are concentrated around a vertical and a horizontal axis, meaning that they are either economically or environmentally beneficial, the combination of both is hard to achieve. It is also easily observable that the scale of the Wide Body transitions' strategy values is much smaller than that of the Narrow Bodies'.

The summary strategy value map presents that emission reduction of up to 8% can be achieved compared to the base (*BAU*) case, i.e. opting for *radical* innovation instead of following *incremental*. Early transition strategies S6, S8, S10 lead to the highest emissions reductions. Profit gains of up to 15% can be realized, when only Airbus innovates either soon or late (S4, S5). Good compromise strategies are the follow strategies (S6, S7, S8, S9), but with no clear better option, with Airbus moving first resulting in higher profits, but with Boeing moving first resulting in higher emissions reductions.

4. Conclusions

The commercial air transportation system has been consistently growing at a rate faster than the background global economic growth, achieved through the development of a tightly coupled ecosystem of airlines, aircraft manufacturers, airport operators, regulators and the traveling public and influenced by the exogenous but still coupled impact of fuel prices and economic growth. However, as fuel prices and economic growth remain highly volatile, the aviation industry will be greatly affected and possible innovation strategies have to be developed, analyzed and their values clearly quantified in order for it to transition into an economically sustainable state. As air transportation accounts for ≈2.8% of global CO2 emissions (Raper, 2009), reduction of greenhouse gas emissions are also important for the aviation industry and are among the top priorities of the main aircraft manufacturers.

Possible transition options have been identified, on par with ongoing research in field and the Global Aviation Industry Dynamic Transition (GAIDT) system dynamic model was developed for strategy assessment. The model exhibits advanced features (modularity, extensibility, autocalibration), some considered unique in system dynamics, such a dynamic module structure or compatibility with other simulation modeling techniques. For easier use, a visual user interface has also been developed for the GAIDT model.

In order to assess the value of the different strategies investigated and decide between options, a composite indicator $\bar{V}$ (normalized strategy value) that combines the economic and environmental benefits of different strategies has been created and used throughout the analysis.

Then strategy assessment has been conducted through a sensitivity analysis with the GAIDT model. This has been carried out separately for one-dimensional (Narrow Body and Wide Body) and multi-dimensional changes. In all cases, the strategy values compared to the Business as Usual (BAU) strategy (where aircraft manufacturers keep their current development strategies and release the currently planned aircraft at the currently planned time in the future) have been quantified and analyzed. The entire analysis has been carried out for 3 different fuel price scenarios, *High*, *Current* and *Low*. The winners between the manufacturers of the transition strategies have also been identified.

It has been found that the strategy values will highly depend on the fuel prices. However, if the fuel prices continue to rise, making any kind of innovation is beneficial. When decoupled from fuel prices, it has been found that late transition options (innovation in 2030, BAU strategy until then) are preferred. It has also been found that in most of the cases when one manufacturers decides to innovate and the other manufacturers follow with a delay, the first-movers will have an advantage.

We have found that radical innovation is more beneficial both when looked from the innovators perspective in a competitive market, as well as for the industry as whole. Yet, the industry does not seem to be in harmony with this, with innovation in commercial air transportation being a very slow and incremental process, with new aircraft rollouts occurring decades apart and not bringing very substantial improvements over previous incarnations. One might wonder what is the possible explanation for this, which leads us to our analysis' assumptions.

One of the most volatile parts of the study, but also a very crucial one is estimating the cost of research and development of new aircraft. Since the new technology is not entirely known or even forecastable, estimating further costs is highly uncertain. Also, other, ancillary technologies which can impact its development or costs might become available, about which there is also high uncertainty. Moreover, it is very challenging to decipher the research and development costs of past aircraft development programs of aircraft manufacturers, as the data is highly protected by them. This has been extensively studied by Norris (2005) (2009).

In order to properly quantify the impact of technology innovation, its penetration and assess the value of different transition options, further research is needed. Dynamics of market with 3 major manufacturers could also be investigated. Furthermore, the airline (and lessor) competition dynamics need to be also modeled for a complete industry assessment. The GAIDT model has been developed with this intent in mind and the option to expand and incorporate dynamics airlines has been preserved. Also, shifting the bias between the climate and economy factors in the normalized strategy value indicator can lead to different results, depending on the players', stakeholders' and regulators' purposes.

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6. Appendixes and other supporting materials

When creating the GAIDT model described in the attached paper, AnyLogic 6 software has been used.

Furthermore, a live working version of the model can be accessed at the following link: http://tiny.cc/sdconf2013csala_model (It requires JAVA to run).

For your convenience, I all of the appendices can be found in the cloud folder http://tiny.cc/sdconf2013csala_files.

Here is a list of files that have been included in the cloud folder:

Nr.	Name	Type	Size (MB)
1.	Appendix 1	*.pdf, Portable Document Format file	1.04
2.	Appendix 2	*.pdf, Portable Document Format	1.11
3.	Appendix 3	*.xlsm, Macro Enabled Excel 2007 file	0.35
4.	Appendix 4	*.pdf, Portable Document Format file	1.31
5.	Appendix 5	*.pdf, Portable Document Format file	1.26
6.	Appendix 6	*.pdf, Portable Document Format file	1.25