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System-Level Aviation Emissions Solutions Through Operations and Dynamic Scheduling Systems

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Abstract- **Due to the vast growth of aviation industry systems and its relation to the transportation infrastructure and design, a significant environmental impact was incurred in the shape of Green House Gases (GHG) emissions into the atmosphere(stratospheric levels), which ultimately participate in the devastating effects of global warming. This literature review paper discusses the system level solutions that the aviation industry and academic stakeholders have provided to tackle this issue. These solutions have been classified into two categories: High-level operational system solutions and low-level Aviation Dynamic Scheduling Systems. Finally, the paper concludes the gaps between industry and academia in this perspective, and the critical venues that academia and industry have not tapped on yet, which are critical to the advancement of this field.**

INTRODUCTION

The increasingly problematic effects of global warming have controlled media, industry and academia in the past two decades. It is estimated that civil commercial aircrafts generates around 700 million tons of carbon dioxide (Co2) annually , which equates to around 2% of global Co2 emissions worldwide , this figure will increase to 3% by 2050 (IATA 2008) . These emissions will be exacerbated by the rapid growth of aviation industry, which is estimated at 5% per year (IATA 2010). Aviation stakeholders in terms of industry actors such as International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO), and academics have embarked on studying tools, systems, and policies to curb the increasing affect of these emissions, using multiple frameworks, such as Biofuels, enhanced designs of aircrafts, significant change and make-over in conceptualizing , planning and designing of transportation infrastructure and its sub-systems, to align their business goals with environmental constraints. These modifications indeed have and will have a positive impact on the environment; however, the amount of funding and timeline of implementation makes it prohibitive or futile for the shorter term, a great example of such situation is the new Next Generation Air Transportation System (NextGen) implementation by the US government (FAA) (Lovegren and Hansman 2011)

From this perspective, this paper does not tackle the above-mentioned means, but rather high level operational solutions and low level scheduling systems solutions to tackle the issue of environmental impact of aviation. As known, environmental impact is a very broad term and could have many meanings. For this reason and for quantification reasons, we chose the variable fuel consumption to quantify the environment framework in our analysis. In essence, fuel consumption is positively correlated to waste and emission levels and therefore, is an object of interest and focus. This paper surveys how aviation stakeholders proposed systems operational and scheduling solutions to emissions in respect to this variable. Afterwards, it directs the attention to the advantages and disadvantages of some important solutions covering both extreme abstraction levels (high and low). At the end, this paper suggests some venues and loopholes in the research literature regarding this field of study.

PROBLEM FORMATION

Shedding the light on the relationship between aviation system's efficiency and CO2 and green house gases' emissions can be a daunting task. A resounding question in this domain is how can we increase the efficiency of aviation systems - from a systems perspective - while reducing the greenhouse emissions?

Another important facet to this problem is to analyze aviation scheduling and operations in a multi-objective framework, where safety and scalability are of great concern. This problem can be modeled from different aspects covering different functional and physical entities. However, the measure that we are going to depend on is the rate of emissions that is related to each process in the aviation systems. Therefore, many processes will not be taken into consideration as they do not have significant impact on the emissions related to aviation systems.

The domains that are covered within the scope of this paper are: Aviation Operational Side, Air Traffic Management , component design , information flow between aviation subsystems. It is worth mentioning that these domains are highly inter-related, and optimization of a process in one domain can directly affect another.

1. High level Systems Operational solutions

This paper will focus more on the operational perspective rather than the physical modifications needed to enhance the fuel efficiency in airplanes. As suggested by Kar, Bonnefoy, & Hansman,
(2010), aircraft modifications have less impact on aircraft's fuel performance in the near term compared to operational improvements .One of the most important issues in aviation operational systems is air congestion. Due to the sheer amount of traffic at the international airports such Chicago ORD or Heathrow airports, aircrafts have to wait for a long time in the air flying

at different altitudes – to avoid collision – with different speeds and different separation distances in order to wait for their turn to land. This procedure forces the aircrafts to burn extra fuel in the air, and therefore, further polluting it. This problem could have many solutions that are related to infrastructure and airport designs, but since these activities are not related to operational activities, they will not be considered in our analysis.

A) Aviation Decision Support Systems

What is important in this aspect is the decision support systems that can be developed in order to increase the bandwidth of these airports, while maintaining safety and reduction of $CO2$ emissions in the air. These decision-support systems can be manifested in different forms: such as automation tools that rely upon advanced traffic congestion and conflict algorithm that can optimize the use of the different capacities of the airports (Kumar, Undated). However, it seems that most of the industrial publications such as of the Air Transport Aviation Group and International Air Transport Association tend to de-emphasize the need to develop a problem solving methodology such as TRIZ to reconcile the often conflicting objectives of the aviation systems i.e. environmental concerns and safety.

From the 1970s, there has been a great deal of development in decision support systems that can minimize fuel usage and thus less emissions . For example, the development of flight-planning and flight management systems that allows the flight crew to make use of the following:

- Wind conditions: for example riding wind flows can help aircrafts reduce the thrust needed to resist the opposite air flow
- Digitally calculate fuel usage needed accurately
- Smart usage of flight levels especially on the approach.
- Smart usage of flight vertical and horizontal speed. Speed is highly correlated with fuel consumption and thus emissions (Federal Aviation Administration , 2012)
- The center of gravity for aircrafts is of utmost importance to fuel consumption and other related environment parameters. For example, if we place less weight on the front of the aircraft compared to the back will improve fuel consumption up till 0.5% (ATAG, 210). Simulation models can be used before they load the aircraft, in order to figure out the best configuration for an aircraft reconciling the fuel consumption constraints with safety and operating costs. To come back, aviation-related decision support systems integrate simulation and other tools to intelligently calculate the center of gravity for aircrafts (Giliam , 1984)

The emphasis on this aspect is primarily done in academic articles, for example Kroo and Antoine (2005) focused in their research on developing multi-objective genetic algorithm to determine some of the variables configuration at one aviation system conceptual design phase such as emission levels, operating costs and noise levels. This does not stand out in any industrial publications; only to show the chasm between academia and industry in this field.

Other aviation-related decision-making systems can be intelligently used by aviation systems actors: flight crew, Air Navigation Service Providers (ANSPs) and/or Air Traffic Controllers (ATCs) to enhance aircrafts fuel efficiency. In this sub-section, we will delve into the ANSP sector and investigate what sorts of related decision-making systems can be utilized.

Air Navigation Service Providers: "Is an organisation that provides the service of managing the aircraft in flight or on the manoeuvering area of, and which is the legitimate holder of that responsibility."(EUROCONTROL EATM Glossary of Terms). One of the most important systems that this country-specific organization leads are the earlier Area Navigation (RNAV), Required Navigation Performance (RNP) and the recent Performance Based Navigation (PBN) . The emergence of these systems have helped the airlines to stop basing their navigation on the ground-based navigation aid – VHF,VOR, DME, and/or NDB - with all of the disadvantages that came with it (Boeing n.d). To elaborate more, before the emergence of RNAV aircrafts had to pass from one relative ground-based position to another, thus preventing the aircraft from taking direct flight paths. This increased the distance travelled which logically increased the flying time, and therefore, the burnt fuel.

According to Boeing (n.d) RNAV and its components have revolutionized navigation by removing the need to overfly ground bases, and established the concept of fix points, which are longtitude and latitude points that define the flight paths. There are special navaids that help the ANSPs to define the relative position of the aircraft to this particular fix point. Therefore, less separation is needed between flight paths, also aircrafts may choose more paths to travel on , which can reduce the time of the flight and can better exploit the weather conditions to decrease the engine power usage(such as riding the wind streams) .

Moreover, RNP provides satellite vertical guidance to navigation by permitting the aircraft to "accurately navigate along flexible, linear surfaces rather than point-to-point as does a standard GPS" (Marasa 2010, 2) . The consequence of such is opening new routes, whereby fuel efficiency is radically enhanced (Boeing, n.d) . It is worth mentioning the RNAV is meant to tackle the en-route phase of flight whereas; RNP tackles the approach and landing phases of flights. Furthermore, the emergence of RNP also made the procedure of Continuous Descent Approach (CDA) possible, which radically cuts the length of flight path by using the most efficient and shortest one to runway; this means less green house gas emissions and less noise, thus less pollution. Before inventing the CDA procedure, aircrafts used to use stair-step descents using a long landing pattern. The CDA proved its efficiency in reducing system-wide emissions in many airlines, for example in Alaska Airlines , The CDA approaches to Seattle-Tacoma airport led to the decrease of 2.1 million gallons per year of fuel consumption, which means 22,000 tons of green house gases less emissions (ClimateBiz Staff 2009).

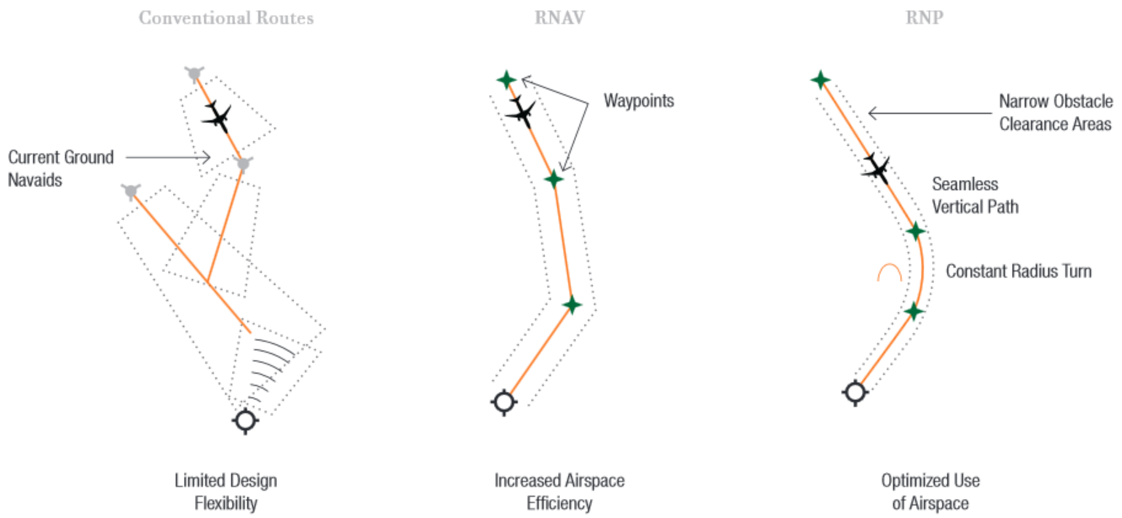

Figure 1: The enhancements that RNAV and RNP Systems brought to navigation . Courtesy to AEROMAGAZINE.

Figure 2: The vertical guidance that RNP System brought to Flight Crew, which has significant impact on fuel efficiency and safety. Courtesy to NAV Canada.

Of course with introducing new systems and new technologies, the problem of integration and interoperability surfaces when the system is being implemented. The implementation of RNP systems across countries and ANSPs were done inconsistently and lacked common framework for interoperability which hampered the harmonization process of air traffic management across countries (Boeing n.d). International aviation organizations and stakeholders such as ICAO and IATA found it difficult to establish a conceptual framework to standardize the processes and procedures regarding the RNP.

This gave rise to PBN (performance-based navigation) system, which encompasses the specifications and the conceptualizations of both RNAV and RNP systems , which will provide a general framework for design and implementation of flight path systems that are completely automated . This will enhance and ease landings queuing systems, the design of different airspaces by ANSPs and others, and better organization of air traffic flow. The advantages of such system are:

1) Rendering aircraft navigation system technology-independent of the ground equipment when conducting approach and landing flight phases (Marasa 2010). ➔ More available efficient routes (ICAO 2007)

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2) Radically reduce the need for communications with ground base such as the ATCs (FAA 2011)
3) Providing direct routes between busy cities (FAA 2011) ➔ Reduction of delays, increased system throughput, predictability of air traffic system flow states (FAA 2011)
4) Tackles the obstacle of changing terrain data (dynamic data), as it has constant feed of satellite information (ICAO 2007).

The International Air Transport Association expects that the successful implementation of PBN system will decrease CO2 emissions by 13 million tonnes per year (ICAO 2007).

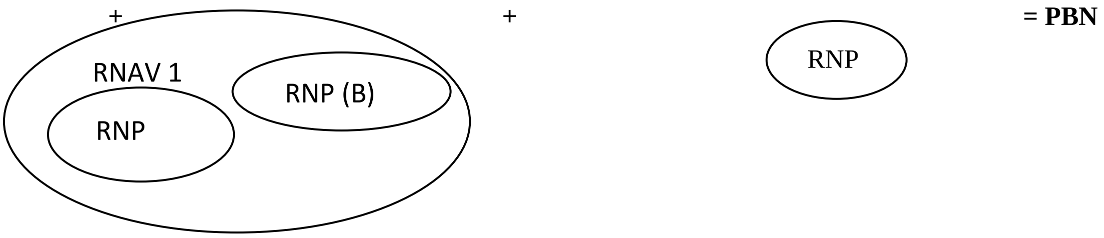

Figure 3: RNAV Systems, and its RNP subcomponent with the problem of under lapping

B) Sub – optimal Aircraft Path trajectories

Another important facet is the design of aircraft path networks using code-sharing partnerships with other airlines mixed with novel techniques for Yield Management. The objective of these actions are to maximize the fuel efficiency per aircraft seat thus fuel efficiency. Within these new paths airlines can use different fleet types of aircrafts that better suite the path's length and weather condition. A good example of that is using smaller twin-engine aircrafts in operations that are relatively longer. This will radically decrease the fuel usage per kilometer (a portion of the operating cost) while reducing emissions and noise incurred by bigger aircrafts (ATAG 2010). This facet of the problem has an upward trend in terms of emphasis from a research perspective , as according to ATAG (Air Transport Action Group) inefficient routes account for more than 8% of all aviation fuel waste . This drew many scholars and aviation stakeholders to study this problem and to produce many solutions that are on a system level not component or sub-system levels (FAA 2012). The majority of such literature in this topic focuses on the following variables to determine the optimal path for aircrafts:

1) Optimal Altitude: when discussing the altitude at which aircrafts can fly optimally (decreasing the fuel consumption and thus CO2 emissions), few system-wide variables have to be taken into consideration. These variables are heavily depending on aerodynamics systems and laws. The weight of the aircraft plays a significant role in determining the performance of the plane at the flying attitude according to the lift-drag ratio and the related density of the aircraft. The higher the aircraft climb, the less air density is. Now, by looking at the continuous system state of the aircraft system , we can infer that its weight is decreasing as the flight goes on (due to the burning of the fuel). The following aerodynamics law is important in this context :

$$C_L = \frac{L}{q_\infty S} \qquad q_\infty = \frac{1}{2}\rho V_\infty^{\ 2}$$

Expression 1: shows the equations for the lift-to-drag ratio and the free stream dynamic pressure

C_L = Lift Coefficient (lift-to-drag-ratio)
L: lift of the aircraft
S: Reference area (constant)
q: free stream dynamic pressure
ρ = air density
V = airspeed

When the weight of the aircraft decrease, the more lift there is. This means that as the flight progresses, the dynamic pressure should be decreased in order to keep lift coefficient at its optimum value (C_L). Decreasing the dynamic pressure will take place only when the air density decreases, which can happen when the aircraft climbs to higher altitudes.
To summarize, in order to radically enhance the altitude profile of each flight, there should be a slow and gradual climb of the aircraft as the time goes by on the flight (Lovegren and Hansman, 2011). This result has been accentuated by quite few researches done on the field of aircraft fuel efficiency and aerodynamic laws. Other factors that directly affect the aircraft weight, such as the amount of the cargo on the airplane, where the cargo is situated (center of gravity), number of passengers and their location. Using the aforementioned variables as an input to a simulation model, before the aircraft takes off, will help us decide the weight limitation dictated by the passengers, cargo and fuel configurations and systems state changes over the flight. This weight

limitation and configuration analysis can help in producing a fine-tuned altitude profile for aircraft systems in real time . Out of the simulation and modeling surveyed, the work of Jie and Zhongke(2008) systems modeling and simulation may be considered as a benchmark for such analysis , even though its objective was not for fuel-efficiency but rather cargo airdrop; however, the strength of his work lies in using rigorous scientific laws to feed into the model, such as Euler angle relation of rigid body and Newton second law of motion.

2) Optimal Speed: As we know aircrafts have different chronological phases (On ground, Departure and Climb , En route cruise, Descent and Approach , and On ground) . In this section we will only focus on En route cruise speeds because it is the longest phase of the aforementioned. One of the most important variables to look at when the Air Traffic Controllers decide the optimal speed at the cursing altitude (36,000 to 38,000 feet above ground) is the Cost Index (CI) related to fuel-optimal aircraft state, because it models the critical balance between the time cost of the flight and the operating cost of the fuel , which is heavily used as an important input variable in aviation efficiency simulation system models such as of NASA LaRC simulation models (Brian and Moreilli, 2011) . The relationship between the flight time and fuel cost is rather tricky when looked at from fuel efficiency perspective at a system-wide high level (which always the case because with more granularity, variables tend to be more conflated). the figure below describe the relationship:

Flying faster ➔ More Fuel Consumed ➔ Less travel time ➔ Less maintenance ➔ Less Labour
➔ Aircraft more Available (Lovegren and Hansman, 2011)

The trick here is to understand the subjectivity of system perspectives and its effect on our calculations, which are not tackled often by aviation industry stakeholders publications, in my opinion. If we are looking at the system operation from the environmental perspective , we should conduct a high-level cost-benefit analysis between the amount of fuel consumed as a result of flying faster to the fuel consumed as a result of flying for less time and based on which decide the optimal speed . However, this calculation is very simplistic because of many reasons, most notably is that aircraft systems are complex system of systems that interface with other systems, such as the airport systems, and/or other aircraft system, therefore, a particular speed inferred from the previous cost-benefit analysis could render the aircraft state less safe and/or violating its flight envelope. Therefore, in this aspect there is a need to develop multi-objective solution methodology taking into account the importance of the systems of systems perspective.

3) Atmospheric Data: Like we discussed in the previous sections, atmospheric data can be a double-edge sword in the fight against high fuel consumption and aviation systems operating costs. We mentioned that understanding air flows can help aircrafts in riding wind flows and thus less thrust (engine power) needed for aircraft movement. This approach is used extensively in the route between Heathrow and New York. However, severe high altitude cells of bad weather can exist and therefore, present a danger to the operations of the plane. This requires the plane to divert to another altitude, path and/or to another speed . Much of these problems are related to turbulence and rough air, and as a result incur delays and over/speed to make up the time lost due to diversions. The calculation behind taking a decision whether to divert or not is very complicated and has to factor a lot of variables related to the complex system of aircrafts, the most important of which are (according to Lovegren and Hansman, 2011)

A) Passenger comfort (Difficult to quantify from a systems human factors perspective according to Mercer 1975)
B) Safety Considerations and parameters: depends on the risk architecture used in the different development phases of the aircraft operations and trajectories)
C) Congestion at the destination airport
D) Congestion at the specific flight path different altitudes.
E) The delay incurred at the destination airport which is hard to predict unless using advanced Queing theory applications.

The literature indicates that there is a state of consensus over these variables mentioned above . Some other publications advocate for the use of the levels negative externalities such as pollution when faced with the decision of diverting or not, such as of IATA, FAA and Eurocontrol.

2. Low level Aviation Dynamic Scheduling Systems:

The recent trend of research focuses on the approach and landing phases of the aircraft flight to apply novel algorithms to schedule flight arrivals (optimal landing sequence and landing time as output variables) in way that preserves the consumption of fuel, therefore incur less CO_2 and green house gases emissions. There is a rare if not any research done on the topic of scheduling aircraft while they are in the en-route phase, a venue that I think could be of significant importance.

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Finding an optimal sequence of aircrafts to land at particular runway that satisfies the different operational constraints, such as the minimum separation time (due to Wake Vortex) and horizontal and vertical distance between aircrafts, the time between two arrivals, type of aircrafts, wake turbulence and others, is an NP-hard problem (Axelsson 2000). This may drastically affect the efficiency of the optimization methods suggested by the different literature in this respect. Furthermore, if such an optimization method exists, the dynamic state of the scheduling system is very non-deterministic due to the potential emergence of new operational constraints on a daily basis, in the fast paced environment of the air traffic management, supported by the air traffic controllers (ATCs) system entity (Hinchey et all 2010).

summarize the literature, there are many heuristics-based dynamic scheduling systems for aircrafts that are attempting to land at a particular airport tackling the ALP problem (Aircraft Landing Problem), each made for certain objectives that tackles certain functional requirements. Two of which are primary and deserve to be mentioned in this paper, because they are widely used and have a direct affect on fuel efficiency, and thus CO2 and greenhouse emissions.

A) First-Come-First-Served (FCFS) System

First, we introduce the First-Come-First-Served (FCFS) system whereby the whole system depends on the ETA variable (Estimated Time of Arrival). The calculation of such variable is done by Trajectory Synthesizer complex system located at the Center Boundary. The simplicity of conceptualizing and implementing FCFS system makes it the preferable choice for airlines, on top of the low workload and interfacing needed with the ground ATC system: The whole idea is that aircrafts are organized to land according to their respective scheduled arrival time. If we would like to look at this system from environmental perspective, we conclude that it produces more than needed spacing requirement, due to lack of factoring of other critical requirements such as aircraft type and wake turbulence. This is translated to more emissions with more fuel consumption that needed.

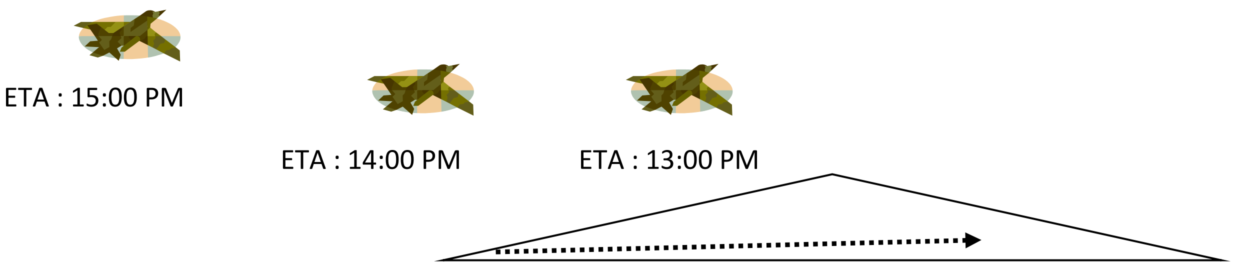

Figure 4: FCFS aircraft landings on a runway

The other disadvantage to this system is that system's state predictability is very low. The arrival time for aircraft can be affected by many other variables (e.g. Wake Vortex) and therefore, once one aircraft have a problem, the propagation of the error can be significant through the system (lack of agility). Lastly, the average delay of passengers, increasing system throughput and backlog are negative characteristics of such system (Mesgarpour et all n.d) . These issues have a significant impact on any CO2 cap the airline or the ANSP is trying to enforce, as there is no way to ensure the conformance of each aircraft to reduction in fuel consumption, due to the system's lack of predictability.

B) Constrained Position Shifting (CPS)

The second system is the Constrained Position Shifting (CPS) which was first coined by Dear 1976, aimed to preempt "unfair" delay of certain aircrafts in queue ready for landing, by introducing the concept of Maximum Position Shift (MPS) denoted by K. In a regular ALP problem, an aircraft cannot be shifted (backward or forward) in the queue more than K positions . The smallest the K is, the closer it is to the FCFS scheduling system.

However, the problem that arises with such scheduling scheme is that since K is pre-defined amount, it does not leave much room for tolerance shall an incident occurred with one aircraft which renders it unable land from the first time (e.g. unstabilized approach). This paved to the way to a new variant of MPS which is called Relative Position Shifting (RPS) , which factors the distance to runway as input to decide the K value.

The CPS scheduling system has many advantages over the FCFS system in terms of safety, system throughput, average passenger delays and most importantly environmental externalities. Further enhancement to the CPS system include the strict use of RPS instead MPS , not permitting either RPS or MPS to be more than 3 in a k-CPS environment (Lee and Balakrishnan 2008).

More advantages in the CPS system are that it gives more flexibility to the ATCs to vector incoming planes, also increases the predictability of the landing process in terms of time and efforts needed. These advantages can play a pivotal role in the environmental emissions of aircrafts: More flexibility means less wasted separation times, and maximized used of the runway throughput. By a simple linear equation, this can be translated into less fuel consumption and by our first assumption, less greenhouse emissions.

The disadvantage for the CPS system is that it requires a lot more interfacing and communications between the aircraft communication systems and the ATCs' systems (Hinchey et all 2010). This can increase the load on ATCs and pilots, and thus requires more Crew Resource Management (CRM) training on a system level. From human factors perspective, the more human communications exists, the bigger probability for error.

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C) Tackling the complexity of scheduling systems and its environmental impact

The FCFS and CPS are both simplified version of reality because their corresponding models represents a static offline environment (Mesgarpour et all n.d.); However, in reality there should be a model that re-evaluates the knowledge base as the planes arrive, feeding the data in this model and then produce the results .Moreover, FCFS and CPS do not accommodate the existence of uncertainty and complexity in the landing process of planes. The complexity comes as a natural result of continuous growth of aviation industry coupled with limited infrastructure of aviation such as airports, runways, ATCs…etc.

Many tools have been extensively researched to tackle the above mentioned issues and to attempt to model more dynamically the ALP problem, which can be classified into two:

1) Optimization –related tools such as Mixed Integer Programming (MIP), Travel Salesman Problem (TSP), and Queuing Theory.
2) Search techniques such as Dynamic Programming, Branch-and-Bound, Branch-and-Price, Genetic Algorithms, and Ant Colony Optimization etc (Mesgarpour et all)

As we mentioned before, since the ALP in real time is an NP-hard problem given all of the operational constraints, which may affect the efficiency of the optimization methods, the focus of research was more geared toward the search techniques, especially Dynamic Programming and Genetic Algorithm.

To tailor it to environmental impact, the environmental objectives that are emphasized most when using these search techniques was to reduce the fuel costs. There is a clear lack of emphasis and/or use of other critical variables such as fuel consumption or most importantly green house gas emissions levels. Other variables (objectives) that are emphasized on through the literature that may have a relationship to fuel consumption are:

1) Delay costs
2) Airborne time
3) Airborne delays which are defined as the deviation of actual landing time from estimated landing time in a dynamic environment.
4) Runway throughput
5) Earliness and lateness of aircraft landing (minimizing)
6) Difference between the estimated landing time and the actual landing time (minizing).

In essence, the flight phases that these variables tackle are the descent and landing phases. In our analysis, we could not spot significant research that uses optimization or search techniques that tackles the speed and elevation of aircrafts in the en-route phase, which is the longest phase in any flight.

Conclusions and Further Work

It is clear that there is upward trend in research volume in terms of high-level operational systems solutions and low-level scheduling systems for aviation-related emissions in the past two decades, which goes in parallel with the increasing effects of global warming. However, more integration efforts have to take place in order to ensure the harmonization and interoperability of all of these systems, resembling the example of PBN encompassing the RNAV and RNPs sub-systems, and the example of NextGen System of Systems (SoS) in the United States of America. Moreover, other enhancement can be to incorporate rigorous scientific laws into various simulation models, in order to decide the operational constraints during the en-route phase such as the optimal altitude and speed.

The use of advanced operations research tools, such as optimization (Mixed Integer Programming), Genetic Algorithms and Ant Colony Optimization is highly under-used in the high level operational system solutions for aircraft emissions, however, abundantly researched in the low level scheduling systems (only within academic circles), with no significant implementation in the industry, only to show the gap between academic institutions and industry stakeholders in aviation such as IATA and ICAO. Few reasons as to why there is no significant implementation of these operations research tools in industry could be related to lack of incorporation of industry stakeholders requirements in the models developed, relaxation of critical operational constraints , and/or assumptions related to static environment rather than a dynamic fast paced one. These variables can be an interesting area of research which is widely under-investigated. The aforementioned reasons necessitate the industry to resort to simple scheduling systems such as CPS and FCFS (both have advantages and disadvantages clearly stated in the previous sections), which results in an increase in more fuel consumption and thus upward trend in environmental emissions.

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