Transportation Research Part C 121 (2020) 102872

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

An eco-friendly aircraft taxiing approach with collision and conflict avoidance

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ARTICLE INFO

Keywords:
Airport operations
Greenhouse gas emission
Collision and conflict-free taxiing
MILP

ABSTRACT

Among several crucial objectives of the air transportation system, minimization of fuel consumption has a profound impact on the economic viability of airline companies and their effect on the environment. Given that many large airports around the world are located in the heart of residential areas such as Chicago's O'Hare, New York's JFK, and Montreal's Pierre Elliott Trudeau, the Greenhouse Gas Emissions (GGE) released by aircraft flying through such urban airports directly impacts the health of nearby residents. In this paper, we propose a hybrid taxiing solution to reduce the airports' impact on GGE where part of the taxiing operations is handled by tow-trucks powered by renewable energy while some other aircraft continue using their engines to complete taxiing. The main contribution of the work presented in this paper is the inclusion of collision of conflict avoidance in the formulation of taxiing operations planning with an objective to minimize fuel consumption and to maximize the desired service quality. The conflict-free taxing operations planning model is tested on Montreal's Pierre Elliott Trudeau airport. Furthermore, the detailed economic analysis on the adoption of electric-powered tow-trucks is provided.

1. Introduction

Demand for civil aviation has been steadily increasing for many decades. According to the International Civil Aviation Organization (ICAO), passenger traffic has grown an average of 5.2% per year between 1995 and 2012. ICAO estimates demand for aviation to continue to increase at an annual rate of 4.6% until 2032 and 4.5% until 2042 (ICAO, 2016). Despite its current contribution to global GGE being estimated to be only around 3–6%, increasing demand on air travel suggests that, in near future, aviation's contribution to the global GGE will increase significantly. In recent years, both automobile and rail industry have introduced several alternative power sources with potentials to reduce their CO_2 emission. Unlike for the automobile and rail industry, advances in technology is not promising a breakthrough alternative power-source for the aviation industry. Both increasing demand on air-travelling and lack of alternatives for the fossil fuel-powered engines will only increase the contribution of aviation industry for the CO_2 emission.

The objective of airline companies is to transport passengers or cargo from an origin to destination with minimum deviations from the schedule, safely and comfortably while sustaining a profitable business. In the literature, the Air Traffic Management (ATM) problem is mostly tackled as an operations research problem with an objective to minimize flight delays. Outputs of such mathematical models include departure times from origins (gates or runways), set of air sectors to be visited during flight, and the arrival and

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https://doi.org/10.1016/j.trc.2020.102872
Received 13 December 2019; Received in revised form 6 September 2020; Accepted 27 October 2020

An Eco-Friendly Aircraft Taxiing Approach with Collision and Conflict Avoidance

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Abstract

Among several crucial objectives of the air transportation system, minimization of fuel consumption has a profound impact on the economic viability of airline companies and their effect on the environment. Given that many large airports around the world are located in the heart of residential areas such as Chicago's O'Hare, New York's JFK, and Montreal's Pierre Elliott Trudeau, the Greenhouse Gas Emissions (GGE) released by aircraft flying through such urban airports directly impacts the health of nearby residents. In this paper, we propose a hybrid taxiing solution to reduce the airports' impact on GGE where part of the taxiing operations is handled by tow-trucks powered by renewable energy while some other aircraft continue using their engines to complete taxiing. The main contribution of the work presented in this paper is the inclusion of collision of conflict avoidance in the formulation of taxiing operations planning with an objective to minimize fuel consumption and to maximize the desired service quality. The conflict-free taxing operations planning model is tested on Montreal's Pierre Elliott Trudeau airport. Furthermore, the detailed economic analysis on the adoption of electric-powered tow-trucks is provided.

Keywords: Airport operations; Greenhouse gas emission; collision and conflict-free taxiing; MILP.

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1. Introduction

Demand for civil aviation has been steadily increasing for many decades. According to the International Civil Aviation Organization (ICAO), passenger traffic has grown an average of 5.2% per year between 1995 and 2012. ICAO estimates demand for aviation to continue to increase at an annual rate of 4.6% until 2032 and 4.5% until 2042 (ICAO, 2016). Despite its current contribution to global GGE being estimated to be only around 3-6%, increasing demand on air travel suggests that, in near future, aviation's contribution to the global GGE will increase significantly. In recent years, both automobile and rail industry have introduced several alternative power sources with potentials to reduce their CO_2 emission. Unlike for the automobile and rail industry, advances in technology is not promising a breakthrough alternative power-source for the aviation industry. Both increasing demand on air-travelling and lack of alternatives for the fossil fuel-powered engines will only increase the contribution of aviation industry for the CO_2 emission.

The objective of airline companies is to transport passengers or cargo from an origin to destination with minimum deviations from the schedule, safely and comfortably while sustaining a profitable business. In the literature, the Air Traffic Management (ATM) problem is mostly tackled as an operations research problem with an objective to minimize flight delays. Outputs of such mathematical models include departure times from origins (gates or runways), set of air sectors to be visited during flight, and the arrival and departure times at these air-sectors. At the operation level on the other hand, the foremost important objective of the Air Traffic Controllers (ATCOs) is the management of collision and conflict-free air traffic. Consequently, significant deviations from the suggested flights plans (outcome of ATM models) are frequently observed in practice.

While flight safety will continue to be the foremost important aspect of air transportation, both as a significant cost item for airline companies and as an important contributor to the global GGE (estimated to be between 3-6% (Unger, 2011)), the fuel consumption problem is a noteworthy challenge for the civil aviation industry. It has been observed that operations management has the potential to improve airlines' fuel consumption (Zou et al., 2014). However, the fuel consumption management issue has not been tackled as an integral part of the general ATM models in the literature. It is mostly seen as a technology issue where aircraft manufacturers and researchers focus on the design and development of more fuel-efficient engines, and lighter and more aerodynamic aircraft bodies. In addition, for the technological advances and choice of materials used to manufacture aircraft, flight operation conditions such as speed, wind impact, take-off load, flight-altitude, and congestion management significantly impact on the fuel consumption performance of aircraft (Ryerson 2011). In particular, the congestion both in the air and on the ground considerably impact the unplanned fuel usage. According to Zou et al. (2014), those airlines focus on operational excellence with an objective to minimize fuel consumption burn by up to 25-42% less fuel than those less efficient carriers. In their works both Khadilhar (2012) and Nikoleris (2011) provide aircraft fuel-burn rate on ground as 7% in average based on the data available in ICAO. However, Nikoleris (2011) argues that the "true ground idle" fuel consumption rate is about 4%. According to Gebicki (2018), a Boeing 747 consumes more than one ton of fuel in 15 minutes taxiing during take-off which is comparable to the cumulative fuel consumption of 1600 passenger-cars in 15 minutes drive during rush-hour traffic (average 23 km/hr) (Kan, 2018).Given that the fuel cost is the second largest cost-item for airline companies and GGE is one of the greatest challenges for the humanity, any reduction on fuel consumption while still sustaining an economical viable business is welcomed by the airline companies and the society.

In this paper, we introduce an alternative taxiing method to reduce fuel consumption during taxiing. In another words, this paper discusses the scheduling and operation of electric-powered tow-trucks similar to the TaxiBot (Lukic et al., 2018) to enable collision and conflict-free taxiing operations. Airline companies have been experimenting with either electric-powered tow-trucks (Lufthansa with TaxiBot), or on-board systems such as the WheelTug, to eliminate fuel usage at airports. The work of Lukic et al. (2018) provides a more comprehensive review of the current state of the electrification of taxiing operations. In this paper we introduce a Mixed Integer-Linear Programming (MILP) model for operating electric-powered tow-trucks to provide taxiing services for airline companies. The output of the proposed MILP includes the assignment of tow-trucks to aircraft, pick-up time, drop-off time and the set of taxiways to complete the taxing operations. The main contribution of this paper is its capability of incorporating collision and conflict avoidance as part of the taxing operations planning while using electric-powered tow-trucks. To the authors' knowledge, the research presented in this paper is the first of its kind.

The remainder of the paper is organized as follows. In Section 2, a brief literature review is provided. In Section 3, the formulation of the MILP model for handling the proposed hybrid taxiing operations management system is discussed. Sample cases are solved and discussed in section 4. Finally, in Section 5, conclusions are provided.

2. Literature Review

Climate change is one of the greatest challenges of our time. Scientific communities predominantly agree (more than 97% of the published works) that human activities are the main cause for the rapid changes on climate around the globe (Cook, 2016). GGE from human activities such as manufacturing, household heating, transportation and farming are found to be the leading causes for climate change. While several different sources contribute to the GGE globally, according to World Health Organization (WHO), the transportation industry accounts for more than 23% of all carbon dioxide (CO_2) production in the world. With the increasing globalization, existence of complex supply chain networks and increasing desire to travel around the world, the demand for various transportation mediums from personal cars to large container ships will continue to play a significant role in human lives for the foreseeable future. Based on these realities, both researchers and manufacturers of transportation vehicles have been focusing on designing and developing more efficient and less polluting technologies to mitigate the transportation industry's impact on the climate change.

Electrification and automation of transportation vehicles have gained enormous attention in recent years. While electrification has become a viable option for auto, rail and (to some extend) trucking industry, such a breakthrough has yet to be realised for the aerospace industry. According to UN's Intergovernmental Panel on Climate Change, air-transportation constitutes 3.5% of all greenhouse produced in the world. A study made for UK further suggests that, aviation industry contributes to 6% of all greenhouse gas produced in UK (Chapman, 2007). Due to increasing demand on air-transportation and lack of technological breakthroughs to mitigate from carbon-based fuel sources, the contribution of air transportation for the GGE will continue to increase significantly (Kousoulidou, 2016).

Aircraft engine emissions account for about 70% CO_2 and slightly less than 30% H_2O. Other emissions such as nitrogen oxides, carbon monoxide, oxides sulfur or unburned fuel constitute less than 1% (Wey and Lee, 2017; Aviation & Emissions, 2015). Given that aircraft may burn up to 7% of their fuel during taxiing (Khadilkar, 2012), CO_2 emitted on the ground not only negatively contributes to the global climate change, but also impacts the health of residents living near airports. In recent years, in order to offset the carbon emissions from airport operations, the electrification of airport operations concept has been proposed. The goal is to minimize or eliminate the usage of aircraft engines during taxiing. Two promising solutions (tow-trucks and on-board propulsion systems) have been discussed in the literature (Lukic et al., 2018; Re, 2012) and some experimental work has been tested by various airline companies (Lufthansa with TaxiBot and WheelTug with SunExpress and Kenya Airways). Most experts acknowledge the potentials of both technologies to reduce the aircraft GGE during taxiing. Yet, neither technology has been fully adopted by the industry. Towing options, both driverless and driver-on-board solutions, where aircraft are transported between runways and gates by electric-driven tow-trucks lead to slower taxiing operations. Coupling with an aircraft, towing and decoupling from the aircraft requires either non-value-added delays or slower flow. When a transporter is requested for the next assignment, depending on its current location, there is a possibility for idle travelling which causes significant efficiency losses. Onboard solutions such as WheelTugs are more efficient than towing technologies. Since they are embedded within the aircraft's landing gears, they are not causing delays due to coupling and decoupling. However, on-board push systems add permanent weight on an aircraft not only during taxiing, but also during the flight. Consequently, aircraft carry and burn extra fuel to compensate for the additional weight of the on-board propulsion systems.

In general the airport operations management problem has been well studied in the literature as gate scheduling (Dorndorf, 2007, Capa, 2015), runway scheduling (Idris, 1998, Clare, 2011, Sama, 2017) and ground delay management problems (Odoni, 1987 and Navazio, 2007). In the work of Jacquillat and Odoni (2018) it was stated that airport capacity, operations management and the flight scheduling are the three major factors impacting on the airport performance. In their study, Idris et al. (1998) showed that under normal flight conditions (weather or safety issues are not a concern) most delays are the results of uneven distribution of flights throughout a day. The study they conducted in Boston's Logan International Airport shows that most delays occur during the busy periods (morning and afternoon) where the demand for airport resources (runways, taxiways and gates) is near the available capacity. Their study further concludes that 70% of airport delays are associated with the problems in "runway systems". While the data analyzed for their study was the summary of pilots' voluntary reports and interpretations, all four airports compared in Idriss et al. (1998) reported similar statistics. Yet, the detailed explanation of the runway system suggests that original flight schedule and conflict between arriving and departing aircraft (separation distance to avoid wake vortex) are the major causes for the inefficiencies in runway systems.

In order to introduce more efficient runway management strategies, Pujet et al. (2000) studied the departure process using a queuing model. Their simulation studies enable them to define several control strategies which in theory show potentials to improve runway utilization, reduce delays, cost, and the environmental impact of airports. However, their study did not consider the interaction between individual airplanes., rather they focused on the average performances. Later, Zografoz et al. (2017) introduced a slot scheduling model to manage airport capacity. Once again, the airport capacity was defined based on the historical data; the interactions of airplanes on the ground and in the air were not considered in the determination of the airport's capacity.

The strategic or tactical planning objectives for an airport can only be achieved when the traffic conditions at other airports and in the airspace are included in the consideration throughout the planning horizon. The concept of Air Traffic Flow Management (ATFM) aims at scheduling flights between airports in such way that the capacity of airports and the air-sectors are not violated at all times while the delays in the entire system are minimized. Odoni was one of the earliest researchers to tackle the ATFM problem. In his earlier work, Odoni (1987) studied the ground holding problem in a single airport. Later, Vranas, Bertsimas and Odoni (1994) extended this work to a multi-airport ground holding problem which can be considered as the foundation for the future studies in ATFM. Bertsimas and Patterson (1998) formally introduced the concept of ATFM with an elegant but powerful formulation. Finally, Bertsimas, Lulli and Odoni (2011) introduced an improved modeling and solution technique to tackle the real-life-size problems (United States airspace in their case). These studies are important for strategic or tactical planning, yet in order to automate the airport surface movements and increase the efficiency, operational planning tools that explicitly handle interactions between all airplanes (on the ground and in the vicinity of the airport) are required.

Airport operations management deals with the effective usage of gates, runways and taxiways in order to provide an on-time service to all customers (passengers and airlines). ATFM on the other hand focuses on eliminating conflict during flight while minimizing delays. However, aircraft movements both within the airport and in air-sectors are controlled manually by the Air-Traffic Controllers (ATCOs) or airline employees (ramp managers). Due to high volume of traffic, ATCOs' focus mostly becomes a *safety-first* approach, and they frequently neglect the business and environmental objectives of air transportation. Since the current airport operations management models do not include strong collision and conflict avoidance features, ATOs intervention in order to avoid collision and conflict lead to significant deviations from the planned optimum solutions at the execution level. In the literature, collision and conflict avoidance are studied using simulation models (Jones et al., 2010; Alam, 2008) or technological solutions (Holland, 2013) independently from scheduling and taxiing operations. Sophisticated collision avoidance systems such as traffic-alert and collision avoidance systems (CAASD 200), collision avoidance radar able to discriminate objects (Swaer, 1997) and NASA's millimeter-wave radar forward system (Mewhinney, 1996) embedded in today's modern aircraft to help offsetting various human (pilotage or air traffic controller) and modeling (mathematical or computational) errors. In recent years, due to increasing popularity of Unmanned Aircraft Systems (UAS), various control models have been proposed for collision and conflict avoidance (Lin, 2017; Chen 2013 and Gunasinghe, 2018 and 2019) to safely separate UASs from other UASs and other commercial and military aircraft. Akgunduz (2017) introduced a set of constraints to tackle the collision problem during flight for both UASs and commercial aircraft. These conflict avoidance techniques that are currently available in the literature for air-traffic collision and conflict avoidance only focus on real-time decision support. Based on the current information from the surrounding traffic, current models either dispatch conflict warnings or suggest new collision free path plan. Since these collision avoidance tools and methods cannot be embedded in the air-traffic planning algorithms where airline and passengers' business and personal objectives are considered, most air-traffic control and airport operations management models produce poor results at the implementation level. Frequently, significant deviations from the planned flight plans are observed.

In this paper, we study the impact of electric-driven tow-truck usage to facilitate taxiing operations.

As mentioned earlier, one of the main shortcomings of the current air-traffic management tools is their lack of inclusion of collision and conflict avoidance as part of the overall airport operations management. While scheduling and sequencing models similar to Clare and Richards (2011) and Sama et al. (2017) covers conflict avoidance, the proposed formulations are either approximations or includes assumptions which cannot be valid at all times. In the context of airport operations, the outputs of mathematical models which are gate and runway sequencing and scheduling, and route plans for ground operations, cannot be executed as desired when collision and conflict avoidance is not imbedded in the model. The foremost important concern in aviation operations is the safety. Hence the developed mathematical models should not only be addressing the airline, airport, and customer expectations in terms of cost and on-time performance; but also, should include strong collision and conflict avoidance features.

3. Modeling of the hybrid taxiing operations

The objective of airport operations is to enable an uninterrupted traffic flow for both incoming and outgoing aircraft between runways and gates while all aircraft support services such as catering, fueling, luggage transportation and towing are provided effectively so that airport capacity is utilized at the highest level. Between runways and gates, aircraft follow physical taxiway lines. Collectively, physical lines that guide airplanes in today's airports generate a mesh network which is suitable to write a MILP model for the aircraft scheduling problem. In Figure 1, a mesh network that approximates the taxiing paths at Montreal's Pierre Elliott Trudeau International Airport is provided.

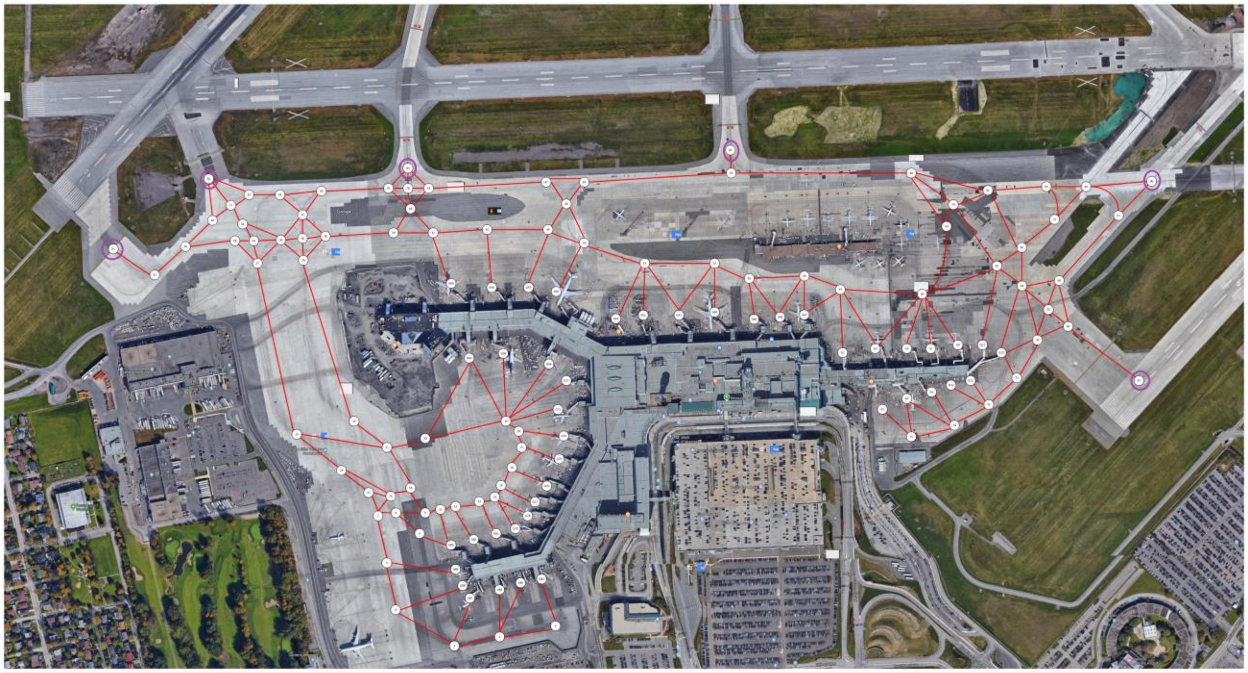

Figure 1: Montreal’s Pierre Elliott Trudeau International Airport Taxiing Network

As seen in Figure 1, using gate locations and taxiway lines on the ground, a mesh network between runways (three runways with 20 entrance/exit nodes, six of these nodes are visible in Figure 1) and gates (total 52 gates from Figure 1 – gates 17-34 are excluded) is established.

Let’s now describe the given network as a $G(N,V)$ where N is the set of nodes that represents gates, runways and intersection points and V is the set of links (connecting taxiways) between nodes. The objective of the taxiing operations is to move aircraft between runways and gates by following the consecutive nodes. In order for any mathematical model to be considered as a viable solution to the taxiing management problem, the following conditions should be included in the formulation.

- A gate can only be used by a single aircraft at a time:
  a. If an aircraft leaves or arrives at the gate after the scheduled departure or arrival time, a penalty will be imposed.
  b. If an aircraft arrives or departs at the runway after the planned departure or landing time, a penalty will be imposed.
- Aircraft can follow each other on the taxiways (on $v \in V$) while respecting the separation distances.
- No two aircraft can travel from opposite directions on a taxiway $(v \in V)$ at the same time

3.1 Assumptions

In order to formulate the taxiing operations problem in consideration with conflict and collision avoidance and towing-service between runways and gates options, the following assumptions were made:

i. As long as an aircraft is on the taxiway, it will not be in a collision situation with other aircraft travelling on different links.
ii. As long as aircraft respect the separation distances both on edges when they follow each other, and on nodes when they are transferred to the next taxiway, they will not be in a collision situation (separation distance between aircraft is aircraft-type specific).
iii. Traffic due to auxiliary services is ignored. It is assumed that they always clear the way for aircraft.
iv. When they are not serving an aircraft, tow-trucks movements are ignored. It is assumed that they always clear the way for aircraft.

3.2 Model parameters and decision variable

In the model, four different sets are introduced. Moreover, links arriving to a node and departing from a node are defined as sets.

Sets	
F	Set of aircraft
V	Set of tow-trucks
N	Set of nodes, including flight origin (ORG^f) and destination ($DEST^f$)
L	Set of links connecting nodes indexed as $l \in L$. When stated as $l(ij)$, it represents a link from $Node\ i$ to $Node\ j$
$L(n)^+$	Set of links arriving at node n
$L(n)^-$	Set of links leaving node n

In order to formulate the proposed taxiing operations, following parameters are considered.

Parameters	
$t_{EARLY\_LEAVE}^{f}$	Scheduled earliest departure from origin node
$t_{EARLY\_ARRIVE}^{f}$	Scheduled earliest arrival to destination node
$t_{LATE\_LEAVE}^{f}$	Scheduled latest departure time from origin node
$t_{LATE\_ARRIVE}^{f}$	Scheduled latest arrival to destination node
t_l^{SELF}	Travelling time on link l when aircraft self-taxi
t_l^{TOW}	Travelling time on link l when aircraft is towed
$t_{nn'}^{SP}$	Travelling time for the tow-truck when travelling alone between two nodes (n, n'). Assumed that, vehicles always travel on the shortest path between given nodes (n, n')
$\Delta^{ff'}$	The minimum separation distance between aircraft in terms of time
$LENGTH_l$	Link length in meters
$FUEL^f$	Fuel consumption per unit distance when f is not towed.
$COST_{FUEL}$	Unit fuel cost
$COST_{DELAYS}{}^f$	Penalty cost for deviation from schedule ($ per minute)
M	A large real number

The following decision variables are introduced in order to formulate the proposed taxiing operations management problem.

Decision Variables

$x_l^f = \begin{cases} 1, & if\ aircraft\ travels\ on\ link\ l \\ 0, & otherwise \end{cases}$	
$y_v^f = \begin{cases} 1, & if\ towing\ vehicle\ v\ is\ assigned\ to\ flight\ f \\ 0, & otherwise \end{cases}$	
$z_v^{ff'} = \begin{cases} 1, & if\ towing\ vehicle\ v\ is\ assigned\ to\ flight\ f\ immediatly\ after\ f' \\ 0, & otherwise \end{cases}$	
a_l^f	The time aircraft enters the $link\ l$
d_l^f	The time aircraft leaves the $link\ l$
$\varphi_l^{ff'} = \begin{cases} 1, & a_l^{f'} - a_l^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$	Collision and conflict avoidance control variable I
$\pi_l^{ff'} = \begin{cases} 1, & a_{l(ij)}^{f'} - d_{l(ji)}^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$	Collision and conflict avoidance control variable II
$\tau_n^{ff'} = \begin{cases} 1, & \sum_{l \in L(n)^+} d_l^{f'} - \sum_{l \in L(n)^+} d_l^f \geq \Delta^{ff'} \\ 0, & otherwise \end{cases}$	Collision and conflict avoidance control variable III
$DELAY^f$	Total delay time of aircraft = {Delay at Origin + Delay at Destination}
$DELAY\_ORIGIN^f$	Delay time to leave origin node
$DELAY\_DEST^f$	Delay at arriving to destination node
$TOTAL\_FUEL^f$	Total fuel consumed by flight f

3.3 Model:

In this section, the formulation of taxiing operations with the gate-to-runways/runways-to-gates towing option is introduced. First, the objective is defined. Next, routing and timing constrains are introduced. In the 3rd sub-section, we provide the set of constraints to handle collision and conflict. Finally, in the 4th sub-section, necessary constraints to provide gate-to-runways/runways-to-gates towing option are introduced.

a. Objective Function

The objective of the proposed mathematical model is to minimize fuel consumption during taxiing operations. The main business objective of both airline companies and airport management is to provide an on-time arrival and departure service for all customers. Therefore, in the formulation of objective function, deviations from the scheduled arrival and departure times are also penalized.

$$\min \sum_{f \in F} COST_{FUEL} * TOTAL\_FUEL^f + \sum_{f \in F} {COST_{DELAYS}}^f * DELAY^f \tag{1}$$

b. Routing constraints

In this section, the set of constraints that is required to navigate aircraft between gates and runways through taxiways is introduced.

$$\sum_{l \in L(ORG^f)^-} x_l^f = \sum_{l \in L(DEST^f)^+} x_l^f = 1 \qquad \forall f \in F \qquad (2)$$

$$\sum_{l \in L(n)^+} x_l^f = \sum_{k \in L(n)^-} x_k^f \qquad \forall f \in F;\ \forall n \in N \backslash \{ORG^f, DEST^f\} \qquad (3)$$

$$\sum_{l \in L(ORG^f)^-} a_l^f \geq t_{EARLY\_LEAVE}^f \qquad \forall f \in F \qquad (4)$$

$$\sum_{l \in L(DEST^f)^+} d_l^f \geq t_{EARLY\_ARRIVE}^f \qquad \forall f \in F \qquad (5)$$

$$d_l^f \geq a_l^f + t_l^{SELF}\left(x_l^f - \sum_{v \in V} y_v^f\right) + t_l^{TOW}\left(\sum_{v \in V} y_v^f\right) \qquad \forall f \in F;\ \forall l \in L \qquad (6)$$

$$\sum_{l \in L(n)^-} a_l^f \geq \sum_{l \in L(n)^+} d_l^f \qquad \forall f \in F;\ \forall n \in N \backslash \{ORG^f, DEST^f\} \qquad (7)$$

$$x_l^f * M \leq a_l^f \leq d_l^f \qquad \forall f \in F;\ \forall l \in L \qquad (8)$$

In Constraint 2, it is ensured that the aircraft leaves the origin and reaches its destination. Aircraft arriving to a transition node is forced to leave the node in Constraint 3. Constraints 4 and 5 coordinate the arrivals and departures according to given schedules. Travelling time on a link change depending on the nature of taxiing (self-powered vs tow-truck assigned navigation). Constraint 6 sets the bound for the earliest departure from a link. Arrival time at a consecutive link depends on the departure from the previous link (Constraint 7). Finally, in Constraint 8, it is ensured that arrival and departure times at a link is only possible if the aircraft visits the link.

c. Collision and conflict avoidance constraints

The foremost important consideration in aviation is safety. Both in the air and on the ground, air traffic controllers (ATCs) spend most of their time and energy separating aircraft from one another to ensure the safety of the public and the environment. Hence, in order for a decision support system to be a viable option to manage the air/ground traffic, the collision and conflict avoidance must be well incorporated. In our case, we modeled the collision and conflict avoidance to handle three important conditions during taxiing:

i) Two aircraft must sustain a separation distance when they travel on the same link at the same time

ii) Aircraft must sustain sufficient separation distances when they pass through intersections.

iii) Two aircraft cannot travel on the same link at the same time from opposite directions

If an aircraft enters a link earlier than another aircraft, than they should sustain a desirable separation distance ($\Delta^{ff'}$) from each other both at the time of their entrance to a link $\left(a_l^{f'} - a_l^f \geq \Delta^{ff'}\right)$ and at the time of their exit from the link $\left(d_l^{f'} - d_l^f \geq \Delta^{ff'}\right)$. Constraints 9-12 ensure the separation of aircraft using the same link at the same direction.

The following set of constraints are considered for $\forall f, f' \in F: f \neq f', \forall l \in L$

$$a_l^{f'} \geq a_l^f + \Delta^{ff'} - \left(1 - \varphi_l^{ff'}\right)M - \left(2 - x_l^f - x_l^{f'}\right)M \tag{9}$$

$$a_l^f \geq a_l^{f'} + \Delta^{ff'} - \varphi_l^{ff'}M - \left(2 - x_l^f - x_l^{f'}\right)M \tag{10}$$

$$d_l^{f'} \geq d_l^f + \Delta^{ff'} - \left(1 - \varphi_l^{ff'}\right)M - \left(2 - x_l^f - x_l^{f'}\right)M \tag{11}$$

$$d_l^f \geq d_l^{f'} + \Delta^{ff'} - \varphi_l^{ff'}M - \left(2 - x_l^f - x_l^{f'}\right)M \tag{12}$$

When an aircraft reaches the same node from different links, possible collision is avoided by separating them from each other by $\Delta^{ff'}$amount of time by using the following set of constraints (Constraints 13 and 14). In this paper, the arrival time at a node is equal to the departure from a link where the end-node of this link is the node in consideration. For any $l \in L(n)^+$ if $\sum_{l \in L(n)^+} x_l^f = 1$ for both airplanes, we know that both airplanes travelled through the same node. Consequently, arrival of the leading airplane on the node ($\sum_{l \in L(n)^+} d_l^f$) must be earlier than the follower airplane by the required separation distance $\tau_l^{ff'}$.

The following set of constraints are considered for $\forall f, f' \in F: f \neq f', \forall n \in N$

$$\sum_{l \in L(n)^+} d_l^{f'} \geq \sum_{l \in L(n)^+} d_l^f + \Delta^{ff'} - \left(1 - \tau_l^{ff'}\right)M - \left(2 - \sum_{l \in L(n)^+} x_l^f - \sum_{l \in L(n)^+} x_l^{f'}\right)M \tag{13}$$

$$\sum_{l \in L(n)^+} d_l^f \geq \sum_{l \in L(n)^+} d_l^{f'} + \Delta^{ff'} - \tau_l^{ff'}M - \left(2 - \sum_{l \in L(n)^+} x_l^f - \sum_{l \in L(n)^+} x_l^{f'}\right)M \tag{14}$$

Finally, the collision and conflict-free taxiing operation is ensured by introducing the following set of constraints. Constraints 15 and 16 eliminate the possibility of traveling from opposite directions on the same link at the same time. The decision variable $\pi_l^{ff'} = 1$ if the aircraft f leaves the link l from node j before aircraft f' enters the link from node j.

The following set of constraints are considered for $\forall \mathrm{f}, \mathrm{f}' \in \mathrm{F}: \mathrm{f} \neq \mathrm{f}', \forall \mathrm{l} \in \mathrm{L}$

$$a_{l(ji)}^{f'} \geq d_{l(ij)}^{f} + \Delta^{ff'} - \left(1 - \pi_l^{ff'}\right) M - \left(2 - x_l^f - x_l^{f'}\right) M \quad (15)$$

$$d_{l(ji)}^{f} \geq a_{l(ij)}^{f'} + \Delta^{ff'} - \pi_l^{ff'} M - \left(2 - x_l^f - x_l^{f'}\right) M \quad (16)$$

d. Towing option

The main objective of the work presented in this paper is to design a collision and conflict-free taxiing operation with an objective to minimize the contribution of airports towards GGE. Once collisions and conflict avoidance is guaranteed, the operations research solutions to taxiing operations would significantly improve the traffic flow which ultimately helps airports to reduce their GGE. However, further GGE reduction is possible through electrification of airport operations. In recent years, alternative technologies have been proposed to reduce or eliminate aircraft engine usage during taxiing: electric-powered tow-trucks (TaxiBot, Lukic et al., 2018) and onboard aircraft electric drive systems (WheelTug, Postorino, 2017).

Today, tow-trucks only assist aircraft during push-back from gates. On the other hand, systems such as TaxiBot considers 100% coupling with the aircraft during the entire taxiing process between gates and runways. Such a system clearly requires a considerable number of additional tow-trucks in the system. On the other hand, systems such as WheelTug, require modification on current aircraft designs. Furthermore, fuel carried by the aircraft may be increased in order to offset the impact of additional weight of the WheelTug system which consequently causes more fuel usage during flight. In this paper, we evaluate the utilization of electric-driven tow-trucks during taxiing. The following set of constraints is introduced to handle the assignments of available tow-trucks on aircraft. Once a tow-truck is assigned to an aircraft, the entire taxiing operation is completed as a pair. Once the tow-truck is decoupled from aircraft, it is available for the next assignment.

Let us assume that there are V tow-trucks available in the system. All tow-trucks are introduced to airport operations from a dummy ENTRANCE node (N_{ENT}). At the end of the day, all tow-trucks are removed from the airport operations through a SINK node (N_{SINK}). In order to minimize delays due to lack of available tow-trucks, the model enables some aircraft to self-taxi. As shown in the objective function, the mathematical model aims at minimizing the cost associated with delays and fuel consumption. Consequently, when the delay cost offsets the fuel consumption cost, aircraft select the self-taxiing option. Given that smaller aircraft burn less fuel, when there is a competition for a tow-truck, the mathematical model assigns the tow-truck to a large (less fuel efficient) aircraft.

$$y_v^f \leq \sum_{f' \in F: f \neq f'} z_v^{f'f} + z_v^{N_{ENT}f} \qquad \forall f \in F;\ \forall v \in V \qquad (17)$$

$$y_v^f \leq \sum_{f' \in F: f \neq f'} z_v^{ff'} + z_v^{fN_{SINK}} \qquad \forall f \in F;\ \forall v \in V \qquad (18)$$

$$\sum_{f \in F} z_v^{N_{ENT}f} = \sum_{f \in F} z_v^{fN_{SINK}} \leq 1 \qquad \forall v \in V \qquad (19)$$

The constraint (20) is valid for $\forall f, f' \in F: f \neq f';\ \forall v \in V$

$$\sum_{l \in L(ORG^f)^-} a_l^f \geq \sum_{l \in L\left(DEST^{f'}\right)^+} d_l^{f'} + \left(z_v^{ff'} t^{SP}_{DEST^{f'}ORG^f}\right) - \left(1 - z_v^{ff'}\right) M \qquad (20)$$

Constraints (17) and (18) are formulated for managing the tow-truck assignments. A tow-truck can be assigned to an aircraft $\left(y_v^f = 1\right)$ either after completing the towing operation of another aircraft $\left(z_v^{f'f} = 1\right)$ or entering the system directly from the dummy node $\left(z_v^{N_{ENT}f} = 1\right)$. After serving to an aircraft, the tow-truck is either assigned to another aircraft $\left(z_v^{ff'} = 1\right)$ or leaves the system through the SINK node $\left(z_v^{fN_{SINK}} = 1\right)$. In Constraint (19), those tow-trucks used for taxiing operations are forced to enter the system through serving an aircraft and leave the system after serving to an aircraft.

In order for an aircraft to leave its origin (a gate or a runway node) with a tow-truck, the assigned tow-truck first must complete the previous task $\left(y_v^{f'}\right)$ and travel from the destination of f' $\left(DEST^{f'}\right)$ to the origin of f (ORG^f). The travelling time from $DEST^{f'}$ to ORG^f $\left(t^{SP}_{DEST^{f'}ORG^f}\right)$ is estimated by the shortest path between these two nodes and it is assumed that tow-trucks do not cause collision and conflict with aircraft while they travel alone. Consequently, the Constraint (20) is formulated.

e. Fuel consumption

The following set of constraints determine the fuel consumption and delay costs:

The fuel usage occurs when aircraft is self-taxiing ($Y_v^f = 0, \forall v \in V$). Constraint 21 determines the total amount of fuel used during taxiing by an aircraft.

$$TOTAL\_FUEL^f \geq \sum_{l \in L} FEUL^f * LENGTH_l * X_l^f - \left(1 - \sum_{v \in V} y_v^f\right) M \qquad \forall f \in F \qquad (21)$$

If an aircraft leaves the gate or the runway after its scheduled departure/arrival time, it is subject to a delay penalty. The following constraints determine the duration of delays if they occur.

$$\sum_{l \in L(ORG^f)^-} a_l^f - t_{LATE\_LEAVE}^f \leq DELAY\_ORIGIN^f \qquad \forall f \in F \qquad (22)$$

$$\sum_{l \in L(DEST^f)^+} d_l^f - t_{LATE\_ARRIVE}^f \leq DELAY\_DEST^f \qquad \forall f \in F \qquad (23)$$

$$DELAY\_ORIGIN^f + DELAY\_DEST^f \leq DELAYS^f \qquad \forall f \in F \qquad (24)$$

Consequently, the total cost, incurred due to fuel usage and delays, is formulated in the objective function (Constraint 1) with an objective to minimize the total cost of taxiing operations.

4. Results and Discussions

In order to test the capabilities of the proposed mathematical model, a network model, based on Montreal's Pierre Elliott Trudeau International Airport (YUL) was designed. A total of 52 gates were considered in the model. In order to provide access to 3 runways at the airport, 7 entrance locations were selected. Finally, 79 nodes were identified from the satellite image (Figure 1) of the airport to determine the taxiing network. Arrival and departure times of flights for a given day were pulled from the airport webpages.

Based on ICAO data concerning Montreal's YUL airport, 68% of aircraft are small size with less than 45,000 kg weight, and 32% are heavier aircraft. Below are the fuel consumption and emission statistics during taxiing operations for different types of aircraft (Table 1).

Table 1: Emission and fuel burn during taxiing statistics for different airplanes (ICAO, 2011)

		Emission(kg) during landing/takeoff			
Aircraft type	**Fuel burn (kg/min)**	**CO_2**	**NOx**	**CO**	**HC**
Boeing 767-300	29.66 (8.72 Gallon)	5610	28.19	14.47	1.19
Boeing 737-800	14.66 (4.31 Gallon)	2780	12.3	7.07	0.72
Airbus A320-200	12.83 (3.77 Gallon)	2440	9.01	6.19	0.57
CRJ-100ER	5.5 (1.94 Gallon)	1060	2.27	6.70	0.33

While all aircraft types differ from one another in terms of their fuel consumption patterns, based on the available data from Chati (2014), we categorised aircraft into three different groups and assumed that aircraft in the same group emit similar amounts of CO2. Accordingly, the information for 205 flights was extracted from Montreal's Pierre Elliott Trudeau International Airport webpages.

4.1 Complexity Analysis

The MILP model introduced in Section 3 is known to be an NP-Hard mathematical model. The proposed model is a synthesis of the well-known economic lot-size scheduling problem (Drexl, 1997; Raza, 2006) and vehicle routing problem with time-window (Solomon, 1987; Braekers, 2016). Moreover, the collision and conflict avoidance constraints further increase the computational complexity. For a taxiing operations planning problem that consists of 52 gates, 79 transitional nodes (taxiway intersections), two (2) runways and 205 flights, no feasible solution could be obtained by IBM ILOG CPLEX Optimization Studio 12.5.1.0 on a personnel computer with 64 bit operating system, 3.40 GHz Intel Core i7-2600 CPU and 16.0 GB RAM. Consequently, alternative solution techniques (schedule segmentation) have been explored.

4.2 Sequential Taxiing Operations Planning

Airlines determine their flight schedules based on several factors. The most important criterion is the demand. Next, the availability of resources such as the aircraft, pilots and flight attendances. Finally, the available capacity at the origin and destination airports and the airspace to execute the flight during the planned time frame. Once these conditions are satisfied, airlines prepare a flight schedule which follows a sequential order throughout a day (or a planning horizon). In this paper, flight schedules, as determined by the airlines, are considered as inputs to the model. While bottlenecks in the air or on the ground may impact the execution of these predetermined schedules, the excess capacity in the system would not change the predetermined schedules. This paper does not focus on the improvement of flight schedules. Consequently, a solution technique based on the sequential nature of the flight schedules is developed. The proposed sequential solution method, as a secondary benefit, can incorporate the schedule changes during the planning period. At the operation level, if an aircraft fails to follow the suggested route, the new route can be determined in the future solution sets without disrupting the routes already determined for other aircraft.

Let the flight set F be $F = \{f_1, f_2, \dots, f_F\}$ where arrivals and departures to/from an airport is indexed according to their scheduled arrival or departure times: $t^{f_i}_{EARLY_{LEAVE}(or\ DEPARTURE)} \leq t^{f_{i+1}}_{EARLY_{LEAVE}(or\ DEPARTURE)}$. Given that arrivals and departures are realized during the day sequentially according to their original schedules, flights are allocated in N groups according to their arrival and departure times as $F = \{F_1, F_2, \dots, F_N\}$ where F_j includes a subset of flights from F as $\left(F_j = \left\{f_i, f_{i+1}, \dots, f_{i+n_j}\right\}\right)$, and earliest flights in set F_{j+1} expected to enter the system later than the last flight in set F_j. Subsets of flights (n_j flights in each groups) are extracted from F based on the average arrivals observed within 10 minute intervals. The first departure is realized in the morning at 6 AM. Since all resources (taxiways, tow-trucks and runways) are free at 6 AM, earlier aircraft do not need to compete for resources. Later flights slowly start being affected by the limitations on resources. Finally at some point during the day, the airport reaches a steady state operation level and all arriving and departing aircraft start competing for limited resources (gates, runways, taxiways and tow-trucks). In the sequential solution strategy, the model is first solved for flights in F_1. A solution for a given flight (s^f) includes the path-plan $\left(x_l^f\right)$, arrival and departure times at each link $\left(a_l^f \text{ and } d_l^f\right)$, tow-truck assignment $\left(y_v^f\right)$ and next assignment for the tow-truck $\left(z_v^{ff'}\right)$. Hence $s^f = \left\{x_l^f, a_l^f, d_l^f\ \forall l \in L: x_l^f = 1;\ y_v^f\ \ \forall v \in V;\ z_v^{ff'}\ \ \forall v \in V, f' \in F\right\}$.

The outcome of the first solution is included in set $S_1 = \{s_1^1, s_1^2, \dots, s_1^{n_1}\}$ and is generated for $\forall f \in F_1$. In the consecutive step, flights in F_2 are included in the problem set and the new problem is solved for $\forall f \in F_2$ in consideration with the previous information from S_1. By the time flights in F_2 enter the system, some of the resources such as tow-trucks and taxiways are already allocated for aircraft in F_1. Therefore, the information available in S_1 is introduced in the second problem as constraints for flights in F_2. The flowchart below depicts the overall strategy implemented for the sequential solution method (Figure 2). While the proposed sequential solution method helps us to tackle the real-life-size problems, as a secondary benefit, it also enables decision makers to handle schedule changes (arrival and departure time changes). Those airplanes which cannot leave the gate or arrive to the airport before the latest arrival/departure time, are reconsidered in the future batches.

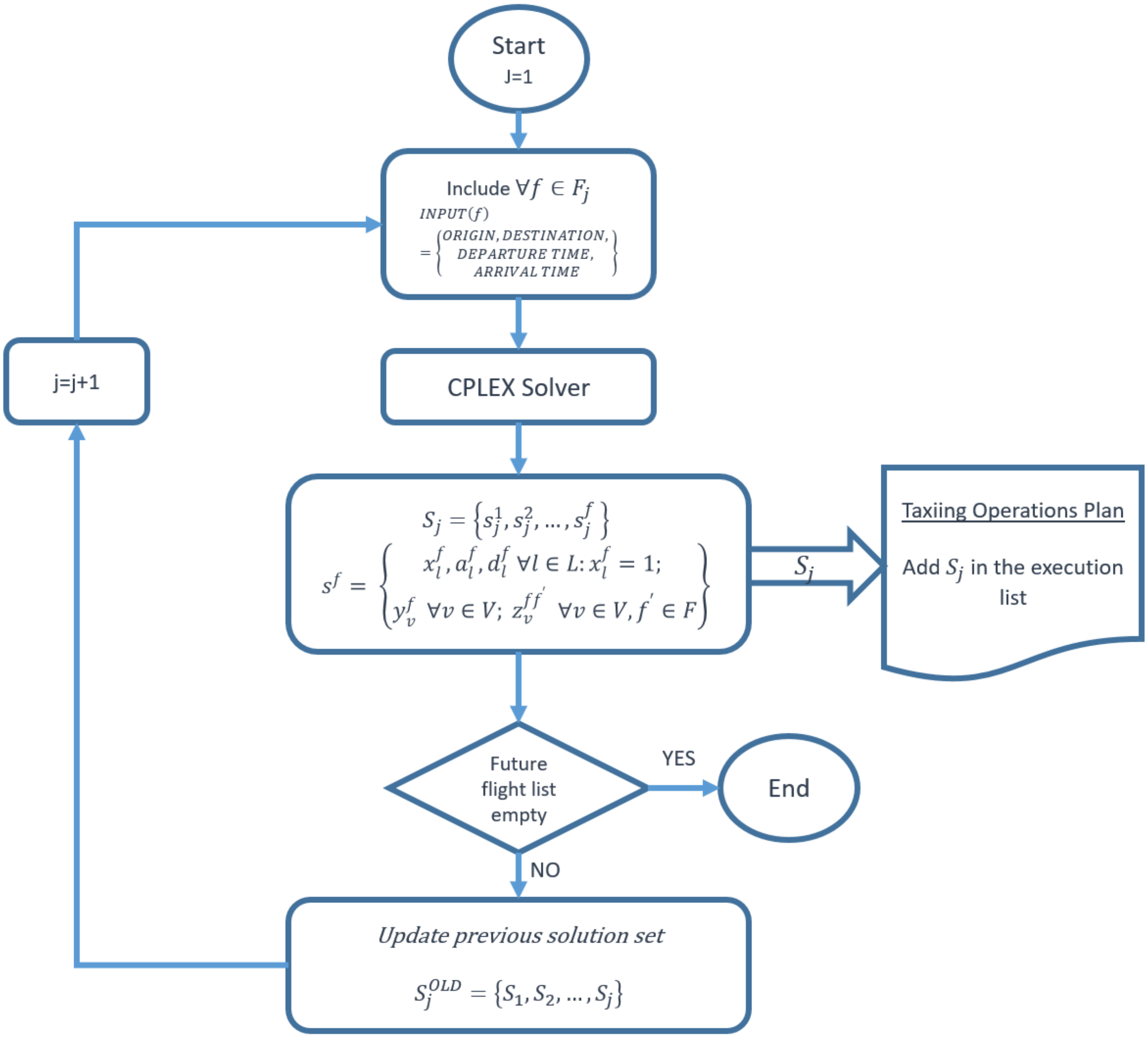

Figure 2: Sequential solution method

4.3 Results: Alternative scenarios and analysis

The main objective of the electrification of taxiing operations is to provide an environmentally friendly alternative to the current air-transportation practices without jeopardising flight safety and continue ensuring on-time arrival and departure performance. Our objective function is the minimization of cost that includes: i) tow-truck operating cost; ii) fuel consumption cost; and iii) delay cost.

Tow-truck operating cost: According to alibaba.com, the TK-QY400 aircraft tow-truck with 450-ton towing capacity is priced at USD $355,000 and TK-QY200 with 200-ton towing capacity is sold for USD $120,000. Both vehicles are powered by diesel engines. Given that the sale price of electric-powered cars are on average 20-30% higher than gas-powered options, we estimate an electric-powered aircraft-tow-truck to be marketed at $150,000 (QY200) and $400,000 (QY400). In recent years, self-driving options for passenger vehicles have gained enormous attention. Similarly, self-driving options for aircraft-tow-trucks will be a possibility in the near future. Given that the current technology is still being developed and the air-transportation industry requires additional guaranties (both as a safety measure and public assurance), in this paper we assume tow-trucks are operated by drivers. Airports are more active from 6 AM to 10 PM (see Figure 3 for airport activities during a day); hence we anticipate tow-trucks to be operational for 2 shifts per day. According to available information concerning the operation of these vehicles, we conclude that two operators (each costing $50,000/year salary + 50% benefits) are required to operate a single tow-truck. Given that airports operate 365 days, the average number of people required to operate a single tow-truck is four (4). Moreover, according to Hooper (2017), tow-trucks require $6.65/hr for maintenance and repairs and $3 for insurance ($154.40/day). Consequently, the operating cost for a single tow-truck is estimated to be $356,000/year. Assuming a 7-year depreciation period, the cost of operating a TK-QY200 is $378,000/year and a TK-QY400 is $414,000/year.

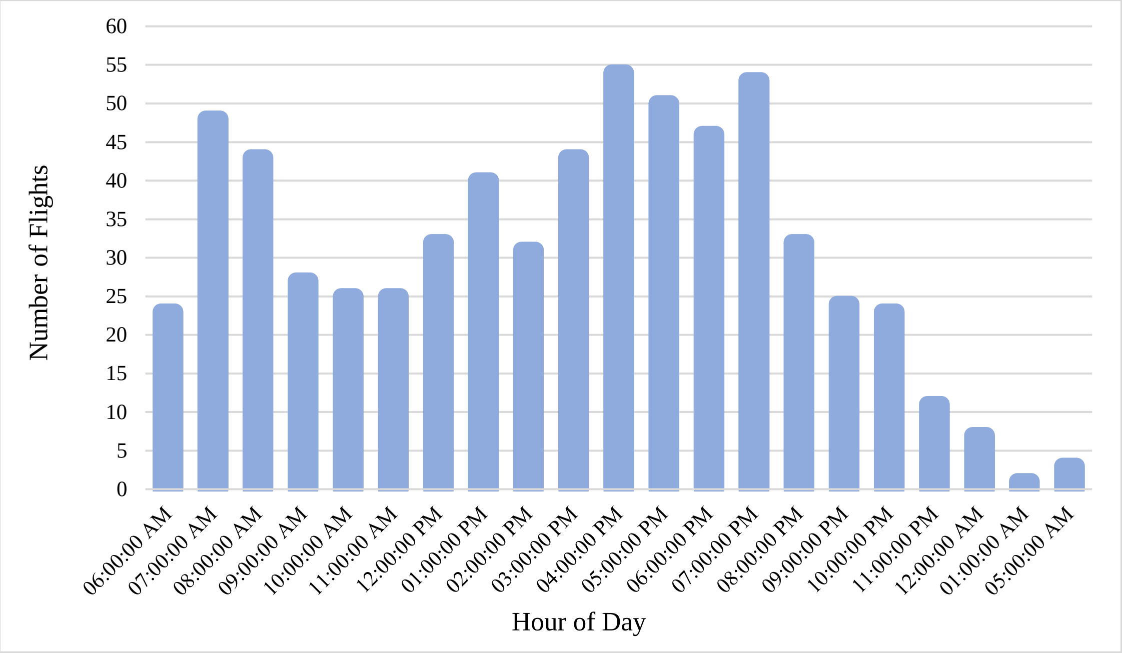

Figure 3: Frequency of arrivals and departures based on hourly intervals

Fuel cost during taxiing: In the mathematical model, it is assumed that an airplane does not consume any fuel during taxiing if the tow-truck is coupled. On the other hand, aircraft that complete their taxiing by using their engines would consume up to 8 gallons (large aircraft), 5 gallons (medium aircraft) and 2 gallons (small aircraft) for per minute taxiing (per minute fuel consumption rate is captured from Table 1 which presents samples from ICAO data). It should be noted that, these values are rough estimates. More precise fuel consumption rates for each aircraft, in theory can be identified based on the type of engine and the collected statistics from individual aircraft. In 2018, the average jet fuel cost was $2.50 in the US. The fuel consumption amount is calculate based on the speed and the distance travelled during taxiing. As mentioned earlier, we categorized aircraft based on their fuel consumption patterns in three groups: wide-body aircraft (WB); narrow-body (NB) aircraft; and regional jets (RJ). We estimate WB, NB and RJ aircraft to burn $27, $17 and $10 worth of fuel per minute respectively during taxiing. The impacts of stops and starts on fuel consumption are not considered. The proposed mathematical model eliminates the need for full stops at intersections, hence the impact of stops and starts on fuel consumption is minimal.

Cost of earliness and delays: According to Airlines for America, the per minute direct aircraft delay cost was $74.20 in 2018. In addition to the direct costs, delays also cause significant productivity losses for the airlines. Furthermore, various forms of congestion occur due to access delays throughout the network; consequently, this leads to over $28 billion US losses for the industry in the US (Airlines for America, 2018)

4.3.1 Case 1: All airplanes towed by a truck

We solved the aforementioned airport operations planning problem with an objective to tow all aircraft from gates to runways (or from runways to gates). First, we run the model for five (5) tow-trucks in the system. As seen in Figure 4, as the new flights enter the system, their waiting times (delays) considerably increase. Figure 4 clearly demonstrates that the system is not steady with five tow-trucks. Hence, we gradually increased the number of available tow-trucks in the system. As seen in Table 2, as the number of available trucks is increased, the number of delayed flights, delay time and consequently the total cost of delays are significantly reduced.

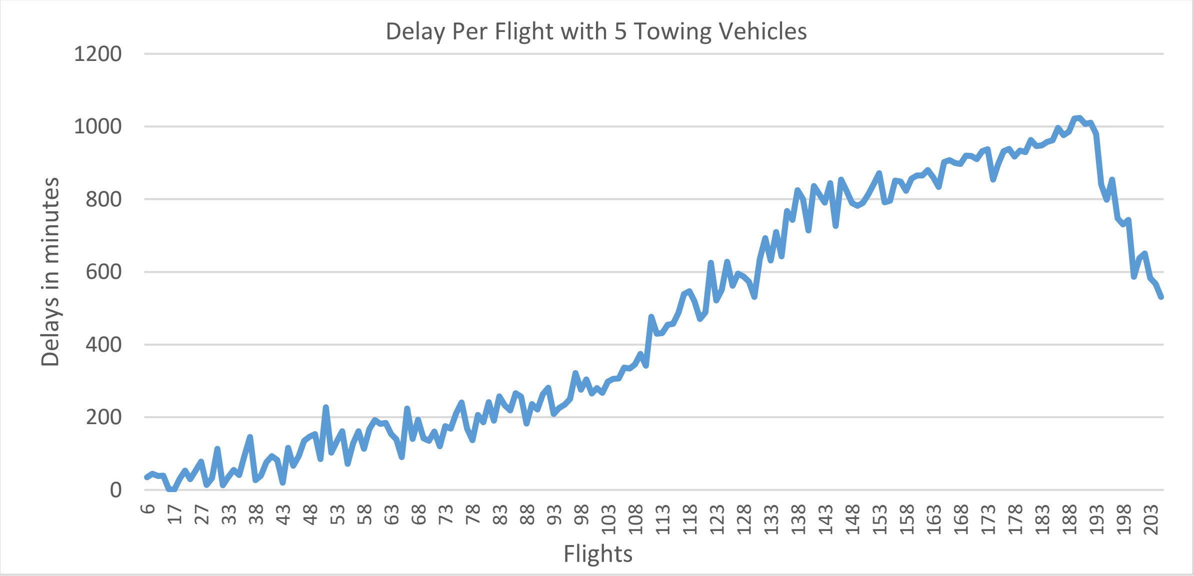

Figure 4: Delays for individual aircraft with five tow-trucks in the system

Table 2: Impact of the number of tow-truck in the system performance and the yearly cost

Number of tow-trucks	Number of workers	Purchase cost (7 years amortization)	Yearly Energy Cost ($0.12/kWh, 33 KWh/hr)	Yearly labor cost	Yearly Maintenance Cost	Total Delays per Day (in minutes)	Yearly delay cost (74$/min)	Total cost
5	20	$321,429	$112,128	$2,000,000	$282,875	88,174	$2,445,938,993	$2,448,655,424
6	24	$385,714	$134,554	$2,400,000	$339,450	45,857	$1,272,066,522	$1,275,326,240
7	28	$450,000	$156,979	$2,800,000	$396,025	24,079	$667,939,254	$671,742,259
8	32	$514,286	$179,405	$3,200,000	$452,600	12,139	$336,740,021	$341,086,312
9	36	$578,571	$201,830	$3,600,000	$509,175	9,273	$257,224,421	$262,113,997
10	40	$642,857	$224,256	$4,000,000	$565,750	5,170	$143,402,485	$148,835,348
12	48	$771,429	$269,107	$4,800,000	$678,900	1,507	$41,798,632	$48,318,068
15	60	$964,286	$336,384	$6,000,000	$848,625	477	$13,232,812	$21,382,107
18	72	$1,157,143	$403,661	$7,200,000	$1,018,350	145	$4,022,023	$13,801,176
20	80	$1,285,714	$448,512	$8,000,000	$1,131,500	87	$2,413,380	$13,279,106
21	84	$1,350,000	$470,938	$8,400,000	$1,188,075	35	$965,352	$12,374,365
22	88	$1,414,286	$493,363	$8,800,000	$1,244,650	30	$289,606	$12,241,905
24	96	$1,542,857	$538,214	$9,600,000	$1,357,800	18	$72,401	$13,111,273
26	104	$1,671,429	$583,066	$10,400,000	$1,470,950	7	$28,961	$14,154,405
30	120	$1,928,571	$672,768	$12,000,000	$1,697,250	3	$5,792	$16,304,382

While increasing the number of tow-trucks in the system decreases the delay costs and improves the airport operations performance, each additional tow-truck increases the operating costs. As seen in Table 2, the least expensive solution is obtained with 22 tow-trucks ($12,241,905/year).

4.3.2 Case 2: Hybrid option – Self-towing option when tow-truck is not available

In the second case, aircraft are given the self-towing option when tow-trucks are not available within a desirable time frame. When the model is tested with six tow-trucks out of 205 aircraft, 60 aircraft are selected to complete taxiing using their engines and the remaining 145 aircraft are towed by tow-trucks. Similar to Case 1 results, the cost of handling taxiing operations is decreased as the number of tow-trucks is increased; however, the impact of tow-trucks' increase on total cost became negative once 12 vehicles in the system is reached (Table 3). In Table 3, the cost of operating tow-trucks is calculated based on purchasing cost (7 years amortized), labour cost, energy consumption (electricity) and maintenance cost. Accordingly, it can be concluded that, for the problem described in this paper, taxiing operations of 205 airplanes can be optimally managed with 12 tow-trucks. While the proposed MILP model for the airport taxiing operation problem enables decision-makers to select the optimum number of tow-trucks to minimize the cost, it also gives an opportunity to study the impact of taxiing operations on the environment. Figure 5 summarizes the fuel usage information for all aircraft which were not assigned to a tow-truck. Moreover, with 12 tow-trucks in operations, for the described problem, the fuel consumption during taxiing is reduced by more than 80% in comparison to 6 tow-trucks in the system and over 95% when no tow-trucks is used.

Table 3: Impact of number of tow-trucks on yearly fuel consumption, delay and operating cost

Num. of tow-trucks	**Number of workers**	**Cost of operating tow-trucks**	**Travelling Time by Aircraft Engine (min)**	**Fuel consumption (gallons)**	**Fuel cost ($2.7/gallons)**	**Delays (min)**	**Yearly delay cost (74$/min)**	**Total Operating Cost**
0	0	0	2,520,322	12,223,564	$33,003,623	43,040	$3,184,936	$36,188,559
6	24	$3,259,718	639,743	3,102,753	$8,377,432	43,041	$3,185,010	$14,822,160
8	32	$4,346,291	455,795	2,210,606	$5,968,635	38,719	$2,865,172	$13,180,098
10	40	$5,432,863	264,990	1,285,202	$3,470,044	27,315	$2,021,292	$10,924,200
12	48	$6,519,436	123,005	596,574	$1,610,750	11,687	$864,850	$8,995,036
15	60	$8,149,295	36,526	177,149	$478,302	10,106	$747,846	$9,375,443
18	72	$9,779,154	31,532	152,932	$412,916	4,204	$311,061	$10,503,131
20	80	$10,865,726	23,886	115,845	$312,782	142	$10,510	$11,189,019

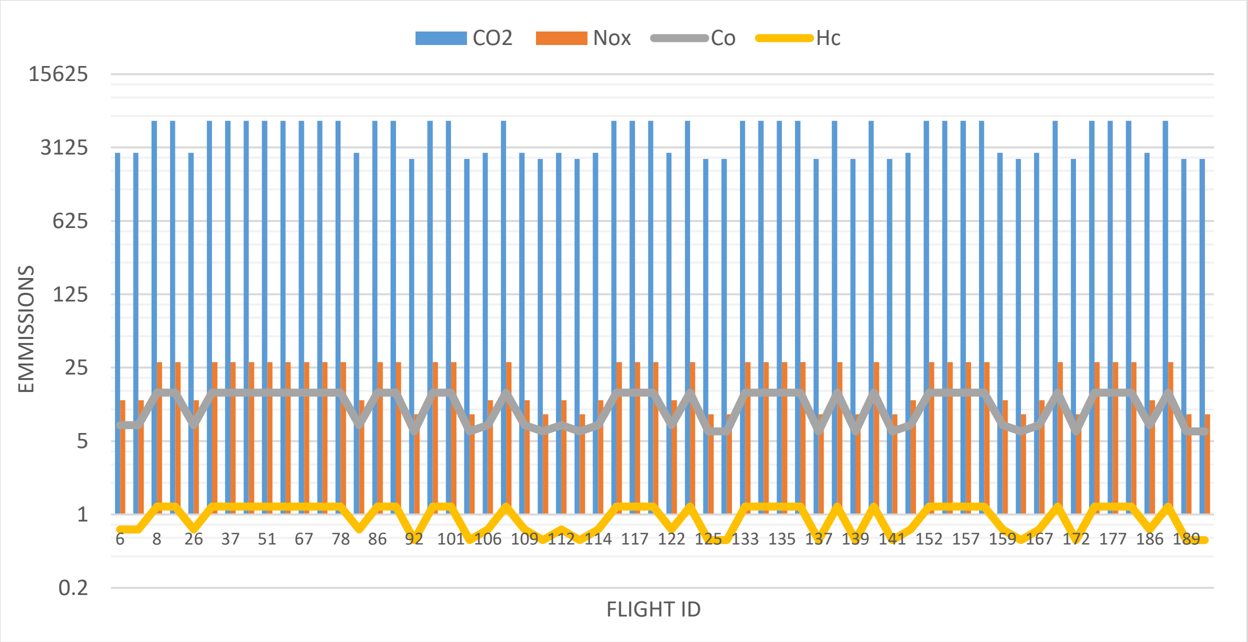

Figure 5: Emission amounts and the composition of emissions for aircraft elected to self-taxiing

Figure 6 illustrates airplanes movements on a time-space diagram. For the illustration, 18 airplanes from the mid-point of the flight set F $(f = \{74, \cdots, 91\})$ were selected in order to demonstrate the flight traffic at steady-state conditions. Furthermore, the time-space diagram helps us to visually verify the conflict resolution. As seen in the figure, no two airplanes violate the defined collision and conflict constraints. In Figure 6, two areas highlighted by circles (also enlarged images are shown) illustrate how two airplanes share the same link without violating the conflict constraints. It is clear from the given time-space diagram that the proposed mathematical model has potentials to help aviation authorities to fully automate the airport surface operations. The proposed mathematical model does not only focus on the GGE, fuel consumption cost and the delay issues, but also handles the collision and conflict during taxiing.

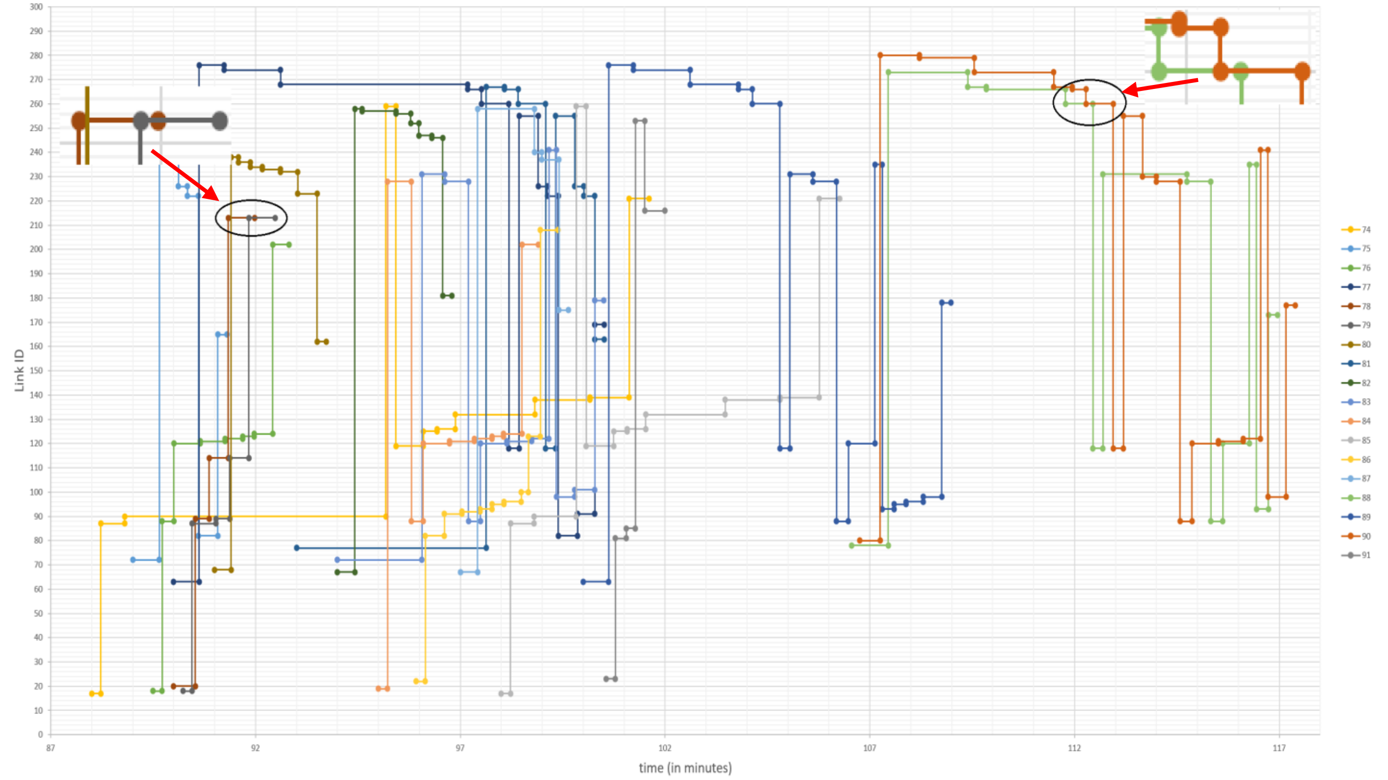

Figure 6: Time-space diagram that demonstrates aircraft movement and conflict-avoidance

5. Conclusions

This paper introduces a MILP model to optimally control taxiing operations in an airport with an emphasis on collision and conflict and GGE problems. The major contributions of the paper are: first, the modeling of collision and conflict avoidance in a unified airline operations management model; second, the evaluation of tow-truck usage to minimize fuel consumption; and finally the analysis of different strategies which may bring further insights to the airline and airport operations problem.

The developed mathematical models to tackle this problem are computationally complex and require unique solution strategies in order to handle real-life-size problems. Hence, we developed a sequential solution method which takes advantage of airlines' business practices. The sequential solution method not only makes it possible to solve real-life size problems, but also provide a flexibility to consider unplanned schedule changes during the planning horizon. For demonstrating the capabilities of the proposed mathematical models, we considered various towing options with our test case: no-towing, 100% towing and optional (hybrid) towing). Hybrid solutions which gives an option to the aircraft to complete taxiing with its own engine-power performed better in comparisons to no-towing and 100% towing options. While the hybrid option provides the most economical solution, it also helps airlines to reduce their GGE during taxiing drastically (average 95% CO_2 reduction in comparisons to no-towing option).

While the mathematical models described in this paper provide an extensive analysis of airport operations with electric-powered tow-truck options, only the deterministic cases are considered. Despite, significant fuel savings and GGE reduction opportunities are demonstrated, several stochastic events such as weather conditions, de-icing operations, reliability of tow-trucks and the impact of other auxiliary operations were not fully considered. Consequently, the results discussed in section 4 tend to favor our mathematical model. Hence, further research is needed to better capture the impact of tow-truck-based taxiing operations management under stochastic operation conditions. Moreover, this paper only considered a single method to decompose the problem. Segmenting based on time-intervals during a day may be a topic of future study. The work presented in this paper would benefit from further studies concerning the impact of coupling and decoupling of tow-trucks with airplanes and availability and reliability of other auxiliary services. In the current paper, the required times to perform these activities are reflected by constant values. Finally, the proposed fully autonomous taxiing operations is only possible through unified control of all activities under a single control center. Hence, further modeling and technological advances along with policy changes toward airport operations-control are needed for fully achieving the desired objectives of this paper.

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