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Airport operations with electric-powered towing alternatives under stochastic conditions

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ABSTRACT

Air transportation has become a common travelling medium for ordinary public in most regions around the world since the deregulation of civil aviation in the US in 1978. While the global economy and the ordinary people have benefited from the growing air-transportation, the negative impacts of such change have not gone unnoticed. Today, civil aviation is a significant contributor to several environmental issues such as conflict with wildlife, noise pollution, and Greenhouse Gas Emissions (GGE). The civil aviation industry is responsible for 2–3% of all greenhouse gas emissions in the world. Moreover, the emissions at airports have an even more significant impact on the local population and the surrounding environment. It is estimated that a typical airplane consumes between 4% and 7% of its fuel for ground operations. The GGE released by airports is not only contributing to global warming, but also impacting the health of local communities living next to airports. Accordingly, this paper discusses operational and technological improvements at airports with the objective of minimizing the negative impact of airports on the environment. First, electrification of taxiing operations is discussed. Next, a Mixed Integer Linear Programming (MILP) model which aims at assigning electric powered tow-tractors for airplanes to complete taxiing operations with minimum jet-fuel usage is introduced. The impact of stochastic conditions on the taxiing operations has been discussed and the impact of traffic density has been incorporated in the model. Finally, an optimum number of tow-tractor purchase strategy is recommended for airports.

1. Introduction

The increasing population and growing purchasing power in most parts of the world have led to a significant increase in all types of transportation mediums, causing high-volume of traffic on roads, railways, seaways, and airways. As a result, the transportation industry has become one of the major contributors to global GGE production (29% in USA and 15% in the world). Civil aviation is responsible for 12% of all GGE produced by the transportation industry. Growing concern over global climate changes caused by human activities and increasing public awareness have been challenging the transportation industry to reduce its environmental footprints. In general, companies focused on technological solutions to offset the transportation industry's contribution to GGE. On the other hand, operations management literature suggests that airline companies focusing on operational excellence with an objective to minimize fuel consumption burn up to 25–42% less fuel than those less efficient carriers (Zou et al., 2014).

Several conditions (internal and external) cause inefficiencies at airports, such as adopted technology, weather conditions, state of the infrastructure, ground service quality, relationship with airlines, runway capacity, and collaboration with other airports and air traffic control authorities. Inefficient operations at airports lead to congestion which eventually results in delays and more fuel consumption. Total cost of flight delays in United States is estimated to be between $30 billion to $38 billons per year (Ball et al., 2010 and Peterson et al., 2013). Additional fuel consumption due to delays constitutes 20% of the total delay cost (Ball et al., 2010). Until recently, the aviation industry had tackled the fuel consumption problem as a cost issue. In recent years, due to the increasing public awareness and government regulations, the environmental impact of fossil fuel usage has become an important consideration in aviation industry. Today, airline companies are not only focusing on reducing their fuel consumption costs, but they are also working with governments and the public to reduce the negative impact of the airline industry on the environment.

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I. INTRODUCTION

The increasing population and growing purchasing power in most parts of the world have led to a significant increase in all types of transportation mediums, causing high-volume of traffic on roads, railways, seaways, and airways. As a result, the transportation industry has become one of the major contributors to global GGE production (29% in USA and 15% in the world). Civil aviation is responsible for 12% of all GGE produced by the transportation industry. Growing concern over global climate changes caused by human activities and increasing public awareness have been challenging the transportation industry to reduce its environmental footprints. In general, companies focused on technological solutions to offset the transportation industry's contribution to GGE. On the other hand, operations management literature suggests that airline companies focusing on operational excellence with an objective to minimize fuel consumption burn up to 25-42% less fuel than those less efficient carriers (Zou et al., 2014)

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As fuel expenses are the second largest cost item for airline companies, aircraft manufacturers have invested a great deal of resources to produce more fuel-efficient aircraft in order to gain market share. As a result, significant gains in fuel consumption have been observed. Today, the new aircraft burns an average of 45% less fuel than aircraft made in 1960s (Kharina, 2015; Mirazova, 2013). While the impact of technological improvements on fuel consumption was considerably rapid in between 1960 to 1990 (35% reduction), rate of improvements due to technological advances has been relatively small since 1990 (total 10% from 1990 to 2015) (Kharina, 2015). The literature suggests that the further reduction of fuel consumption is possible through the improvement of air traffic and airport operations management (Zou, 2014 and Sama 2019).

The airline industry estimates that an average of 4% to 7% of fuel is burnt during ground activities at airports (taxing, waiting, and extra fuel carried in order to complete the journey at the destination airport) (Khadilkar, 2012, Nikoleris, 2011, Gebicki, 2018). Aircraft burns 5 to 18 gallons of fuel per minute during taxiing. The average fuel consumption during taxiing at Chicago's O'Hare airport is estimated to be an average of 9 gallons per minute. While emissions created by airport activities directly impact the GGE problem around the world, having been located very close to residential areas, airports pose significant health risks to the public (Upham et al., 2003 and Lu, 2011). Accordingly, the objective of this paper is to study the impact of the electrification of airport taxiing operations on both GGE and airport traffic efficiency. In other words, this paper evaluates the electric powered taxiing alternatives and introduces a mathematical model for optimal aircraft tow-tractor assignment and aircraft routing to perform taxiing operations.

In order to optimize the terminal area traffic flow at airports (runway utilization, gate utilization and taxiing operations), several academic studies in the form of linear programming (LP) have been proposed (Ng, 2020, Das, 2020). Although many of these LP solutions to airport operations in theory show promising results to improve traffic flow, due to their lack of collision and conflict resolution capabilities, they are either not implemented or only used as a planning tool to support ATCOs to manage the actual traffic. In the literature, only a handful of researchers have tackled the collision and conflict avoidance issue as part of network optimization, vehicle routing, assignment, or scheduling problems. Clare and Richards (2011) modeled aircraft taxiing process in consideration with collision avoidance. Yin et al. (2012) used similar conflict resolution constraints to model taxiing operations at George Bush Intercontinental Airport. Moeini (2012) and Soltani (2020) utilized similar strategies to model conflict resolution as part of a Mixed Integer Linear Programming (MILP) solution for ground traffic control. Yet, the large body of researchers tackled airport operations management and collision and conflict avoidance problems aviation industry separately (Tang, 2019, Akgunduz, 2018). Consequently, those airport ground operations management models without collision and conflict avoidance features, have never been fully implemented in real-life applications. As a result, today, both air-traffic and ground-traffic operations are still being managed by Air Traffic Controllers (ATCOs) and ramp managers. While the availability of sophisticated technology provides more comfortable working conditions for the ATCOs, monitoring airplanes and giving instructions to pilots, to provide save flight conditions, still requires experience, knowledge, and strong emotional stability. Moreover, human controlled airport ground operations management practices lead to less efficient taxiing operations resulting in delays and extra fuel consumption.

In their work, Soltani et al. (2020) formulated the collision and conflict avoidance as part of a general aircraft taxiing operations planning model. Their work, on the other hand, did not consider the stochastic nature of airport operations. Accordingly, this paper further extends the capabilities of the MILP solution proposed by Soltani et al. in order to manage airport operations under stochastic conditions. The proposed method considers the usage of electric powered airplane tow-tractors as an alternative taxiing method, while incorporating collision and conflict avoidance. The MILP model enabled us to minimize fuel usage, delay costs, and separate airplanes from each other by the desired minimum separation limits. In order to demonstrate the capabilities of the proposed MILP under stochastic conditions, a sensitivity analysis has been performed. In this study, we also introduce a tow-tractor purchasing policy in order to help airport authorities to make the most economic decisions during tow-tractor acquisition.

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 collision and conflict free airport operations is formulated as a MILP model. Sample cases are solved and discussed in section 4. Finally, in Section 5, conclusions are provided.

II. LITERATURE REVIEW

The literature on airport operations can be categorized into three major groups: Flight gate scheduling; Taxiway scheduling; and Runway scheduling. Moreover, airport operations are closely studied as part of the air-traffic flow management problem since ground delay strategies and coordination with destination airports have direct impacts on the overall air traffic flow performance. In recent years, academic and industry interests in the environmental impact of civil aviation operations have also grown substantially. In this section, we provide a brief discussion on literature closely related to airport operations, electric powered taxiing alternatives, vehicle sequencing and impact of airport operations on the environment topics.

In terms of computational complexity, flight gate scheduling and taxi route planning problems are the most complex problems to study. The objective of the gate scheduling problem is to determine the assignments of flights to gates. The problem complexity is further increased by introducing additional objectives such as minimization of terminal area movements. In their review paper, Dorndorf et al. (2007) discuss the state-of-the-art developments prior to 2007. Later, Aktel et al. (2017), Graham (2020) and Das et al. (2020) summarized the recent developments in the gate scheduling problem. While Das et al. (2020) compared literature based on their single or multi objective natures, and Aktel et al. (2017) focused on the performance of solution techniques. Taxi route planning, also known as airport surface operations planning, focuses on managing aircraft movements on the ground with an objective of minimizing total movement and/or congestions (Marin and Salmeron, 2008, Capa, 2015, Ravizza, 2014, Morris, 2016, Yu, 2017 and Adacher, 2018). Ibanez and Marin (2018) formulated the taxi planning problem as a multi-commodity flow model using time-space network. In order to solve the problem, a price and branch algorithm was proposed. Both Marin and Salmeron (2008) and Ibanez and Marin (2018) considered airport or sector capacity limitations to tackle conflict avoidance during taxiing. Similar strategies are utilized in general Air Traffic Flow Management (ATFM) problems in order to address flight safety concerns (Bertsimas, 2011 and Bertsimas and Patterson, 1998). The overall objective of the capacity-based conflict resolution strategies is to keep the number of moving aircraft within manageable limits at all times so that the available resources (ATCOs) can manage the current traffic safely. While ATFM models perform well at the tactical level, their contribution to manage air traffic at the operational level is limited. Since the exact collision and conflict avoidance issues are not addressed in real-time, frequent human intervention is required (Lancelot, 2015).

In recent years, researchers from operations research/management field have contributed to the literature to address the need for collision and conflict avoidance in Air Traffic Management (ATM). Clare and Richards (2011) introduced a MILP model for taxiing and runway scheduling. Their work is one of the earliest mathematical models that explicitly includes collision avoidance as part of the airport taxi planning problem. A similar formulation was implemented in Moeini (2012) to model Air Traffic Flow Management (ATFM) problem with an objective to avoid mid-air collision and conflict. Similar collision and conflict avoidance formulations with varying degree of differences have been introduced in later studies such as Yu et al. (2017) aims at solving gate reassignment problem, and Akgunduz (2018) focuses on speed-dependent fuel consumption optimization as part of the ATFM problems. Gurtner et al. (2017) introduce an agent-based simulator to study free-routing solutions within SESAR scenario where collision and conflict avoidance are always assured through intelligent controllers. It is clear that studies integrating collision and conflict avoidance with the business objectives of civil aviation will further improve the efficiency of airport and airspace management and will eventually lead to adoption of fully autonomous airplane movements both on the ground and en-route.

Since the conceptualization of Autonomous Guided Vehicles (AGVs), the autonomous vehicle control problem including AGVs and Unmanned Aerial Vehicles (UAVs) have gained significant attention from both academia and the industry (Lu, 2016, Liu, 2019, Grote, 2022). In their review papers, Huang et al. (2019) and Yu et al. (2021) summarize the collision and conflict avoidance methods in the context of UAV and AGV control respectively. The focus of these studies is to develop self-navigating vehicles. Self-awareness, recognition of objects and obstacles in the environment, and the capability of avoiding obstacles during a journey from an origin to a destination, are the main objectives of the research in autonomous vehicle control. Today, ariel vehicles, including commercial airplanes, are equipped with sophisticated collision avoidance equipment that enable aircraft to make autonomous decisions upon identification of a conflict risk (Akgunduz, 2002, Gurtner, 2017). Katrakazas et al. (2015) review the state-of-the-art works and evaluated the future trends in autonomous vehicle control. These studies show that the main focus of autonomous vehicle control is to ensure collision avoidance while performing given tasks. As a result, business objectives, such as minimization of delays and energy consumption, are either neglected or considered as secondary objectives.

As mentioned earlier, the civil aviation (without the impact of manufacturing and supply chain) is responsible for 2 to 3% of all greenhouse gas emissions in the world which ranks the industry 6th between Japan and Germany (Overton, 2022). While fluctuating significantly due to volatile oil prices, fuel is also a significant cost item (second largest) for airline companies. In response to economic considerations and the increasing awareness for the global warming, both aircraft manufacturers and scientific community have offered various technological and operational advances in recent years to address fuel consumption problem in civil aviation industry. Mainly due to technological advances (new engine types, better aerodynamics, and lighter material usage), significant gains on fuel efficiency (57%) have been achieved between 1959 and 1995 (Lee, 2001). While the rate of reduction is slower, another 10% gain has been achieved from 1990 to 2015 (Kharina, 2015). Researchers have also demonstrated that airlines with efficient operations management tools are able to reduce their environmental footprint significantly while saving costs (Zou, 2014 and Sama 2019). Lee et al. (2001) shows that out of 57% reduction observed in fuel consumption, 17% of it was due to more efficient management of airline operations. Ryerson et al. (2011) suggests that US airlines have potential to reduce both their airborne and taxiing fuel consumption by up to 10%-13% by improving operational performance of airports. In their comparative study among 15 large carriers, Zou et al. (2013) show that airlines with efficient operations management strategies burn up to 9-20% less fuel than the industry average. Moreover, it was found that those airlines without strong operations management cultures burn 25-42% more fuel than top performing carriers. In their works both Hassan et al. (2021) and Park and Kim (2023) studied the influential factors such as flight distance or training of crews that are impacting on the fuel combustion and emission at airports. The empirical study of Hassan et al. (2021) shows that while some of these factors are uncontrollable (e.g., flight distance) many others are controllable, and through efficient operations management strategies, significant fuel reduction is possible (e.g., reduction of takeoff weight, better paid ground crew, better training of the crew, optimization of runways and gate scheduling and taxiing).

Aircraft burns most of their fuels during flight. In average, only 7% of the fuel is burnt during ground operations (Nikoleris 2011). However, due to their proximity to large cities, the GGEs at airports have a much larger impact on the public and the environment (Lu, 2011). Upham et al. (2003) introduced the concept of environmental capacity for airports where they introduced a quantitative method to measure the airport capacity as a function of its impact on the environment. In order to reduce the impact of airports on the environment, a number of companies have developed alternative taxiing options. Honeywell and Wheeltug have introduced electric powered onboard systems that are installed on the front wheel of the aircraft to provide the necessary torque to complete taxiing operations. Companies like Israeli Aircraft Industries and Goldhofer introduced electric powered towing alternatives Taxibot and Phoenix E respectively to provide taxiing operations for the aircraft (Hospodka, 2014). Lufthansa has started to use Phoenix E tow-tractors in their hubs on Frankfurt airport (Soltani, 2020). Salihu et al. (2021) presented a simulation-based approach to study the impact of electric powered tow-tractor usage for airport operations. Later, Di Mascio (2022) compared four different alternative taxiing strategies, including electric powered external towing option to identify least polluting taxiing strategies at airports. Their work concludes that electric powered external towing alternatives provide maximum reduction in fuel consumption reduction yet, this alternative increases the taxiing time.

The mathematical model presented in this paper extends the previously reported works of Clare and Richards (2011) and Soltani (2020) in collision and conflict avoidance and works of Hospodka

(2014), Lukic (2018), Salihu (2021) and Di Mascio (2022) in electric powered towing alternatives with an objective to determine optimum route on taxiways with minimum fuel consumption while respecting the collision and conflict rules. Hence, both business and safety objectives are handled under the same unified mathematical model using linear expressions. Among different alternatives, due to its flexibility to adopt in the current airport system and cost effectiveness, we considered electric-powered airplane tow-tractors as a solution to help airplanes complete taxiing operations with minimum usage of their engine powers.

Consequently, the proposed airport taxi planning strategy is modeled as a task assignment problem. Assignment problems are one of the oldest operations research topics. Earlier works focused on machine and vehicle assignment (Picard, 1978) and communication network assignment (Sengoku, 1980) problems. In recent years, due to the advancing computational power and accumulated knowledge in the field, several exact and heuristic methods have been introduced (Lai, 2017, Li and Tang, 2019). Management of vehicles, UAVs and AGVs, were also studied as task assignment problems (Chen 2019, Monnerat, 2019). One of the most widely researched topics in task assignments is the job-shop scheduling problems. Several exact (Bierwirth, 2017) and heuristic solutions (Li and Gao, 2016 and Raza, 2006) have been proposed. Koc and Laporte (2018) reviewed the influential works in vehicle routing problem, and Das et al. (2020) reviewed the gate assignment literature. The MILP model introduced in this paper is inspired from multi-vehicle task assignment problem. Yet, the proposed model differs from the aforementioned literature with its capability to successfully unify collision and conflict avoidance with the vehicle routing and task assignment problem with an objective to minimize airports' impact on the environment. By incorporating safety in the real-time decision-making loop, the method proposed in this paper fills the gap in the literature and contributes to the knowledge which is necessary to attain fully autonomous airport surface management. In the paper, it is assumed that fuel consumption is linearly correlated with the GGEs. The amount of greenhouse gases such as CO2, NOx and SO2 emitted by aircraft are not studied individually. While noise pollution is also a significant environmental issue for airports, it is not addressed in this study.

III. ENVIRONMENTALLY CONSCIOUS AIRPORT SURFACE MANAGEMENT

In this section, we discuss the details of the proposed airport surface management philosophy. The objective of the mathematical model is to minimize: i) deviation from the scheduled arrival and departure times; ii) total taxiing time; and iii) fuel consumption. In order to make all objectives comparable to each other, they are formulated as a cost (delay costs and fuel consumption costs) in the objective function. In our analysis, we also considered the cost of operating airplane tow-tractors in order to provide guidance for determining the optimal number of tow-tractors in the system.

3.1 Assumptions

In this research, the gate utilization (gate selection) is not considered. Hence the flight schedule which includes aircraft type, arrival time, departure time and the gate number, is known in advance. Each aircraft completes its taxiing operations by following physical lines which are available in most airports as taxiways. Figure 1, which is the Google Earth image of an airport, illustrates taxiway lines. Accordingly, a mesh network is generated to enable surface movements. Each intersection is a node ($\mathcal{N}$) and nodes are connected to each other by arcs (links, L). The following list provides the remainder of assumptions related to the technical details of the problem.

- Airplanes can follow each other on the same link by respecting the minimum allowed safety distance.
- No two airplanes can travel from opposite directions on the same link at the same time.

- All parallel links are assumed to be separated from each other by a sufficient distance to ensure collision free taxiing.
- Travelling times between two nodes is bounded by a fastest travelling time.
- In practice, when aircraft speed is changed, their fuel consumption rate changes disproportionally. In our model, fuel consumption rate is assumed to be constant per minute of operation.
- Fuel consumption amount between two nodes is calculated based on the travelling time on the arc.
- Traffic, due to auxiliary services, is ignored. It is assumed that such traffic always clears the way for the aircraft.
- When they are not serving an aircraft, tow-tractors would not be in conflict with other moving aircraft.

  When they are towed, aircraft use their engine at the lowest power which is sufficient for pilots and flight crew to perform required engines, avionics and other safety verifications on the airplane.

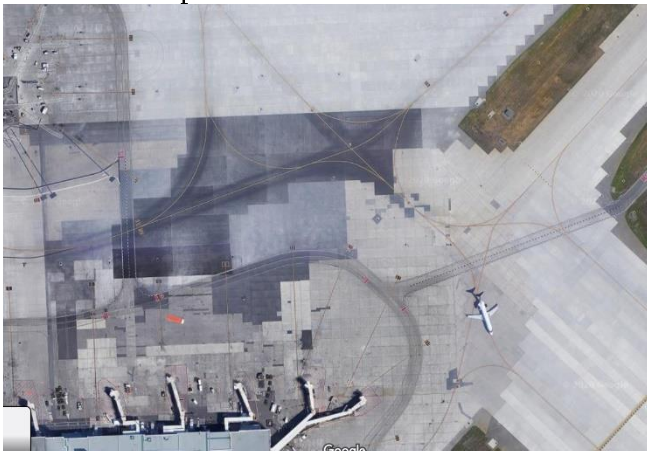

Figure 1. Taxiways outlined by visible lines at an airport.

3.2 Definitions of parameters and decision variables

Sets	**Definition**
Ƥ	Set of flights indexed by p
Ƭ	Set of airplane tow-tractors, indexed by ƭ
Ɲ	Set of nodes to describe mesh network, indexed by n
L	Set of links (arcs) connecting two nodes, indexed by l
$l(n)^+$	Set of links leaving from Node n
$l(n)^-$	Set of links arriving to Node n
$l(ij)$	A specific link connecting node i to node j
Parameters	**Definitions**
$GATE^p$	Gate information for airplane p
$TYPE^p$	Airplane is assigned to an Arrival or a Departure flight
t_{ENTER}^p	Schedule entrance time to system (arrival or departure depending on the type) for airplane p
t_{EXIT}^p	Schedule exit time from the system (arrival or departure time depending on the type) for airplane p

T_{ij}	Travelling time for tow-tractors ƭ based on the shortest path from nod i to node j. This is only valid between gates and between gates and runways when tow-tractor is taking a new assignment at node j after completing a job at node i
$TJ_{\text{ƭ}}^{p}$	Required time for a tow-tractor to couple with an airplane
$TS_{\text{ƭ}}^{p'}$	Required time for tow-tractor to decouple from an airplane
D_l	Length of link l used to determine travelling time
S^p	Maximum groundspeed when using airplane engines for airplane p
${S_{TOW}}^{p}$	Maximum groundspeed of airplane p when towed by a tow-tractor
$\Delta^{pp'}$	The minimum required separation time between two aircraft
F_COST^p	Per minute fuel cost, specific to aircraft type
O_COST	Per minute ground operation cost

Decision Variables	**Definitions**
ω_l^p	$= \begin{cases} 1 & \mathit{airplane\ p\ uses\ link\ l\ during\ taxiing} \\ 0 & \mathit{otherwise} \end{cases}$
$y_{\text{ƭ}}^{p}$	$= \begin{cases} 1 & \mathit{airplane\ tug\ \text{ƭ}\ is\ assigned\ to\ airplane\ p} \\ 0 & \mathit{otherwise} \end{cases}$
$\text{ƶ}_{\text{ƭ}}^{p'p}$	$= \begin{cases} 1 & \mathit{tug\ \text{ƭ}\ is\ assigned\ to\ p\ immediatly\ after} \\ & \qquad \mathit{serving\ p'} \\ 0 & \mathit{otherwise} \end{cases}$
a_n^p	Arrival time at node n
d_n^p	Departure time from node n
$\mu_l^{pp'}$	$= \begin{cases} 1 & \mathit{airplane\ p\ leads\ p'\ in\ the\ same\ direction\ on} \\ & \qquad \mathit{link\ l} \\ 0 & \mathit{otherwise} \end{cases}$
$\lambda_n^{pp'}$	$= \begin{cases} 1 & \mathit{airplane\ p\ leads\ p'\ on\ Node\ n} \\ 0 & \mathit{otherwise} \end{cases}$
$\delta_{l(nn')}^{pp'}$	$= \begin{cases} 1 & \mathit{airplane\ p\ leads\ p'\ on\ link\ l\ when\ they\ travel} \\ & \qquad \mathit{from\ opposite\ directions} \\ 0 & \mathit{otherwise} \end{cases}$
t_op^p	time spent handling the airplane p at the airport
$fuel^p$	amount of fuel used while airplane was on the ground
t_delay^p	deviation from scheduled arrival or departure time

C. Mathematical Model for Airport Surface Traffic Management

Let us consider a mesh network Ǵ with its nodes Ɲ and links L as Ǵ(Ɲ, L), which mimics the taxiways of an airports similar to the one shown in Figure 2. The objective is to navigate airplanes from gates to runways for $TYPE^f = Departnig$ flights and from runways to designated gates for $TYPE^f = Arriving$ flights with the minimum deviation from the scheduled arrival and departure times, while using the least amount of fuel. Two different alternatives are considered. First, we considered all ground movements to be handled by tow-tractors. Clearly, this option requires the acquisition and operation of a large number of tow-tractors. Accordingly, the second option, a hybrid solution is investigated. The hybrid solution considers assigning electric powered tow-tractors to high fuel consuming airplanes and letting more fuel-efficient airplanes self-tow using their engine powers when assignment of a tow-tractor is more expensive. In this way, the airport operations can be completed with less tow-tractors, while still reducing the negative impact of airports on the environment.

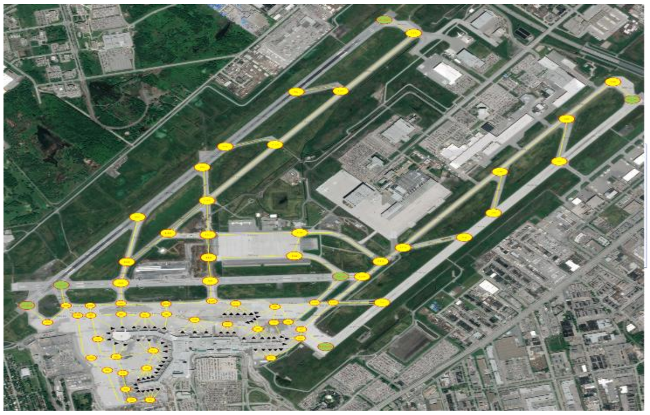

Figure 2. Montreal's Pierre Elliott Trudeau International Airport Taxiing Network

3.3.1 Objective:

The problem is modeled as a multi-objective optimization problem. Hence, the objective function (Eq. 1) is formulated as a minimization problem considering airport ground operations cost, fuel cost and delay cost.

$$Minimize \sum_{p \in Ƥ} t\_op^p * O\_COST + fuel^p * F\_COST + \ t\_delay^p * D\_COST^p \tag{1}$$

3.3.2 Routing constraints:

The following set of constraints ensure that a given aircraft leaves its entrance node (ENT^f) by following available taxiways (links) and intersections (nodes) to reach its destination node (EXT^f). While Eq. 2 forces an aircraft to leave its origin and reach its destination, Eq.3 determines the taxiing path through transitional nodes.

$$\sum_{l \in l(ENT^p)^+} \omega_l^p \ = \sum_{l \in l(EXT^p)^-} \omega_l^p = 1; \ \forall p \in Ƥ \tag{2}$$

$$\sum_{l \in l(n)^+} \omega_l^p \ = \sum_{l \in l(n)^-} \omega_l^p \le 1; \ \forall p \in Ƥ; \ \ \forall \ n \in Ɲ \backslash \{ENT^p, EXT^p\} \tag{3}$$

3.3.3 Modeling towing option:

Ithnan et al. (2013) investigated the existing aircraft taxiing operation methods including full-engine, single-engine, tow-tractor supported, and electrical nose-gear embedded systems at Amsterdam Airport Schiphol. In their work, jet engine powered taxiing operation, which is considered as the traditional taxiing method, is found to be the least desirable taxiing method in terms of its economic and environmental consequences. The results of their study suggest that the utilization of airplane tow-tractors for taxiing purposes has potential to reduce fuel burn by at most 36.6% for the full engine and 14% for the single engine taxiing alternatives. As reported in this research, CO_2 emissions, which is the most produced pollution from burning fuel, is decreased from 3.39 million kilograms to 2.51 million kilograms. Given that the airplane tow-tractor usage for taxiing operations has significant potential to reduce airports' contribution for the GGE, we propose a hybrid airplane-tow-tractor assignment policy to facilitate taxiing operations. The concept of hybrid operations suggests that airplanes are coupled with a tow-tractor when tow-tractors are available. When the tow-tractor is not available or assigning one to an airplane is more expensive (the cost of waiting for a tow-tractor exceeds the expected fuel burn reduction), then airplanes are free to use their engines for taxiing.

Let us consider an airplane tow-tractor ŧ from the set Ƭ. When ŧ is available, it is coupled with an airplane (Eq.4) and ŧ will take the airplane from its entrance node ENT^p and tow the airplane to its destination node EXT^p by following the set of connecting taxiways. When a tow-tractor is assigned to an airplane ($y_{ŧ}^{p} = 1$), it must either enter the system through a $BEGIN$ node, or from another assignment ($y_{ŧ}^{p'} = 1$). Similarly, when a tow-tractor completes an assignment, it either moves to the location where the next assignment is ($y_{ŧ}^{p''} = 1$) or leaves the system through a $SINK$ node (Eq.5).

$$\sum_{ŧ \in Ƭ} y_{ŧ}^{p} \leq 1; \quad \forall p \in Ƥ \tag{4}$$

$$y_{ŧ}^{p} = \sum_{p' \in Ƥ} ƶ_{ŧ}^{p'p} + ƶ_{ŧ}^{BEGIN,p} = \sum_{p'' \in Ƥ} ƶ_{ŧ}^{pp''} + ƶ_{ŧ}^{p,SINK}; \ \forall p, p' \in Ƥ \backslash p \neq p'; \ \forall ŧ \in Ƭ \tag{5}$$

3.3.4 Travelling time related constraints:

In order to assign a tow-tractor to the airplane p, the tow-tractor must be idle and able to arrive at the entrance node (ENT^p) of p within the allowed time-interval. Accordingly, the following set of constraints are introduced.

$$\begin{aligned} a_j^p \geq & \sum_{j \in l(j)^-} \left[d_i^p + \left(\frac{D_{l(ij)}}{S^p} \left(1 - \sum_{ŧ \in Ƭ} y_{ŧ}^{p} \right) + \frac{D_{l(ij)}}{S_{TOW}{}^{p}} \sum_{ŧ \in Ƭ} y_{ŧ}^{p} \right) \right] \\ & - \left(1 - \sum_{l \in l(j)^-} \omega_l^p \right) M; \ \forall p \in Ƥ; \ \forall \, \mathrm{j} \in Ɲ \backslash ENT^p \end{aligned} \tag{6}$$

$$\begin{aligned} d_{ENT^p}^p \geq a_{EXT^{p'}}^{p'} + T_{EXT^{p'},ENT^p} + TS_{ŧ}^{p'} + TJ_{ŧ}^{p} - \left(1 - ƶ_{ŧ}^{p'p} \right) M; \\ \forall p, p' \in Ƥ \backslash p \neq p'; \ \forall ŧ \in Ƭ \end{aligned} \tag{7}$$

$$d_{ENT^p}^p \geq t_{ENTER}^p; \quad \forall p \in Ƥ \tag{8}$$

$$d_n^p \geq a_n^p; \quad \forall p \in Ƥ \tag{9}$$

$$a_{EXT^p}^p - t_{EXIT}^p \leq t_{delay}{}^{p}; \ \forall p \in Ƥ \tag{10}$$

Arrival time (a_j^p) at a node j for an airplane p depends on the departure time from the previous nodes (since it is not know which node it may be arriving from, a summation is used), travelling time on the link which is subject to the length ($D_{l(ij)}$) and speed (S^p if self-powered, or $S_{TOW}{}^{p}$ if it is tugged) (Eq. 6). However, if the airplane does not visit the node j, then the final part of Eq.6, $\left(1 - \sum \omega_l^p\right) M$, makes the expression feasible at all times without impacting the arrival time. In Eq.7, it is ensured that tow-tractor ŧ has sufficient time between two consecutive assignments. After completing an assignment by reaching the exit node ($a_{EXT^{p'}}^{p'}$), the tow-tractor spends $TS_{ŧ}^{p'}$amount of time for decoupling from airplane p', next travels $T_{EXT^{p'},ENT^p}$ amount of time to reach the entrance node of the next assigned airplane (since it was assumed that tow-tractor would not be in conflict with other airplane when traveling alone, travelling time between two nodes is constant and determined from shortest path), and finally spends TJ_{t}^{p} time to couple with the newly assigned airplane. In Eq.8, it is assumed that airplanes can leave the entrance node after the scheduled departure time (or arrival). Eq. 9 coordinates the relationship between arrival and departure times at a node. If the airplane reaches its EXIT node after its scheduled departure time, a penalty is incurred as a delay (Eq. 10).

3.3.5 Collision and conflict avoidance constraints:

The foremost important consideration in aviation is safety. Both in the air and on the ground, ATCOs spend most of their time and energy separating airplanes to ensure the safety of the public and the environment. Hence, in order for a decision support system to be a viable option for managing the air/ground traffic, collision and conflict avoidance must be well incorporated. In our case, we modeled the collision and conflict avoidance to address three critical conditions during taxiing:

1. Two aircraft must maintain a separation distance when they travel on the same link in the same direction.
2. Aircraft must maintain sufficient separation distances when they pass through an intersection.
3. Two aircraft cannot travel on the same link at the same time from opposite directions.

The following set of constraints always coordinates the movements of two airplanes on taxiways and gates by ensuring the separation between them.

$$\begin{gathered} d_{n}^{p'} \geq d_{n}^{p} + \Delta^{pp'} - \left(1 - \mu_{l(nn')}^{pp'}\right) M \\ a_{n'}^{p'} \geq a_{n'}^{p} + \Delta^{pp'} - \left(1 - \mu_{l(nn')}^{pp'}\right) M \\ d_{n}^{p} \geq d_{n}^{p'} + \Delta^{pp'} - \mu_{l(nn')}^{pp'} M \\ a_{n'}^{p} \geq a_{n'}^{p'} + \Delta^{pp'} - \mu_{l(nn')}^{pp'} M \end{gathered} \qquad \begin{gathered} \forall p, p' \in \mathcal{P} \backslash p \neq p' \\ \forall \text{ n} \in \mathcal{N}, \forall n' \in l(n)^{+} \end{gathered} \tag{11}$$

$$\begin{gathered} d_{n}^{p'} \geq d_{n}^{p} + \Delta^{pp'} - \left(1 - \lambda_{n}^{pp'}\right) M \\ d_{n}^{p} \geq d_{n}^{p} + \Delta^{pp'} - \lambda_{n}^{pp'} M \end{gathered} \qquad \begin{gathered} \forall p, p' \in \mathcal{P} \backslash p \neq p' \\ \forall \text{ n} \in \mathcal{N} \end{gathered} \tag{12}$$

$$\begin{gathered} \mu_{l(nn')}^{pp'} \leq \omega_{l(nn')}^{p}; and\ \mu_{l(nn')}^{pp'} \leq \omega_{l(nn')}^{p'} \\ \delta_{l(nn')}^{pp'} \leq \omega_{l(nn')}^{p}; and\ \delta_{l(nn')}^{pp'} \leq \omega_{l(nn')}^{p'} \\ \lambda_{n}^{pp'} \leq \sum_{i \in l(n)^{-}} \omega_{i}^{p}\ ; and\ \lambda_{n}^{pp'} \leq \sum_{i \in l(n)^{-}} \omega_{i}^{p'} \end{gathered} \qquad \begin{gathered} \forall p, p' \in \mathcal{P} \backslash p \neq p' \\ \forall \text{ n} \in \mathcal{N}, \forall n' \in l(n)^{+} \end{gathered} \tag{13}$$

Previously, Clare and Richards (2011) and Soltani (2020) introduced linear constraints to tackle collision avoidance. Eq.11 includes a set of expressions to ensure two airplanes are not within proximity while they are travelling on the same link in the same direction, $\omega_{l(nn')}^{p} = \omega_{l(nn')}^{p'} = 1$. Depending on who is leading on the link $\left(\mu_{l(nn')}^{pp'} = 1 \Rightarrow p \text{ is the leader}\right)$, the leading airplane ($p$) leaves the origin node (n) at least $\Delta^{pp'}$ unit-time earlier than the follower (p') and reaches the opposite node (n') at least $\Delta^{pp'}$ unit-time earlier than the follower (p').

Two constraints given in Eq.12 are modeled to avoid head-on collision on a link. The same set of constraints also ensures the separation between two airplanes at an intersection. Once again, depending on which airplane is the leader $\left(\lambda_n^{pp'} = 1 \Rightarrow p \text{ reaches } n \text{ before } p'\right)$, a minimum separation distance in terms of time must be maintained $\left(\Delta^{pp'}\right)$.

Finally, the set of constraints grouped under Eq.13 connects airplane paths with the priority conditions. These priority conditions formulated in Eq.11 and 12 are only valid if both airplanes use the same link and/or the same node. Figure 3 illustrates the cases described in Eq.11 and 12.

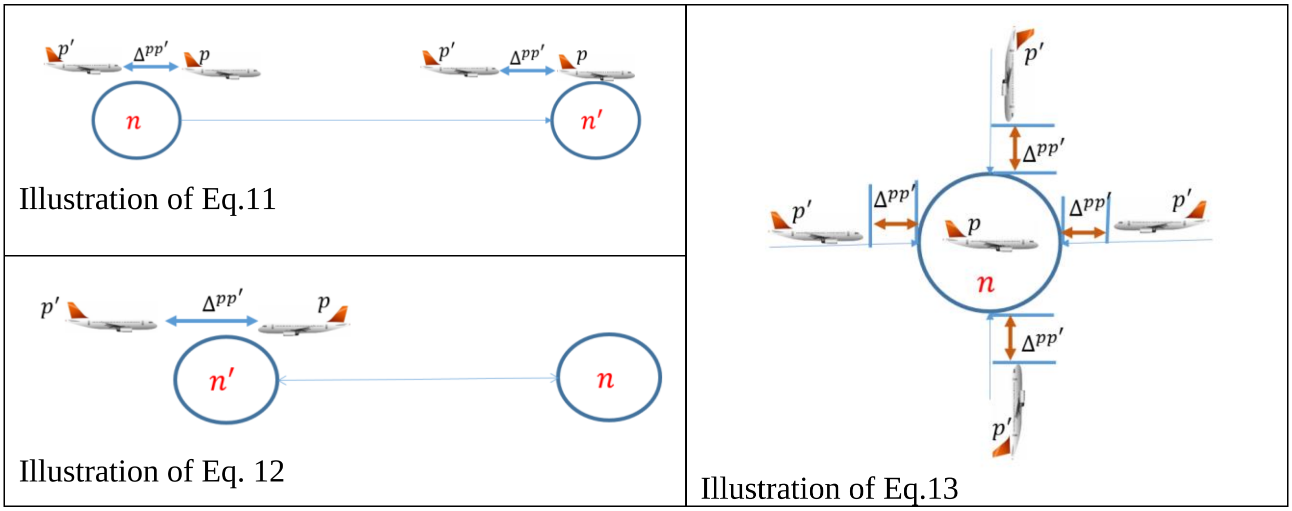

Illustration of Eq.11

Illustration of Eq. 12

Illustration of Eq.13

Figure 3: Illustration of possible collision and conflict situations

3.3.6 Constraints relevant to Delays and Fuel Consumption Cost:

The objective function consists of three different costs: i) delay costs; ii) fuel consumption cost; and operation costs. The main objective is to minimize both fuel consumption and delay costs. However, the proposed method considers the purchasing and operation of airplane tow-tractors. Accordingly, the cost of managing airplane tow-tractors is estimated as a function of their usage time.

Above, in Eq.10, the delay time for each airplane is determined. Eq. 15 determines the duration during which an aircraft burns fuel for taxiing. As mentioned above, airplanes use fuel only when they use their engines. Fuel consumption due to engine checking prior to flight is not considered in this study. Fuel consumption for those airplanes towed by a tow-tractor is negligible. However, when an airplane is towed by a tow-tractor, it is subject to towing expenses as shown in Eq. 16.

$$\sum_{l \in \mathrm{L}} \omega_l^p D_l \quad \le fuel^p + \sum_{\text{ƭ} \in \mathrm{T}} y_{\text{ƭ}}^p \, M \; ; \; \forall p \in \text{Ƥ} \tag{15}$$

$$a_{EXT^p}^p - d_{ENT^p}^p \quad \le t_{op}{}^p + \left(1 - \sum_{\text{ƭ} \in \mathrm{T}} y_{\text{ƭ}}^p\right) M; \; \forall p \in \text{Ƥ} \tag{16}$$

In the objective function the towing cost is determined as $t\_op^p * O\_COST$ where O_COST is the per unit of time operating cost of an airplane tow-tractor. The fuel consumption cost is determined by $fuel^p * F\_COST$ where F_COST is the average, per unit, distance fuel consumption cost.

3.3.7 Airport Operations Modeling under Stochastic Conditions

Deviation from planned travelling time on the mesh network is likely to occur due to various environmental and mechanical reasons at airports. Hence, a robust mathematical model that can absorb small variations from planned schedule is desired. Let us assume that travelling time for aircraft p on link $l(ij)$ may deviate by a random amount $\theta(d)_l^p$. While many factors may have an impact on the travelling time, traffic density on the link and the intersection is of greatest concern. Consequently, we calculate the $\theta(d)_l^p$ as a function of the traffic density around the link during a time interval. The time interval considered in this paper is the time between arrival to the link and the departure from the link for aircraft p.

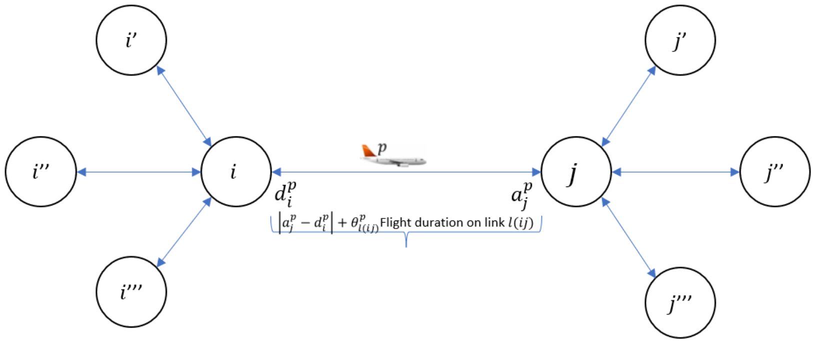

Figure 4: Illustration of traffic situation

Let us assume that aircraft p travels from node i to node j during d_i^p and a_j^p. As shown in Figure 4, both node i and node j have neighboring nodes. Therefore, the number of aircraft travelling on those links connected to node i and node j impact on the travelling time of aircraft p on link $l(ij)$. Thus, we need to introduce a set of constraints to count the number of aircraft on the sub-networks similar to the one depicted in Figure 4. As previously formulated in Akgunduz and Kazerooni (2018), this problem can be solved by considering links in between node-sets $\{i', i'', \dots\}$ and $\{j', j'', \dots\}$ constituting a zone. Accordingly, if any aircraft p' enters the zone before a_j^p and leaves the zone after d_i^p, then it will be counted as a contributing factor for the traffic.

Let $\alpha_{l(ij)}^{pp'} = 1$ if p' enters the traffic zone for link $l(ij)$ before p leaves $l(ij)$ and $\beta_{l(ij)}^{pp'} = 1$ if p' leaves the zone after p enters $l(ij)$. Consequently, when $\alpha_{l(ij)}^{pp'} = \beta_{l(ij)}^{pp'} = 1$, then p' spends time in the zone while p travels on $l(ij)$. We use the binary variable $\delta_{l(ij)}^{pp'}$ to describe the case.

Following constraints are subject to $\forall p \in \mathcal{P}, \forall \mathrm{l(ij)} \in \mathrm{L}$

$$\sum_{k \in \{l(i)^-, l(j)^-\}} d_k^{p'} \leq a_j^p + \left(1 - \alpha_{l(ij)}^{pp'}\right) M \tag{17}$$

$$\sum_{k \in \{l(i)^-, l(j)^-\}} d_k^{p'} \geq a_j^p - \alpha_{l(ij)}^{pp'} \mathrm{M} \tag{18}$$

$$\sum_{k \in \{l(i)^+, l(j)^+\}} a_k^{p'} \geq d_i^p - \left(1 - \beta_{l(ij)}^{pp'}\right) M \tag{19}$$

$$\sum_{\mathrm{k}\in\{l(i)^{+},l(j)^{+}\}} a_k^{p'} \leq d_i^p + \beta_{l(ij)}^{pp'} M \tag{20}$$

$$\alpha_{l(ij)}^{pp'} + \beta_{l(ij)}^{pp'} - 1 \leq \delta_{l(ij)}^{pp'} \tag{21}$$

$$\delta_{l(ij)}^{pp'} \leq \alpha_{l(ij)}^{pp'}; \quad \delta_{l(ij)}^{pp'} \leq \beta_{l(ij)}^{pp'} \tag{22}$$

$$\text{Ŧ}_{l(ij)}^{p} = \sum_{p'\in F: p\neq p'} \delta_{l(ij)}^{pp'} - 1 \tag{23}$$

Consequently, $\text{Ŧ}_{l(ij)}^{p}$ counts the number of aircraft in the zone while aircraft p travels on link $l(ij)$. In order to reflect the traffic factor in the model, Eq. 6 is modified as:

$$\begin{aligned} a_j^p \geq \sum_{j\in l(j)^{-}} \left[d_i^p + \left(\frac{D_{l(ij)}}{S^p} \left(1 - \sum_{\text{ŧ}\in\mathrm{T}} y_{\text{ŧ}}^p \right) + \frac{D_{l(ij)}}{S_{TOW}{}^{p}} \sum_{\text{ŧ}\in\mathrm{T}} y_{\text{ŧ}}^p \right) + \boldsymbol{\text{Ŧ}_{l(ij)}^{p} \theta(d)_l^p} \right] \\ - \left(1 - \sum_{l\in l(j)^{-}} \omega_l^p \right) M \end{aligned} \tag{24}$$

With the support of Eq.24, aircraft are routed through taxiways with lower traffic density. Even though constrains 17 to 23 determine the traffic density, they significantly increase the computational complexity. The complexity issue has been addressed through batching aircraft according to their scheduled arrival and departure times. Hence, time-segmented strategy is adopted to solve the problem for real-life cases. The details of the solution strategy are discussed later in section IV.

IV. SOLUTIONS AND RESULTS

4.1 Case study

In this section, we introduce a case study at Montréal's Pierre Elliott Trudeau International Airport (YUL) with the aim of demonstrating the capabilities of the aforementioned MILP mode. The YUL airport is one of the largest airports in Canada, serving over 20 million passengers per year (YUL, 2020). Moreover, the airport is in the heart of the Island of Montreal, which is home to 1.9 million people and an additional 2.1 million people living in the larger metropolitan area. With its proximity to the residential areas, the air pollution due to airport activities not only contributes to the global GGE problem but also directly impacts the wellbeing of the nearby population. The YUL airport is not unique in terms of its proximity to the residential areas. Today, several other major airports such as Chicago's O'Hare, Paris's Orly, New York's/ New Jersey's Newark, or Los Angeles' international airports are all located in densely populated areas. Given that airplanes burn up to 7% of their fuel to perform their ground activities, the impact of airports on the health of nearby residents is a major concern. Hence, the improvements achieved because of the proposed MILP model not only have the potential to reduce aviation's impact on global GGE, but also bring opportunities to improve the wellbeing of residents living around airports.

YUL airport has three asphalt runways, which can be used in both directions. The longest runway, 06L/24R, being 11,000 ft. long, is parallel to runway 06R/24L, which is 9,600 ft. long. Finally, the third runway, 10/28, which is 7,000 ft. long, intersects the other two runways. The YUL airport handles an average of 730 flights daily through its 89 gates. In the current work, the network of the

YUL taxiways is drawn based on Google Map (Satellite), which includes 125 nodes and 282 arcs. An airplane may enter (or exit) the network through gate or runway nodes. In this case study, we considered 60 gates, 16 entry/exit points on runways, and 49 intersections between taxiways.

4.2 Solution methodologies

In this section, we introduce two different solution methodologies. First, the problem is solved for all-day traffic with an objective to find a global optimum solution. In the second approach, the sequential arrival and departure nature of the airline industry is considered. Accordingly, the planning period is segmented by time-intervals and the problem is solved for a subset of flights in each segment. While the objective is the same (generating a conflict-free aircraft taxiing solution with minimum taxi time, ground delays, fuel consumption), the segmentation approach enable us to solve real-life size problems.

4.2.1 Solution methodology 1: Global optimum

In this solution strategy, the proposed MILP model is solved for all existing aircraft in the system during a planning horizon. As is the case in all vehicle routing problems with time window, the proposed mathematical model is an NP-hard problem (Li, 2016). Therefore, large problems are not easily solved optimally in a polynomial time. In our case, more than 20 aircraft (on a network of 125 Nodes and 282 Links) cannot be solved within 2 hours on a personal computer. Moreover, in practice, a solution obtained from a model that considers all flights at once does not guarantee a better airport taxiing operation. During a day, due to several stochastic events (e.g., de-icing, loading/unloading, catering services, reliability and maintenance issues, security issues etc.), prepared flight plans may not be executed. Accordingly, the second approach is evaluated.

4.2.2 Solution methodology 2: Adaptive solution

In the adaptive solution method, the problem is solved iteratively depending on the selected number of time intervals (periods). In each iteration, a sub-set of aircraft, which are scheduled to arrive/depart during the given time-segment, is considered by taking into account the solution from the previous period. In other words, the solution for the period t is captured from flights in period t and the solution obtained from period $(t-1)$

$$SOLUTION^{t} = f(SOLUTION^{t-1}, FLIGHTS^{t});\ \forall \mathrm{t} \in \text{Ƥ}eriods \qquad (25)$$

The proposed adaptive solution strategy can be executed by most standard PCs for all major airports around the world in real-time. Furthermore, solving the problem in a sequential order for each period gives the opportunity to capture deviations from optimum solutions during the implementation phase, and reflect these deviations in the next solution. Since each iteration is executed with an updated information, deviations from optimum results during implementation would not result in significant errors. As a result, solutions can be executed without significant human intervention, hence, autonomous airport operations management would be a possibility.

Considering the complexity of the presented mathematical model and the problem size used for the case study, only the results obtained from the adaptive strategy are discussed in the following section. All scenarios are solved using IBM ILOG CPLEX Optimization Studio 12.9.0, using Optimization Programming Language (OPL) on a personnel laptop with a 64-bit operating system, 2.71 GHz Intel Core i5-7200U CPU and 16.0 GB RAM.

4.3 Data Collection and Parameter Estimation

In this experiment, we used the YUL airport layout visible from Google Earth (Figure 2). A total of 60 gates, 16 entry/exit locations on runways, 49 intersection points on taxiways are considered. The dimensions of runways and taxiways are approximated from the Google Earth images. Single day traffic was considered. As shown in Figure 5, peak traffic is observed during early morning from 7:00 to 9:00 AM and afternoon from 4:00 to 7:00 PM. Consequently, we solved the model for the afternoon rush hours traffic from 4 PM to 7 PM. The flight data, extracted from airport webpages on August 26, 2019, shows that the airport served 150 flights during the specified time-interval, consisting of 91 arrivals and 59 departures. Due to insufficient data, entrance and exit nodes for airplanes were determined randomly. As mentioned earlier, we assumed that the airport serves three classes of airplanes: Light, Medium and Heavy. The aircraft types are also assigned randomly: 48 light, 58 medium and 44 heavy aircraft. Also, in this study, the taxiing speed for jet-engine powered and tow-tractor assisted scenarios are determined as 600 m/min ($\cong 20\ knots$) and 400 m/min ($\cong 14\ knots$), respectively (Zhang, 2017).

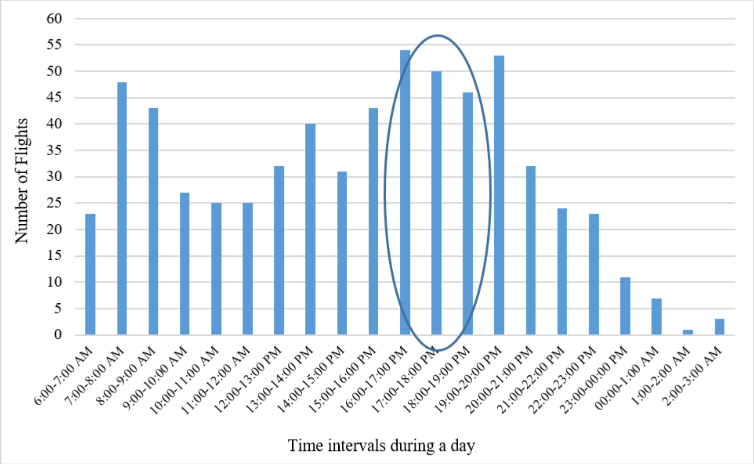

Figure 5: Distribution of flights on August 26, 2019, at YUL Airport

The Table 1 presents the minimum required separation-distance between aircraft according to their size. This feature allows the planes to move through the mesh networks safely regardless of the taxiing method.

Table 1: The required minimum separation distance between two consecutive planes in minutes

	The follower aircraft		
The leader aircraft	Light	Medium	Heavy
Light	0.5	0.5	0.5
Medium	0.5	0.5	0.5
Heavy	0.75	0.75	0.75

The average, per minute, fuel consumption cost is estimated to be $27,01 in 2017 (Outlook, 2017). Since the introduced case study includes three types (sizes) of airplanes, the fuel consumption cost per minute is estimated according to airplane-size: $20 for light; $27 for medium, and $50 for heavy aircraft. Furthermore, Airlines For America estimates the impact of delays as a cost for each passenger: $49 per hour (Airlines For America, 2019). Accordingly, the cost of delays is estimated based on the aircraft capacity: $41/minute for light, $98/minute for medium and $164/minute for heavy aircraft. Finally, the cost of operating an aircraft by the airport system is estimated to be $47/minute.

4.4 Numerical results: Alternative scenarios and analysis

The numerical results discussed in this section are obtained from the adaptive solution strategy. We evaluated three different airport management strategies with specific assumptions and compared them based on the cost and fuel consumption criteria.

4.4.1 Case 1: Zero tow-tractor in system

In the first airport management strategy, we assumed that all airplanes complete their taxiing operations using their own engines. This case is named as the baseline scenario which is also the worst-case strategy from an ecological point of view, since the fuel consumption and GGE are the highest compared the other two strategies. Including YUL airport, all major airports use tow-tractors (mostly diesel powered) to push aircraft from the gates to taxiways. Once the airplane reaches the taxiway, they complete the taxiing operations using their engines. The proposed airport operation management strategy aims at navigating all airplanes on the ground with minimum human involvement and with the highest efficiency (minimum delays and operating costs).

4.4.2 Case 2: All-towed option– All airplanes coupled with a tow-tractor

In the second strategy, all aircraft are forced to couple with a full-time electric-powered tow-tractor to complete taxiing operations between gates and runways. The objective is to assess the impact of utilizing electric-powered tow-tractors on delays, taxiing time, and fuel consumption. The second airport management strategy also aims at handling airport operations with a minimum human involvement; yet the minimization of fuel consumption is the primary objective.

4.4.3 Case 3: Hybrid towing option – Self towing option when a tow-tractor assignment is more expensive

Finally, as the third airport management strategy, we investigated a hybrid approach where airplanes were given the option to complete taxiing operations using their jet engines. When the tow-tractor is not available or assigning one to an airplane is more expensive (the cost of waiting for a tow-tractor exceeds the expected fuel burn reduction), the hybrid solution considers assigning electric powered tow-tractors to high fuel consuming airplanes and let more fuel-efficient airplanes to self-tow using their engine powers. In our model, aircraft are not separated in two distinct groups as high-fuel and low-fuel consuming aircraft. The proposed MILP model determines which aircraft to self-tow based on the traffic conditions at that particular moment and how each assignment contributes to the objective function. Accordingly, the hybrid solution strategy enables decision makers to consider the efficiency, the environmental-impact, and the operating costs simultaneously.

4.4.4 Solution analysis

In the first case, all 150 aircraft are forced to complete their taxiing using their engine-powers. A summary of the statistics for the first case is provided in Table 2. We compared the average taxi-in (ground travelling time from runways to the gates) and taxi-out times (ground travelling times from gates to runways) with the previous 13 weeks of data (Monday traffic) collected from YUL airport to demonstrate the potential benefits of using the optimized path planning approach (Figure 6). Undauntedly, the first point in both graphs that draw attention is the large difference in taxi-out times between our results and the actual performance of the airport. The reason behind these long taxi-outs in the existing system is directly related to the inefficiency of the manual controlling of the system. In most cases, the control tower keeps the departing airplanes in the stand to clear the way for the arriving airplanes. On the other hand, it should be noted that the impact of various stochastic events such as maintenance issues, catering services, passenger boarding process etc. is not precisely captured in our model. Therefore, the results presented in this paper should be considered as potential improvements.

Table 2: Summary statistics for the scenario 1

Title	Value
Objective Function (USD)	$66,821.31
Total Taxi Time (Min)	854.21
Avg. Taxi Time (Min)	5.69
Avg. Taxi-in (Min)	5.66
Avg. Taxi-out (Min)	5.76
Longest Taxi Time (Min)	18.07
Fuel Cost (USD)	$23,330.64
Total Delays (Min)	23.29
No. of towed airplanes	0

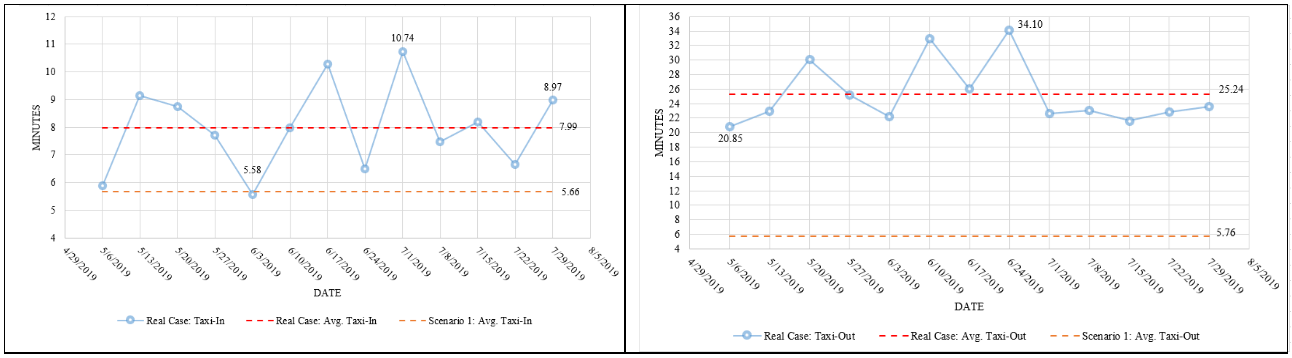

Figure 6: Comparison of the results of Scenario 1 and the previous 13 weeks of data: a) Taxi-in times, b) Taxi-out times

In the second case, we considered all airplanes to be coupled with tow-tractors to complete their taxiing operations. In this scenario, the performance of taxiing operations is closely linked to the availability of tractors. Hence, increasing the number of tractors in the system improves the performance. We tested airport operations with five different tow-tractor scenarios (10, 12, 15, 20 and 25 tow-tractors). As seen in Figure 7, increasing the number of tow-tractors in the system {10, 12 and 15} allows for a significant performance improvement. However, a similar rate of performance improvement is not observed when available tractors in the system is increased from 15 to 20. Moreover, we observe that the performance difference becomes larger when the airport is busier (between flight #1 to flight #100 average time between flights is 1.12 minutes. For the remaining flights, the time between arrivals (TBA) is 1.31 minutes).

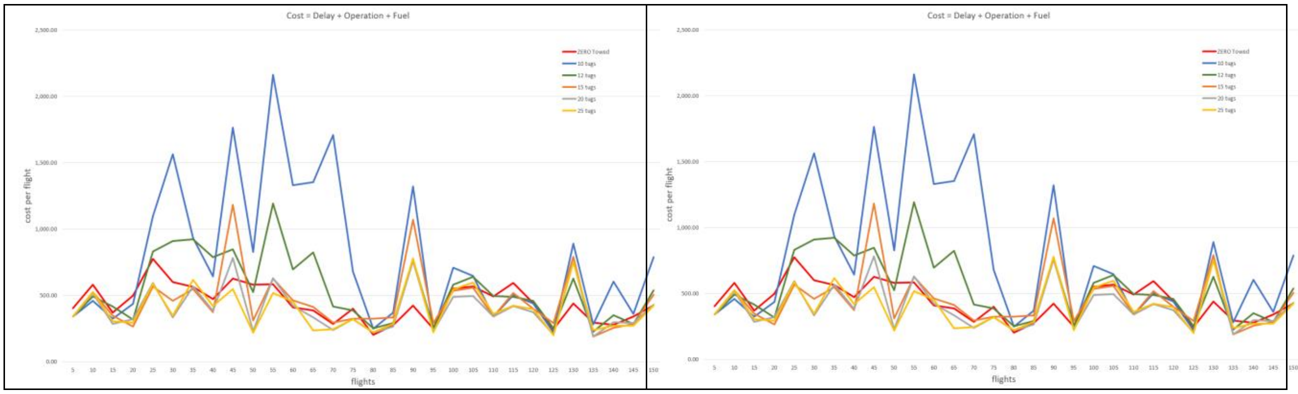

Figure 7: Impact of tow-tractor availability. a) Total cost; and b) Total cost: smoothed moving average

Figures 6 and 7 provide us with an important characteristic of airport operations: cyclical demand for resources. In the context of this paper, it is clear that the demand for tow-tractors will not always be sufficient to justify the purchasing of a large quantity of tow-tractors. Instead, a hybrid system, where larger airplanes use tow-tractors, but smaller, more fuel-efficient airplanes use their engine powers to complete taxiing when tow-tractors are not available, can achieve similar GGE reduction objectives with less towing tractors in the system. Accordingly, we investigated the third case study, the hybrid option with an objective to achieve sufficient gains in fuel consumption with fewer tow-tractors. Once again, the strategy was tested for a different number of tow-tractors in the system. Figure 8 summarizes the performance of i) No tow-tractor and 100% aircraft engine powered taxiing; ii) 10 tow-tractors and 100% towing is required; iii) 10 tow-tractors and hybrid towing option; and iv) 15 tow-tractors and hybrid towing option. Figure 8.a provides the total cost per flight for all aforementioned scenarios. Clearly, the *10 tow-tractors – 100% forced towing* is the most expensive option (the average cost being $786 per flight). When we remove all towing vehicles from the system, due to reduced delay penalties, the cost is significantly reduced (the average cost being $445 per flight). However, a significant part of the cost in this case is due to fuel usage (35%). Both hybrid towing options perform better than the other two cases (the average costs being $374 and $369 per flight for 10 and 15 tow-tractor cases, respectively). Fuel usage cost for the hybrid cases is 18% and 7% of the total cost for 10 and 15 tow-tractor cases, respectively.

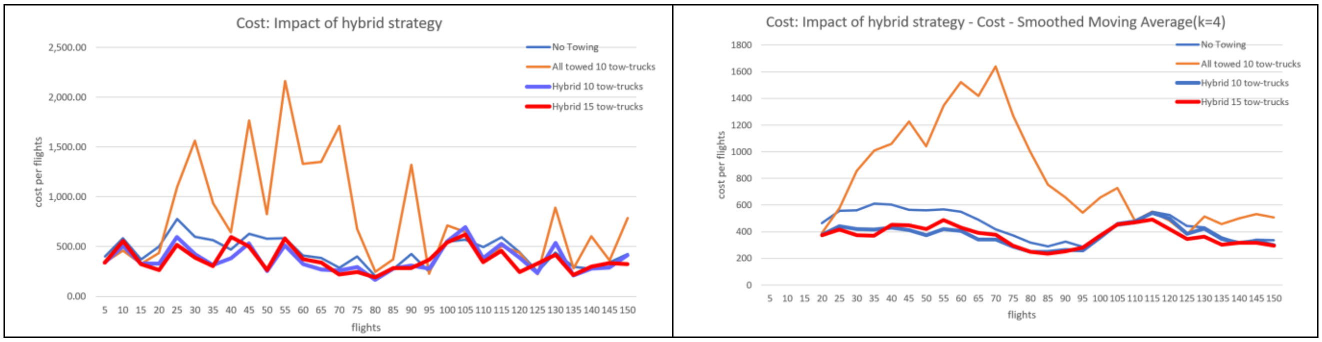

Figure 8: Comparing hybrid towing option vs. no-towing and 100% towing options. a) cost per flights; and b) smoothed moving average.

Finally, on a time-space diagram (Figure 9), we provide the routing of a selected group of flights to demonstrate the collision and conflict avoidance on links (Figure 9.a) and on nodes (Figure 9.b). By enabling a collision and conflict free taxiing environment, the proposed mathematical model demonstrates its potential to fully automate airport operations planning and management.

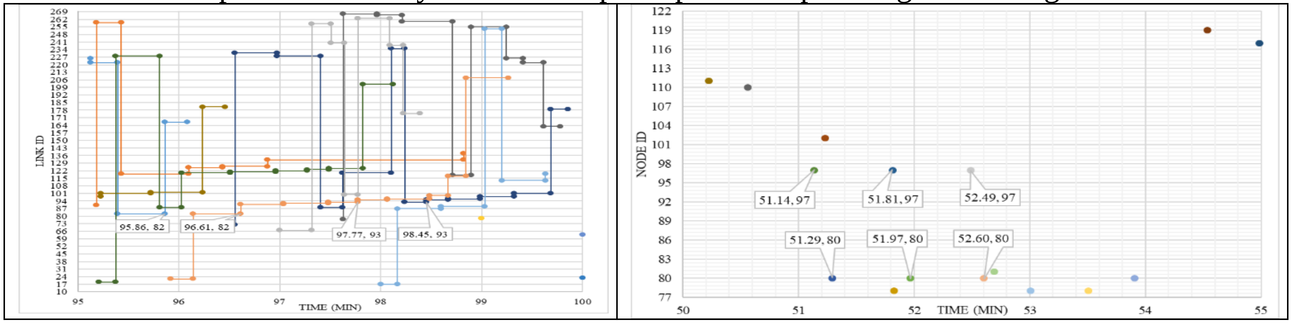

Figure 9: Flights routing information on a time-space diagram: a) Conflict avoidance on links; b) conflict avoidance on nodes

4.5 Selecting the Optimum Number of Tow-tractors for the Airport

The results provided in Figure 7 suggest that when demand for tow-tractor is higher (TBA = 1.12 minutes), 25 tow-tractors provide optimal operating conditions (average cost per flight ≅ \$400). On the other hand, similar operating conditions (average cost per flight ≅ \$400) can be achieved by 20 tractors when TBA is 1.31 minutes. A similar study for all flights between 6 AM and 9 PM (Figure 5) would provide the required number of tow-tractors (R^p) at a given time-segment p (one-hour intervals in our case). Consequently, we obtain a tow-tractor requirements for all time-segments from 6 AM to 9 PM similar to the one given in Figure 10.

In Figure 10, let *k* be the number of available tractors (purchased). When the demand for tow-tractors is higher than *k*, the hybrid towing option would offset the additional tow-tractor needs. On the other hand, when the tow-tractor demand is less than *k*, tractors will be underutilized. Depending on the purchasing cost of tractors and the cost of not having sufficient tractors, an optimum value for k^* can be determined.

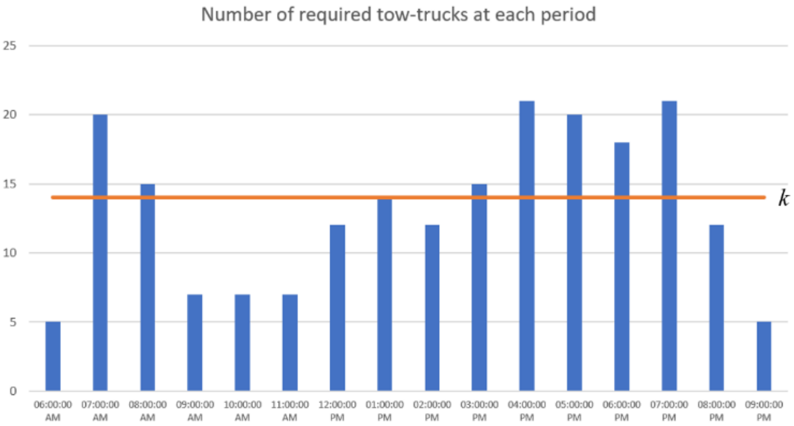

Figure 10: Tow-tractor requirement per period

Let C_A be the amortized cost of purchasing a tow-tractor, C_O is the operating cost of a tractor at period p, and C_S is the cost of not having sufficient amount tractor in period p, which is a function of the additional tractor needs (R^p – k). For a similar problem, Ghiani (2004) formulate the total cost of managing a truck-fleet for a given planning horizon. In Ghiani (2004), the objective is to determine the optimum fleet composition (owned and leased trucks). Accordingly, we estimate the total cost $\left(C_T^p\right)$ of operating taxiing operations with *k* tow-tractors as:

$$C_T^p = kC_A + \min\{R^p, k\}\, C_O + \max\{0, R^p - k\}\, C_S;\ \forall p \tag{26}$$

Next, the total cost (C) for the entire planning horizon is estimated using:

$$C = \sum_p C_T^p = pkC_A + \sum_p \min\{R^p, k\}\, C_O + \sum_{p:R^p>k} (R^p - k)\, C_S \tag{27}$$

Finally, there exists an optimum k^* where $\frac{d(C)}{dk} = 0$.

$$\frac{d(C)}{dk} = kC_A + lC_O - lC_S \tag{28}$$

where, l is the number of periods for $R^p > k$. For $\frac{d(C)}{dk} = 0$:

$$l = p\frac{C_A}{C_S - C_O} \tag{29}$$

Accordingly, the optimum number of tractors to be purchased (k^*) is determined at l^{th}period where R^p is higher than k^*.

V. CONCLUSIONS AND FUTURE WORKS

In this study, we proposed a unique mixed-integer linear programming model to optimize the aircraft taxiing operations. The proposed mathematical model composes of three objectives: minimizing taxiing time, ground delays and fuel consumption. All three objectives are formulated in terms of their costs. Major contributions of the paper are: i) evaluation of tow-tractor usage in airport taxiing operations; ii) collision and conflict avoidance formulation as part of the taxiing operations planning with tow-tractor assignments; iii) modeling local traffic congestion effect on taxiing operations; and iv) determining the optimum number of tow-tractor needs for the most economical service quality. The capability of the proposed MILP model is tested on a sample case study using Montreal's Pierre Eliott Trudeau International Airport. Due to the NP-Nature of the original model, a segmentation method, namely sequential solution, was proposed in order to tackle real-life size problems. Furthermore, different tow-tractor usage options were introduced, and their performances were compared. Our results suggest that the hybrid taxiing option has significant potential to reduce GGE at airports. Moreover, the collision and conflict free route planning future of our model has the potential to automate airport operations planning and to reduce both taxiing time and delays.

While the results discussed in this paper demonstrate the strength of our formulation, further research is required to fully adopt such planning tools. It should be noted that only the deterministic scenarios were evaluated. Stochastic events such as weather conditions, equipment failure, security issues, variability on auxiliary service-provider's performances and passenger boarding process were not considered. Moreover, charging times of tow-tractors are omitted. When they are idle, the movement of tow-tractors is modeled as a simple shortest path problem which assumes no conflict with other objects in the environment. While aircraft fuel consumption rate fluctuates due to acceleration, deceleration, stops and turns, in this paper a linear approximation is used. GGE is measured only as a function of fuel consumption. In reality, a number of different gases emitted by aircraft engines are considered greenhouses. Moreover, the paper considers GGE as the only environmental issue. In fact, noise pollution and the general impact of airport physical structures on wildlife are also significant environmental concerns. Finally, we only considered a single airport in our formulations. In order to successfully implement such techniques, one must integrate the network of airports and study the problem as part of the general ATFM problem.

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