Green Airport Operations:

Conflict And Collision Free Taxiing

Using Electric Powered Towing Alternatives

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ABSTRACT

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Everyday millions of liters of jet fuel are burnt while airplanes are running on the ground and releasing tons of air polluting gases in the earth's atmosphere. Scientists and technicians believe that more efficient taxiing strategies should replace traditional aircraft ground handling methods. Multiple factors should be considered in the airport operation programming. Environment protection, energy efficiency, safety matters, performance restrictions, and airlines' financial profit are some examples of these determinative elements.

Furthermore, aircraft ground operation is the leading cause of airports' air and sound pollution. It also becomes more remarkable to the airline companies when the risk of airplane ground accident is involved. At present, airports' control towers handle the airport's surface traffic manually. Human-made mistakes and slow responding time to high-risk occurrences may put the airplane ground handling system in serious problems. Due to this fact, the traffic control personnel have no choice except keeping departing flights in the gates and let them leave only when the entire assigned path is clear. This manual flow control approach is inefficient and causes long taxi times.

Technically, a robust mathematical formulation is able to offer optimal solutions for the airport surface operation. In this study, a new, environmentally friendly optimization formulation is developed in order to minimize the total taxiing time and aircraft's fuel consumption on the ground by eliminating unnecessary delays. Moreover, solving airplanes' conflict problems in ground movements is guaranteed during the entire taxi-paths, since without considering the aircraft collision avoidance feature, the mathematical model will not be practical.

Based on the presented methodology, a combination of the single-engine taxiing method and truck-towing is suggested as the best practical solution. The conducted investigations indicate that this approach provides both economic and environmental benefits to the aviation industry. The accuracy of the offered model is validated by the daily aircraft's data on the layout of the Montréal-Pierre Elliott Trudeau International Airport. Three extensive sets of numerical analyses have been conducted to provide better insights into the issue. In each part of these analyses, different determinant factors such as total taxi time, total fuel consumption, and total delay have been used to compare the obtained results of the proposed approach with the current situation at the airport. After studying all effective elements and analyzing the results, an environmentally friendly and economically efficient approach is offered.

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In the end, but by no means least, thanks go to my parents, my brothers and my friends for almost unbelievable support and their endless love. They are the most important people in my world, and I dedicate this thesis to them. Without their help, my achievements were simply impossible.

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CHAPTER ONE

1 INTRODUCTION

Regarding the growth of the worldwide demand for travelling, the volume of traffic on roads, railways, skyways, train stations, and airports continues to grow every year. In some cases, it may seem that even doubling or tripling the facilities and equipment does not cover this growth in the demand. As Statista reports, the number of flights, as well as the number of passengers, are steadily rising year over the years (see Figure 1.1 and Figure 1.3). More than 4.38 billion passengers were carried in 2018 by airlines worldwide, which means a growth of 8.4 percent than 2017 (Statista, 2019). As can be seen in Figure 1.2, the increase in the number of passengers had a positive value over the last nine years, and it is predicted to be around five percent in 2019 (Statista, 2019).

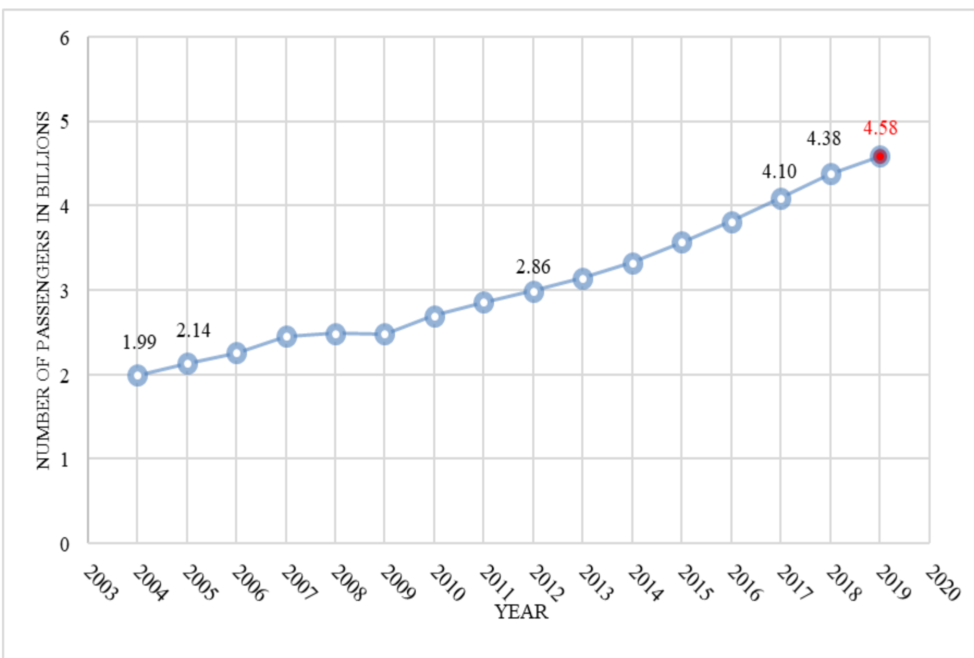


Figure 1.1: No. of Scheduled Passengers Boarded by the Global Airline Industry

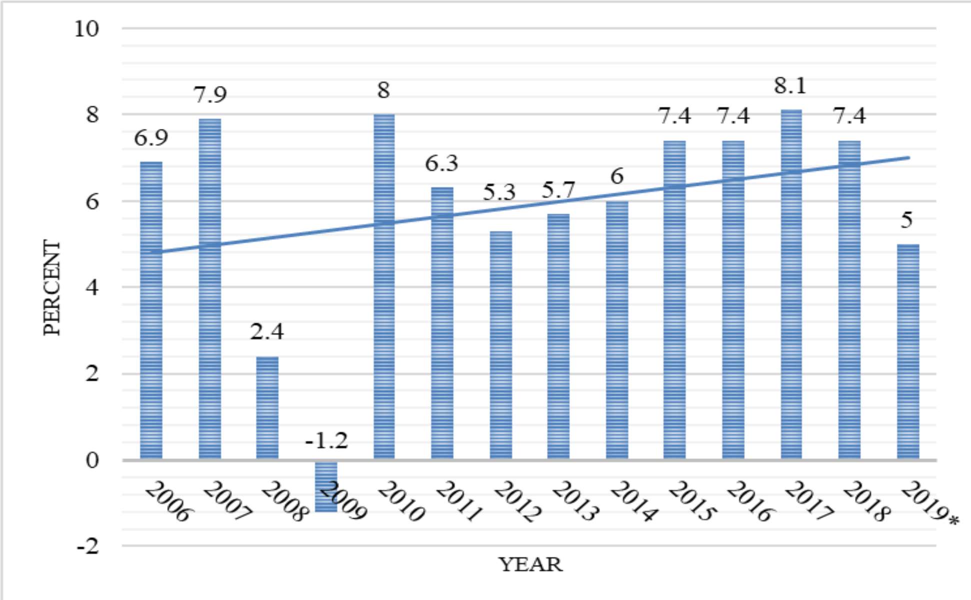


Figure 1.2: Annual Growth in Global Air Traffic Passenger Demand

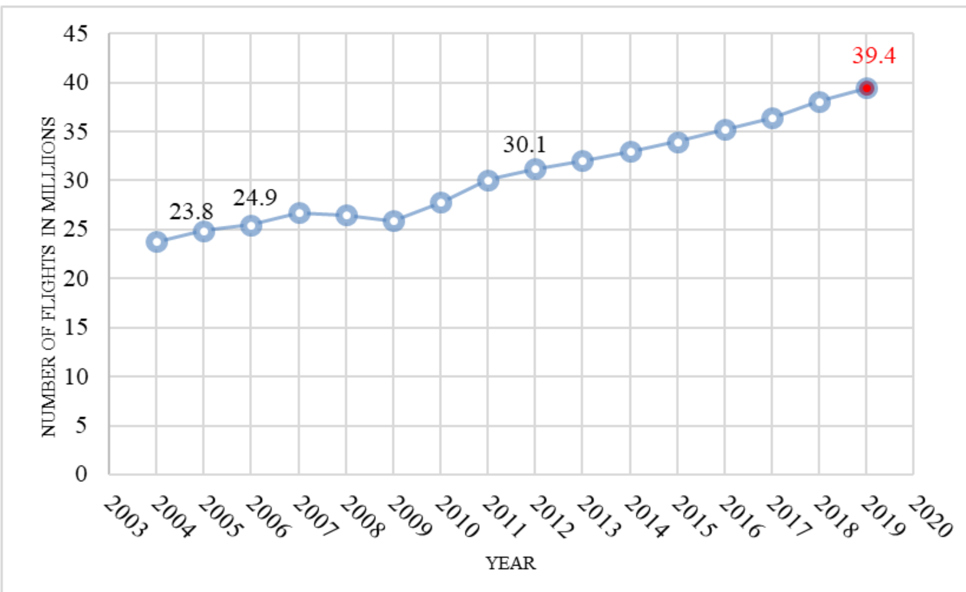


Figure 1.3: The Number of Yearly Flights by the Global Airline Industry

Also, the number of global flights is expected to increase by up to 39.4 million (Statista, 2019). These conditions in the aviation industry have created many challenges as well as benefits for this industry. Not only the importance of air transport in passenger and cargo transportation but also its side problems turned into an interesting subject for both aviation investors and its investigators.

The airline businesses are expanding steadily, and the aviation industry is facing new challenges. Rising operation costs, increasing environmental awareness, rise in demand for air travels, crowded airports, and unpredictable weather conditions are some examples of these challenges. Most of the studies in the air-transport attempt to reduce the risk of accidents, improve the safety of personnel and equipment. Also, aviation investigators intend to increase the capacity of air transportation, reduce fuel consumption by designing new equipment, and enhance overall comfort in travel and performance of the aviation system for passengers.

Many countries around the world have signed an environmental agreement to reduce the Green House Gas (GHG) emissions by 80 percent until 2050. Approximately 20 percent of global GHG emissions are related to the transportation industry, and USA transportation has the largest share of the total. The air transportation sector is responsible for almost 10 percent of GHG emissions in the USA (Greene & Schafer, 2003). These facts draw attention to the importance of the aviation industry's rule in global climate change.

Airways traffic congestion from one side and the growing number of aircraft in the airports waiting in the gates or using the runways from the other side, according to the current capacity of air-sector and airports, cause lengthy delays and potential safety issues. Every kind of delay means the cost to the aviation industry, which can be categorized by various features into direct, indirect, and operational expenses. The majority of delays occur while the engine is working. Consequently, these suspensions lead to an increase in GHG emissions, as well as an increase in fuel consumption.

On the other hand, the safety of passengers, as well as the safety of airport equipment, are the most critical factors for companies and governments. It is evident that, for all airline companies, the cost of an accident in the aviation industry, even for minor incidents, is drastically expensive and could lead to a considerable decrease in their total yearly profit. In such cases, the air transport industry hopes to take advantage of the art of optimization to tackle these problems. Most of the existing issues, like delayed flights, inefficient energy consumption, potential accidents, and environmental pollutions, can be minimized. Studying the current situation and implementing the optimization methods improve the efficiency of this industry considerably.

Studying the current situation of the aviation industry helps in predicting future occurrences in this field. A bright and accurate prediction of ahead troubles can be obtained by statistical analyzing previous data, such as detecting the cause of accidents or delays and discovering the issues that happened in the past. It is worth mentioning that most of these mathematical strategies do not require fundamental changes to the existing systems. It is only required to modify them to enhance their efficiency in a way that they can be used in the best order and at the best time with the highest capacity — for example, allocating the gates to the flights in such a way that the shortest delay achieve.

The Air-Traffic Management (ATM) has been studied in many articles with different hypotheses, which has led to coming up with various methods in the aviation-related subjects. Principally, the ATM is responsible for evaluating and improving the aircraft movements only in skyways. Technically, the Air Traffic Controller (ATC) has the duty of controlling aircraft movements in skyways and on the ground. Radars, computers, and navigation systems aid in monitoring and handling actions in space. The task of managing airplanes on the ground mostly will be done with the help of visual supervision. In such a way, aircraft require permission from the control tower to occupy a taxiway or a runway. The slowness in responding to occurrences, human errors, uncertainty in avoiding accidents, traffic congestions in rush hours, inefficiency, and sequential delays are some of the disadvantages of this method to control airport surface maneuvering.

Due to traffic volume in busy hours, the delay is unavoidable. Also, in the aviation industry, safety has priority over other problems. In some cases, making delays will be used as a solution by the ATC operators to resolve ground conflicts. Undoubtedly, these delays lead to inefficiency in the system. On the other hand, the Airport Ground Movement Problem (AGMP) is an alternative technique to handle the airport ground movements. Generally, the AGMP attempts to solve two aspects of the aircraft ground movements' problem, including tracking and timing. The tracking part is known as the path planning problem, and the timing part is named the scheduling problem. The definition of the path planning problem is stated as, given a vehicle and a network of possible links, planning a sequence of connected links between two specific locations that satisfy optimization criteria. Particularly in the airport surface problem, the path planning issue is defined with the purpose of finding the optimal path to reduce the total taxi operation time. Likewise, the scheduling can be defined as discovering the best order for serving the system entities.

The purpose of a wide range of ground-movement-related studies is to reduce human errors in critical systems as well as reducing the fuel consumption and the CO_2 emissions ejected from jet engines. Hence, inventors are interested in developing automated towing vehicles to decrease the effect of human mistakes and air pollution during taxi operation. The new generation of these automated driverless trucks is able to pull or push aircraft on the ground from the gates to the runways and vice versa. In most of the cases, it is usually expensive and challenging for the industry owners to accept and replace the existing equipment with new generations. The airline industry is not an exception. Although several types of airplane tugs have been made so far, and various papers have introduced new taxiing methods, it is seldom the case to find a practical solution.

A substantial number of previous studies tried to compare different taxiing operators, such as internal electric engines, electric external tugs, and external diesel trucks. Then, they concluded that a specific method is more advantageous than others. Some others suggested mathematical solutions to use jet power for taxi operation with higher efficiency. Both types of investigations are valuable and bring many opportunities to the industry. However, in practice, both types of studies are entirely inseparable.

Today, it is evident that using jet power is not the best way for aircraft ground operations since the environmental impact and the operating expenses are continually increasing. Meanwhile, there is no possibility of substituting all components of the current system with new ones. Hence, in this research, it is attempted to generate a realistic solution for the airport surface operation problem with a combination of two strategies, as mentioned earlier. Besides, to make the offered approach as practical as possible, the aircraft's conflict resolution concerns have also been taken into account.

In the second chapter, the literature review is provided. In the third, we present our optimization programming model in detail. The fourth chapter is dedicated to introducing our case study. It is followed by Chapter five, where we provide the results of the case study using our methodology. Finally, Chapter six concludes this thesis by introducing conclusion and future work.

CHAPTER TWO

2 LITERATURE REVIEW

In this chapter, we categorize the challenges to the aviation industry and provide a definition for technical subjects. Also, the airplane ground movement process and its side concerns are discussed in detail. Then, the present situation and existing solutions for aircraft taxiing are reviewed. In the end, a summary of all previous researches and the contribution of this study is presented.

2.1 Taxi Time and Aircraft Ground Delay

In general, the task of towing an aircraft in the gate, ramp, or parking area using an external power is called push-back operation. Likewise, the definition of the aircraft taxiing is the movement of an aircraft from a stationary position in a gate, ramp area, or parking to the beginning of a runway or vice versa using its power (ICAO, 2013). Therefore, the taxiways are the links that connect each two-point of the airport surface and can be used for aircraft taxiing (ATC Definitions, 2019).

Technically, the delay is the positive difference between the actual time of an event and its scheduled time. If we assume an airport with all of its components as a system, including operators, facilities, passengers, and pathways, it is evident that delay in every single part of it makes trouble for the whole system, which incurs costs to it. Although in the airline industry, the postponement is inevitable in most of the cases, it can be managed. Hence, the aviation industry attempt to find new solutions to decrease and eliminate delays as much as possible.

Overall, aircraft's ground delays may happen in every stage of the ground operation in an airport. For instance, delays while standing in the gate, after departing the parking, before actual take-off. Hence, the total delay of an airport is used as a determinative element to estimate its efficiency, especially delays which occur during taxiing operation of departing airplanes.

In accordance with a report by the Office of Performance Analysis of FAA (Federal Aviation Administration), considering 30 different airports over a year shows a considerable increase of 35% in the number of flights with at least 15 minutes departure delay between 2016 and 2017, specifically delay corresponding to runway operation nearly threefold in this period from 5.2% to 14.6%. Also, in this work, the aircraft delays are categorized by the cause of delay. As is evident in Figure 2.1 and Figure 2.2, exclusive of the weather, the airport surface high traffic is detected as the reason for a large share of delays (FAA, 2018).

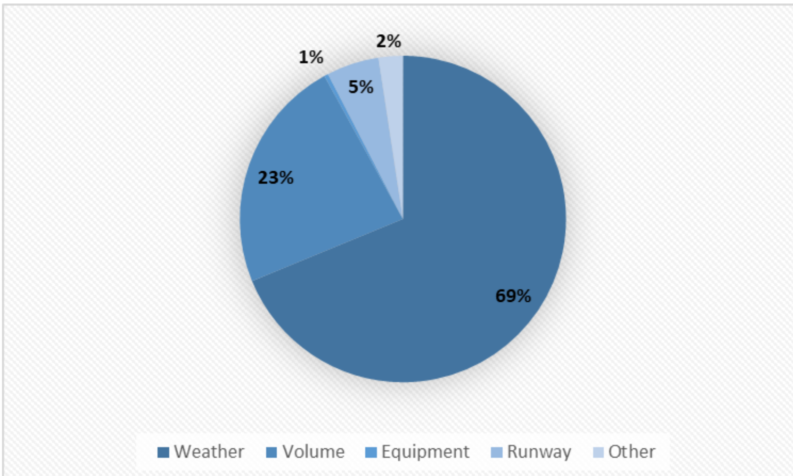


Figure 2.1: Flights Delays by Category – 2016

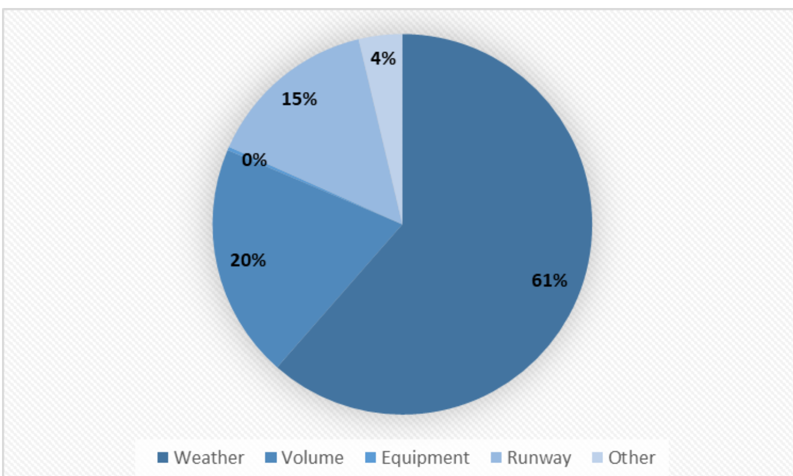


Figure 2.2: Flights Delays by Category – 2107

Simaiakis and Balakrishnan analyzed the United States aviation and statistically indicated that U.S. airplanes were under taxi operation over 213 million minutes in 2007, containing 63 million minutes and 150 million minutes taxiing time for arrival and departure flights, respectively. It has also been measured that 10 to 30 percent of flight time in Europe is involved in the taxi operation.

Mainly, the cost of delay splits into direct costs and indirect costs. Extra crew and personnel salary, more fuel consumption, returning ticket fare, providing meals and refreshments, temporary accommodation for passengers, and cost of effect on the airport’s schedule are some examples of delay costs. Research by the Eurocontrol approximates the cost of each minute of delay to be €99. They also assessed the passenger’s value of time from €40 to €52. Moreover, they indicated that the cost of cancelling a flight is more than €34,000 (NLR, 2008). The total delay cost (direct and indirect expenses) is estimated to be more than 26 billion dollars in 2017, which is extended approximately 11.3% compared to 2016 (FAA, 2018).

AFA (2018) calculated that a passenger has a cost of $74.2 for U.S. airlines in each minute of his/her travel, including taxi operation and air-sector travel time. The fuel cost computed about $27.07 per minute and, with nearly 36.4% of the total. Also, this study has considered the value of passenger time $49 per hour by the average. According to the Canadian Travel Agency (CTA) new regulations, effective from July 1, 2019, Canadian large airlines have to pay an amount of $400, $700, and $1,000 for delays of three, six, and 9 hours, respectively (CBC, 2018). The airlines' financial profit is directly affected by the cost of delay. Although the delays in the scheduling phase are more prevalent rather than the operation phase, the cost of one-minute operational delay is typically higher than the cost of a one-minute planning delay (Cook et al., 2010). Besides airline companies’ interest to increase their profit, several other reasons induce them to estimate delay costs in each phase of operation. Environmental concerns, predicting future demands, justification of improving projects, and decreasing the travel fares are some other causes that motivate airlines to calculate the cost of delay (Diego, 2011).

Leaving the gate through push-back, taxiing in the middle of the airport, and entering the runway are three phases of the aircraft ground handling for a departing flight. Theoretically and practically, the most challenging phase can be the first part. The safety circumscriptions, space limitations, and high traffic volume near stands, and ramp area may cause to delay in entering or leaving the gate. One of the most common incidents occurs when one aircraft is leaving the gate, and the other one is running in the shared path. In the situation mentioned above, they may block each other's way and cause delays (Stergianos et al., 2015). The EUROCONTROL is reporting that in the standard airline measure system (gate-to-gate), flights delay more in leaving the gates compared to entering the parking. Typically, both lateness and earliness have undesirable effects on the airport system. In addition, this study shows that the primary delays at the beginning of the day can affect all enplanements of that specific plane in the next 15 hours (Eurocontrol, 2018).

Growth in the number and the length of the bottlenecks during aircraft ground operation is one of the most challenging issues that aviation is facing. Generally, there are two ways to tackle this problem. One is to expand the airport's equipment and taxi-paths, which is very costly, and it is not efficient in many cases (Ravizza et al., 2014). Besides, for many airports, it is not even possible to add gate, runways, or taxiways to the airport's layout. The second option is to utilize existing equipment efficiently, which can be obtained by applying mathematical methods to real problems (Ravizza et al., 2014).

2.2 Fuel Consumption and GHG Emissions

The AFA reports that after the operating costs, the fuel cost sorted as the second-largest expense to airlines, which has grown drastically by the rate of 15.3% between 2016 and 2017. This website assesses the airline's direct operating costs per block minute for U.S. passengers. They have estimated that the average of total operating costs was about $68.48 in 2017, which is approximately 7.5% greater in comparison with the preceding year. This amount includes ground and space movements' expenses. Moreover, they computed the average value of passenger's time per minute about $49 (AFA, 2017).

It has been calculated that almost 4 to 5 percent of the total power of a jet engine contributes to aircraft self-towing. Also, this feature is usually assumed to be 7%. However, in some other cases, it could reach up to 9%, depending on the utilization of thrust and required maneuvers (ECCAIRS, 2013; ICAO & Council, 2008; Ravizza et al., 2013). It is worth mentioning that almost 40% of total operating expenses to airlines is related to the fuel cost. Studies show that at least 6% of this fuel burns during the ground operation (SAFRAN & Honeywell, 2013). It has also been estimated that burning a gram of jet fuel, emits 3.16 grams of CO_2 (ICAO, 2016). Knowing that a Boeing 747 consumes approximately 1000 kg kerosene in a 15-minute taxi time can help to understand this amount better (Stuff.co, 2018). Ravizza et al. (2014) calculated that the jet engine during single-engine taxiing burns approximately 10.9 kg (25 L.B.) in a minute. Some other papers declared that a medium-size aircraft consumes 11.5 kg/min of fuel while taxiing. Technically, several factors are involved in evaluating the airplane fuel burning rate, such as the size of aircraft, its weight, number of engines, and speed of operating. Different approaches have been studied to minimize aircraft delays during the ground movements, for both push back and taxiing operation separately. However, in this work, we try to generate a new method for a combination of these two levels of aircraft ground maneuvering with optional truck-taxiing to minimizing the delay.

2.3 Foreign Objective Damage (FOD)

Although airplanes can move from the gate to the beginning of runways using jet engines (or vice versa), the jet blast or prop wash may cause damage to the terminal building or equipment. Engine close to the ground may also blow sand and debris forward and then suck it into the engine. This situation can cause severe damages to the engine and has irreparable losses to companies. Towing aircraft by a truck is a preferred method to move it from the gate to the beginning of the runway and vice versa (Hospodka, 2014). Typically, the airport ground movement vehicles and the airport operators are the sources of foreign objects. Every person who works in the parking, ramp, or taxiway areas is in charge of tools or vehicles they use (dgac, 2015).

2.4 Sound Management at Airports

In most developed counties, the main airports of metropolises are located in an entirely urban area and close to city centers. Toronto Pearson International Airport, Canada; Zurich Airport, Switzerland; Changi Airport, Singapore; and Hong Kong International, Hong Kong are such examples. For every airport, the distance from downtown is considered as a popularity factor. However, there are many obstacles to bringing airports to the heart of the cities. One of the most important matters is the airport noise problem. Technically, jet engine and air turbulence are two principal sources of noise in the airport. Current engines are more developed and quieter than models that existed 20 years ago, but they are still annoying, especially for the airport ground personnel who are affected by loud noises every day for long hours. One solution is working on engines to improve their technology to make less sound, which may take more than a decade to produce a new generation of engines. The other solution is to use tugs for taxiing operations. Therefore, the engine stays off during the ground operation, and it goes on precisely at the beginning of the runway. Hence, with the reduction of noise in the airport, even the urban areas which are close to the airport hear fewer noises (ADM, 2017). European Aircraft Noise Measurements System (EANS) is an NGO that is issued to monitor and measure noise levels in Europe. Figure 2.3 is a graph of affected areas of the city of Frankfurt by airport noises (EASA, 2019).

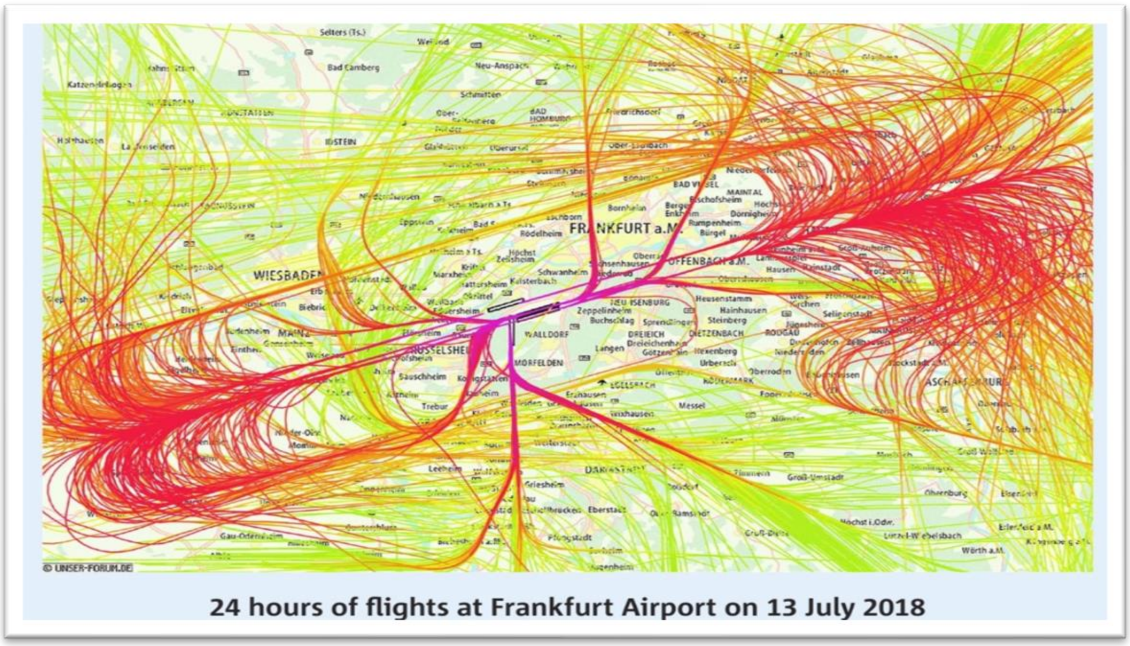


Figure 2.3: Affected Regions of the City of Frankfurt by The Airport's Noises (EASA, 2019)

2.5 Taxiing Methods and Towing Vehicles

Ithnan et al. (2013) investigated all existing aircraft taxiing operation methods including, full-engine, single-engine, using towing vehicles, and using electrical nose-gear. This study indicates that the total taxiing time is increasing at a higher rate than air-sector flight time and the number of flights. The alternative strategy is using an external towing vehicle, which is the base of our study. Typically, this external truck using a diesel-engine or an electrical-engine. In this case, the push back operation is a part of the whole taxiing operation, and a towing vehicle carries the aircraft between two specific points. Therefore, the jet engine turns-on if necessary. For instance, for a departing airplane, an assigned truck to the plane push it back from the gate and extends its operation to the beginning of the runway. Thus, the engine might go on in the last few minutes, since the taxi time is usually longer than warm-up time. It is evident that if the ground operation system relies only on external towing power, the total taxiing time and total delays will increase. The principal importance of self-guided vehicles like automated towing trucks is to decrease the total operation time. Thus, a strong mathematical formulation is required to control the system of multiple trucks. This highly detailed report by Ithnan et al. (2013), compared all possible taxiing methods at Amsterdam Airport Schiphol over a week and pointed out to the most remarkable benefits of using an external tug vehicle instead of full-engine or single-engine taxiing. Based on the results of this study, taking advantage of the towing trucks in place of full and single-engine methods can reduce the fuel burn up to 36.6% and 14%, respectively. As reported in this research, CO_2 emissions, which is the most produced pollution from burning fuel, is decreased from 3.39 million kg to 2.51 million kilograms.

The other possible ground operation method is using electrical nose-gear, which could lead to a 95% decrease in noise level, a 17% decrease in emissions, save more than $200 per flight, and reduction a huge daily amount of fuel. Although this method seems to be more efficient than the other ways, it has several hidden drawbacks, such as carrying extra weight during the entire flight's time, which leads to consuming more fuel and producing more emissions. Besides, with electrical nose-gear, there is still a risk of the ground accident since the pilot controls the aircraft on taxiways. Unreliable obstacle detection by the crew because of the large blind spots as well as late detection were two reasons to Knight (2013) to invent a system that avoids aircraft collisions with the airport surface obstacles.

The tow tractors vary according to their towing capacity, year of production, source of power, and type of control system. In terms of capacity, they can be divided into three groups, such as light, medium, and heavy. The lifetime of a towing truck is predicted to be around 15 years on average. The old generations work with a diesel engine, and the developed models utilize an electric engine. These vehicles split into two classes with respect to the type of driver, including the onboard driver (older productions), the out-board controller (new technology). The out-board driver towing vehicles divide into two types in terms of the controlling technology:

- The manual-control vehicles: an operator (that can be the pilot or ground personnel) conduct the truck via a controller. The controller can be a wired or wireless keypad. One type of truck is being used by the Lufthansa airlines at the Frankfurt airport (Hospodka, 2014; United States Patent, 2001).

- The automated-control towing vehicles: an operator can control the truck via a programmed software. A unit control system is responsible for guiding a system of multiple trucks and airplanes. The operator defines the destination, and then the system drives the tractor to the target point on the optimal path (United States Patent, 2011).

2.6 Airplanes Collisions

Several factors play different roles to guarantee the safety of an aviation system, but always the safety distance between two following flights, which are carrying passengers, and the head-on collision, are the main issues in both airspace and on the ground (Pallottino et al., 2002). Many papers exist in both parts, but in this paper, we intend to tackle problems that may happen for the aviation system on the ground and during taxi handling.

2.6.1 Aircraft Collisions History

A statistical study by Allianz Global Corporate & Specialty (2014) evaluated the challenges, risks, and improvements of aviation safety over 60 years. As stated in the Boeing definitions, a flight can be divided into nine phases, including taxi, take-off, initial climb, the final climb, cruise, descent, initial approach, final approach, and landing. Figure 2.4 and Figure 2.5 show the rate of the accident by the phase of flight in two distinct periods. Due to the lack of information, accidents during the ground operation is not indicated in the first graph.

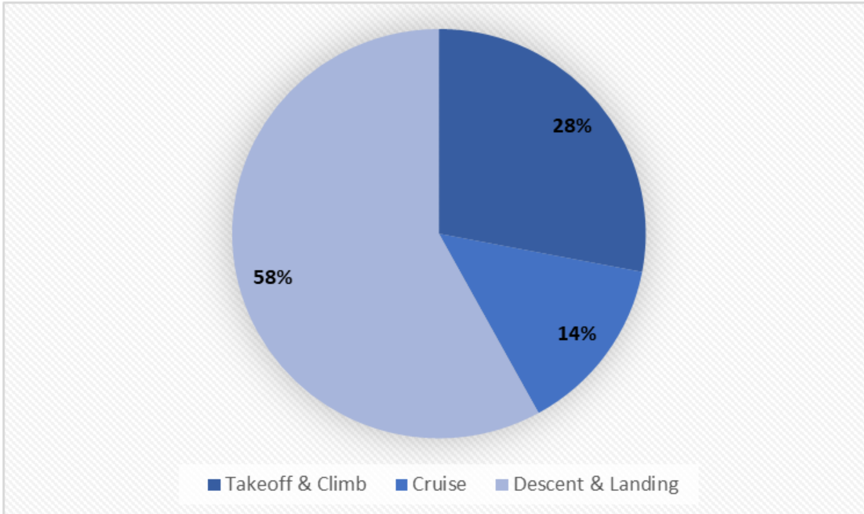


Figure 2.4: Accidents by Phase of Flight 1953-93

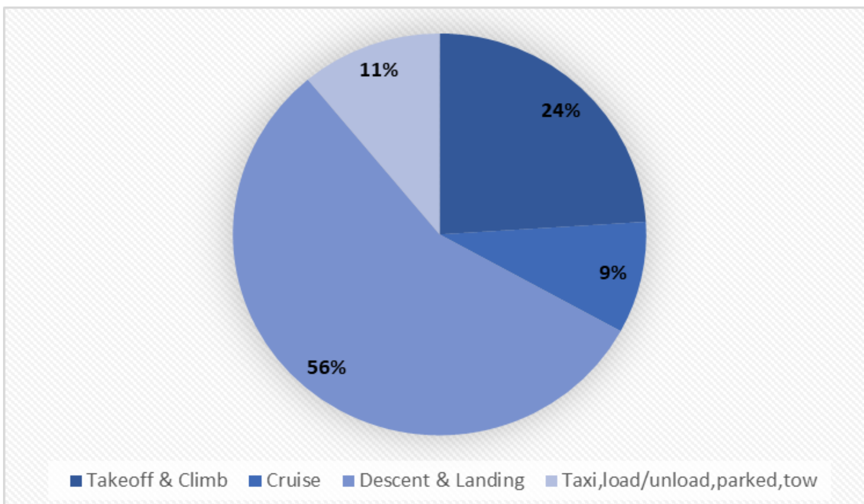


Figure 2.5: Figure 2.6: Accidents by Phase of Flight 2003-12

This article reveals that although the rate of an aircraft accident in the air-sector is decreasing or remained constant over recent years, the ratio of the ground incidents is growing. The massive volume of traffic in the airports can stand as a possible cause of this growth. Figure 2.7 and Figure 2.8 clearly demonstrate that most of the ground accidents occur by arrival airplanes and in the stationary phase.

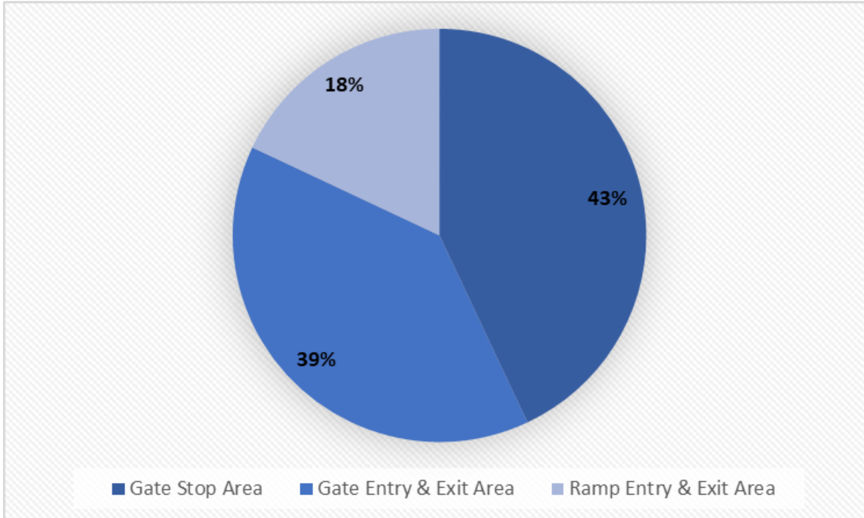


Figure 2.7: Distribution of the Location of Ramp Incidents (Arrival and Departure)

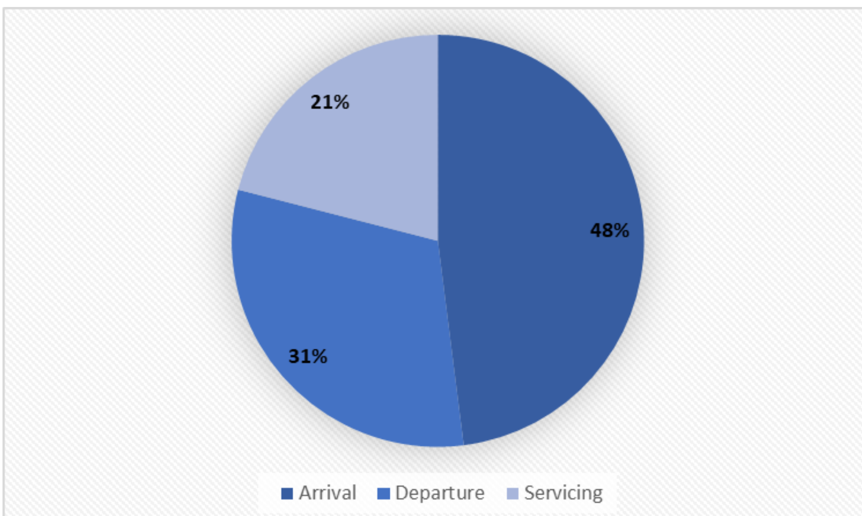


Figure 2.8: Type of Flights Involved with Incident in the Gate Stop Area

2.6.2 Collision in the Air-Sector

Several papers have been published to offer new optimization methods for flight routing problems. Most of them consider the airspace as a mesh network and propose a path planning solution to minimize the total flight time. Some other papers provide solutions for flight safety concerns in addition to tracking problems. Technically, there are two general ways to define a safe path for a flight. One, splitting the airspace to multiple zones and considering a capacity for each zone. Two, applying a safety distance between every two-following aircraft on the same arc. We refer to two samples since airplanes’ conflicts in the air-sector are out of the scope of the current study.

A recent paper by Akgunduz et al. (2018) introduced a new safe and economically efficient model to solve conflicts and crashes in the space during the flight by considering a minimum safety time between every two airplanes in the same zone. An article by Pallottino et al. (2002) applied the path planning problem to minimize the total flight time among a given network for multiple aircraft systems in the airspace. It also offered two different formulations for flight conflictions, one with velocity changes and the other one with heading angle changes.

2.6.3 Collision on the Ground

The same idea for the safety of an aviation system in the airspace prevents aircraft from hitting each other on the ground. The other factor that aids in evaluating an airport's performance is its safety and the rate of ground accidents.

2.6.3.1 Importance of Ground Accidents Prevention (GAP)

The Flight Safety Foundation (FSF) reports that one of each 1000 departures from international airlines is involved in a ground incident yearly. They also estimated the injury rate by 9 per 1000 departures. Every year, accidents in the ramp area lead to an amount of $10 million-dollar cost for airports and airlines. In 2003, the FSF decided to start a new program to supervise the aircraft's ground operation safety. The Ground Accident Prevention (GAP) program, is responsible for developing safety standards in the aviation industry (FSF, 2007).

The direct cost of damages to the aircraft staying in the apron area is assessed five billion dollars worldwide by the GAP program, only in 2007. It is also predicted to reach 10 billion dollars year for direct and indirect costs overall. Likewise, the ground handling operation enumerated as the second most considerable risk management challenge by the number of claims from 2009 to 2013 (Allianz Global Corporate & Specialty, 2014). A study by the NAL (2008) on 14 million flights shows that three flights of each 15,000 trips around the world engaged with a ground accident and caused damage to aircraft and equipment. Nearly 30% of these damages are hard to detect, which can lead to high-risk damages. Technically, the last check that happens in the last moments before leaving the gate has the highest importance, because it is hard to recognize and resolve mistakes in or after these moments (dgac, 2015). Almost 85% of airport ground incidents occur during a stopped situation, as reported by NAL (2008).

The BOEING Statistical Summary of Commercial Jet Airplane Accident (2017) categorized the fatal accidents by the phase of flight and indicates that the percentage of fatal accidents that occurred during ground operation is around 9%, including taxiing, loading/unloading, park, and towing steps.

2.6.3.2 The Main Reasons for the Ground Accidents

Hitting barriers such as airport equipment, buildings, guide signs, parked vehicles, light shafts, stayed aircraft, and other users of the shared areas of airport accounted for almost 18 percent of ground accidents. Studies show an average of 50 accidents occurs during slow-moving ground operation, which rarely results in fatal or injury. It should be mentioned that accidents that happen on the ground due to failing in take-off or landing phases will not be counted as taxi accidents even if they occur on taxiways (Aviation Safety, 2002). Technically, an accident should have three elements to be considered as a taxiing accident, including running under the ground operation, travelling at taxiing speed and occurrence on the airport's surface. For the incidents that happen between two planes, at least one of them should have these three factors.

The collision during taxi operation can occur because of different reasons, but human errors always are the principal causes (Smeltink et al., 2004). Hence, to decrease these kinds of mistakes, creating an optimal and safe system for ground movement of aircraft is essential. Although the line of sight in the nighttime is more limited than in the day, most of the accidents occur in the daytime (Aviation Safety, 2002), since the volume of traffic at night is less than at the day time (Eurocontrol, 2009).

Wing and tail collisions contribute to about 15% of accidents between two aircraft on the ground. This type of incidents usually occur when an aircraft is occupying an intersection of airport paths, and the other airplane is moving through an adjacent way. Tailwheel and wingtip accidents on turns, passing in the opposite direction and, waiting in a shared area close to the runways for the permit to occupy a path are the prevalent aircraft's ground collisions. A reason for the accordance of these accidents is taxiing at high speed by impatient pilots, and few of them are mistakes by the control tower.

Some of the typical crew errors are in results of lack of familiarity with the airport, limitation of pilot viewing angles because of blind spots, vision limitations, especially at nighttime and taxiing without appropriate patience (Aviation Safety, 2002). Due to the position of the pilots' cabin, they are not aware of activities that happen on the ground. In this situation, the lack of communication between the crew and ground personnel is a potential threat to the aircraft's safety. Also, human mistakes in marshalling the aircraft can be a reason for ground accidents (dgac, 2015).

2.7 Literature Review of Solution for Airport Surface Operation Problems

Airport ground operation is an interesting subject in aviation studies because of its rule in connecting different aviation problems, such as runway and gate scheduling, and gate assignment problem (Ravizza et al., 2014). The importance of safety in the aviation system is not hidden to anyone, but most of the previous papers focused on safety airborne subjects or on introducing new technical devices and systems to control airplanes in space or on the ground.

Rathinam et al. (2008) presented an approach to decrease taxiing time at the Dallas Fort Worth International Airport (DFW). According to the FAA's report, in 2018, the DFW ranked as 15^{th} - the busiest airport in the world and fourth – busiest U.S. airport with handling 69.1 million passengers in a year (DFW, 2019; Hetter, 2019). In this airport, in every half an hour, approximately 25 flights leave only from the eastern runways of the airport. The main idea and solution method of this paper is similar to and based on an Air-Traffic Flow Management Problem (ATFMP) by Bertsimas et al. with additional consideration of the type of aircraft and safety constraints which makes it fit with an Aircraft Taxi-scheduling Problem (ATP). Generally, the safety issues in the ATFMP are defined with considering a capacity for each air-sectors and airplanes can overtake each other. This study asserts a six minutes reduction in taxi operation time for each aircraft by using optimization methods instead of FCFS (first-come-first-served) methods. The objective function of the formulation introduced by this work is to minimize taxiing time.

Since each airplane has a scheduled departure and arrival time, they need to receive the ground operation within this time duration. On the other hand, airplanes have to stay in the gate until their whole path to the destination becomes available. Technically, this method may appear efficient in some cases; like only considering departing flights; but it cannot be expanded in all cases since it is not safe and efficient to let arriving flights to have a long delay around runways.

Zhang et al. (2016) introduced a zone-control based algorithm, which generally will be used to control AGV (automated guided vehicles). The time-window controlling strategy expands this idea, which prevents collisions between aircraft, and the entire path-network is marked with specific numbers. Hence, planes have to respect the enter and exit rules of that zone to calculate the travel time on a taken link. Also, other airplanes should respect these rules to avoid collisions. Besides, Ravizza et al. (2014) released a paper intending to introduce a practical method to optimize airport surface operation. They expressed that most of the studies on airport surface operations effort to develop a method to estimate and minimize the taxiing time as accurate as possible. This paper offers a heuristic method based on minimizing aircraft ground movements' time and accumulating waiting times in the gates with the engine off instead of in the middle of taxi-path with the engine turned on. This methodology is applied to Zürich Airport and led to a 30% decrease in the total taxiing time by keeping off the engine of each aircraft for 136.9 seconds.

Adacher et al. (2018) published a paper in 2018 to introduce a new method to minimize aircraft ground movements. This work seeks to minimize the emissions by reducing the occurred delays during taxiing operation while the engine is turned on. Both routing and scheduling problems are considered, and the result is improved using the Greedy Algorithm. The results demonstrate a significant reduction in taxi time, taxi delay, and GHG emissions.

Liu et al. (2010) offered a method for Chengdu Shuangliu airport to optimize aircraft surface operation by considering aircraft's safety issues. They developed this method by the genetic algorithm and compared their results with the results of the shortest path problem. Similar to most of the path planning problems, a network of taxiways as drawn on the airport's map, and the objective is to minimize taxiing time. Three constraints cover the conflict problem. The first one prevents collisions on nodes through exerting a time distance, and the two others avoid head-on collisions.

Moreover, Li et al. (2019) suggested an optimization method to reduce airport surface operation emissions at Shanghai Hongqiao Airport (SHA). The SHA is known as the seventh busiest airport in China in 2016 by handling almost 42 million passengers (worldatlas, 2018), and Statistics show that this airport serves approximately 50 flights during rush hours. They assert that most of the previous works used the strategy of the shortest taxi time to find the optimal solution, and they have not considered the time that takes to aircraft to make a turn. Thus, the objective function of this paper is divided into two parts. First, minimizing travelling time through taxiways, which is a path planning problem; second, to minimize the total time that takes to each airplane to make large turns by multiplying the number of large turns in the average steering time. Due to the complexity of this path planning problem, the Genetic Algorithm is used to find the best solution. As the authors declared, the main aim of this study is decreasing the produced taxi operation's emissions. After applying this optimization method, although the total number of large steering is reduced, total taxiing time has not decreased considerably.

The safety issues in this work are divided into three sub-problems, such as safety on intersections, head-on collision, and tail accidents. A standard separation distance matrix is defined for three sample aircraft's sizes, including light, medium, and heavy. The light and medium aircraft required to respect a 200 meters separation length. In the situation that a heavy plane is running ahead on a link, it has to keep a 300 meters distance with all other types of aircraft. In accordance with the CAA's (Civil Aviation Administration) standards, the highest allowed taxiing speed is 13.8 m/s. Accordingly, the separation distances which are expressed in length can be converted easily to the time unit to be used in path planning problems.

2.8 Literature Review Summary and Contribution

Almost all works in this field intend to reduce the taxi time. Most of them suggest a method based on the shortest path planning to minimize the total airport surface operation's time. In such a system, a First Come First Serve approach is responsible for scheduling the components of the system using existing facilities. Several of the published papers have separately studied scheduling problems, aircraft ground path planning, ground operation delay, aircraft ground maneuvering safety, and fuel consumption or CO_2 emissions while taxiing. Some of the reviewed papers focused on delay reduction methods, like accumulating delays at the parking spot, which technically is only useful for departing flights.

The weakness point of a wide range of these solutions is that they are impractical in real performance. Commonly, the safety issues are the ignored aspects that make them unrealistic in practice. Some other researches defined various strategies to avoid ground incidents, like controlling the taxiing speed, putting safety distance, and considering different taxi-paths for arriving and departing flights.

Few other works have compared different taxiing methods, such as using the jet engine, towing trucks, and nose gears. Some other works assumed that towing trucks serve all of the aircraft, and in several other cases, it is presumed that using jet engine taxiing is the applied method. Due to the limitation in the number of vehicles and their availability carrying all aircraft cannot be efficient. Accordingly, it is not realistic to assign a vehicle to each aircraft.

This work attempts to propose a new and practical approach to the airport ground operation. In the current work, a new mathematical programming model is developed to minimize all unnecessary stops. Besides, a minimum safety distance between consecutive aircraft on the taxiway network is guaranteed. Additionally, the generated model considers the task scheduling and vehicle allocations' problem. The main contribution of this study is to consider towing trucks as an alternative taxi method for the aircraft taxiing operation. In such a system, the airplanes have options to choose between self-towing or truck-towing. The principal purpose of our work is to use the mathematical methods to optimize the decision-making process regarding a system of multiple aircraft and automated trucks to minimize the taxiing operation time and avoiding any collision at intersections and on taxiways.

CHAPTER THREE

3 AN ENVIRONMENTALLY FRIENDLY OPTIMIZATION MODEL FOR AIRPORT SURFACE MANAGEMENT

3.1 Problem Description and Mathematical Programming Modeling

In this section, we intend to provide a mathematical solution for the airport surface flow control problem. The movements of both incoming and outgoing airplanes, as well as the ground handling safety requirements, are modelled. Therefore, the proposed optimization formulation suggests a safe and efficient routing plan for aircraft taxi operation. Also, electric tugs aid in reducing total fuel consumption by offering towing option. Based on this approach, it has been attempted to enhance the productivity of the airport's surface operation to the highest level.

According to the above descriptions, the problem of aircraft taxi operations is formulated as a Mixed Integer Linear Programming (MILP) model. Consider the airport surface marking lines as a network G (N, V). These lines guide aircraft during ground movements. In the given graph, N is the set of vertices that represents the gates, intersections, and the entering and exit nodes to or from the runways. Likewise, V is the set of edges that indicate the connection between two intersections, or one intersection and one gate or node on the runway. The model considers a set of aircraft, indexed by $f \in F$. Each arriving aircraft should enter the taxiway network through an exit node on the runway. The exit node can be any intersection between a runway and a taxiway. Thus, the taxi operation for arriving aircraft will begin after exiting from the runway, until reaching the desirable gate. Correspondingly, for departing flights, the ground operation will start from a gate to the beginning of the desired runway. Therefore, each airplane needs to take several links to run from an origin node to a target node. Also, take-off and landing operations will not be counted as a part of the ground operation. Each link *l* has four features (see Figure 3.1), containing link ID (represented by *l*), $from_l$ (the entering node to link *l*), to_l (the exit node from link *l*), and Len_l (the length of link *l*). The variable X_l^f is equal to one ($X_l^f = 1$) if the aircraft *f* takes link l. It should be mentioned that each direction of a link has a unique identification number since the entering and exit nodes of each direction are different.

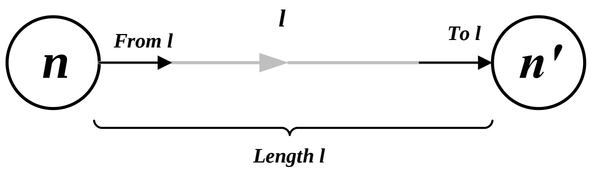


Figure 3.1: All Features of a Link in the Network

The EDT_{ORG}^{f} and LDT_{ORG}^{f} are the earliest and latest time that an aircraft can enter the network, respectively. These two values are making a time window, and if aircraft enter the system after the LDT_{ORG}^{f}, the DIN^{f} rises from zero to a positive value. In other words, the DIN^{f} is the positive difference between the actual enter time to the network (when it is bigger than the LDT_{ORG}^{f}) and the LDT_{ORG}^{f}. Similarly, the LAT_{DES}^{f} is the latest scheduled moment that aircraft leave the network, and the $DOUT^{f}$ indicates the positive difference between actual and scheduled exit time from the graph. In such a system, there always is the options of being towed or doing self-towing for every airplane. In this way, the truck allocation depends on the availability of the towing trucks, meaning that if a towing truck is available at the entering time of an aircraft to the system, it will be assigned to that airplane. Otherwise, the plane starts the self-taxiing operation. Thus, the model always makes a deal between delay and the truck assignment problem. In some cases, the model may decide for an aircraft to delay but only being assigned to a vehicle. It implies this fact that sometimes making a delay is more efficient than using jet power for taxi operation.

In the case that the self-towing is chosen as taxiing method, the fuel cost (FCL_{l}^{f} is fuel cost per link) will be applied. Certainly, the type of aircraft is a determinative factor in this decision, since the fuel burn rate of a huge plane is higher than a light airplane. Although it may seem that the kerosene consumption rate has a crucial role to decide about being towed by a truck or not, several other elements are involved in making an optimum decision, such as delay, length of taxiing, and level of taxiways' traffic. The mathematical programming model determines an aircraft's taxi plan, which can be summarized as:

$$P^{f} = (X_{l}^{f}, a_{l}^{f}, d_{l}^{f}, \forall\, l \in L : X_{l}^{f} = 1;\ FCL_{l}^{f}, \qquad \forall\, k \in K : Y_{k}^{f} = 0)$$

We assume each aircraft's towing task as a job. After carrying an airplane to its destination, the vehicles should go to the origin of the next aircraft. A distance matrix based on the shortest path is defined to apply the travel time between every two nodes, which is demonstrated as $TD^{ff'}$ in the formulation. It is quite clear that this matrix needs only to be contained the distances between nodes on gates and runways. It means that it is not needed to define the distance between two intermediate nodes in the matrix, because aircraft always enter/ depart through a gate or runway. In the next part, we present the developed mathematical model based on the above descriptions and the following assumptions.

3.2 Assumptions

The following assumptions have been made in order to develop the mathematical model:

3.2.1 Routing Assumptions

- The taxiways are assumed to be always available for airplanes, except where another aircraft occupies that link.
- Each link and node can be taken by each aircraft only once.
- The vehicle routing problem is ignored while it is not carrying an aircraft.
- It is assumed that all airport surface users, such as towing trucks, kerosene tank trucks, ladder trucks, and ground personnel, always clear the way for aircraft.
- This research considers the weather condition as an affectless factor to the airport surface operation. In other words, it is supposed that taxi-paths are always clear and ready to serve airplanes.
- The control tower is responsible for managing the traffic on runways, and all aircraft need to have permission from the control tower to enter or exit from the runways.
- The runway crossing for all airport surface users is prohibited. According to the FAA's safety suggestions, it is better if both aircraft and vehicles do not cross through runways' midpoints (FAA, 2015).
- All of the arriving aircraft, depending on their sizes, may take different nodes on the runway to enter to the taxiway network (Figure 3.2). The reason is that the heavier airplanes

need more length of the runway to land, and they usually go to the end of the runway, while the lighter ones may take an exit node in the middle of the runway. Therefore, we assumed that the entering nodes to the network are already defined, and the pilot knows which exit node should be taken.

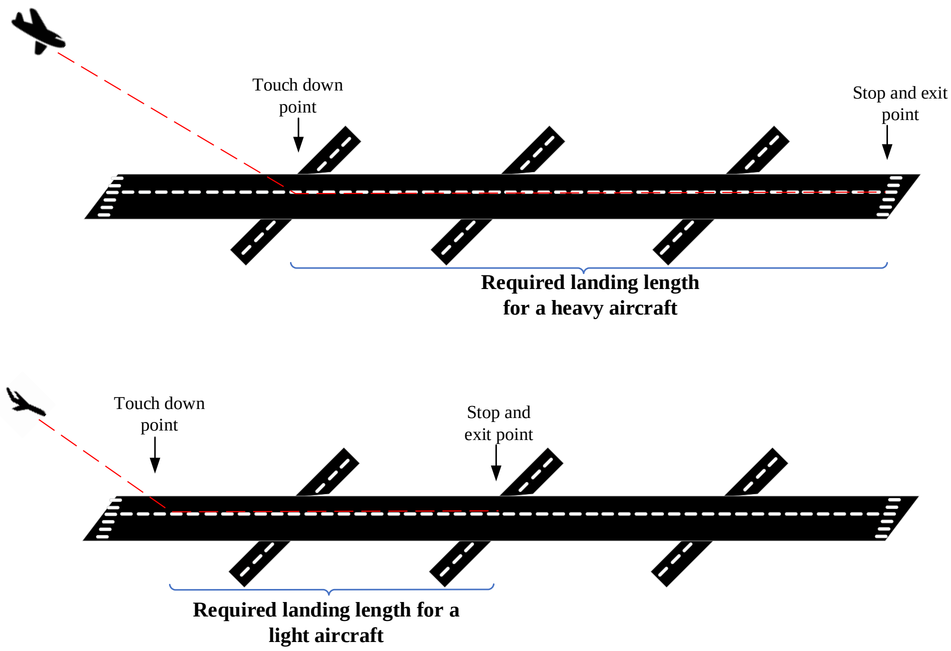


Figure 3.2: Required Runway Length for Landing a Heavy and a Light Airplane

- According to the width of the taxiways, passing in the opposite direction as well as overtaking on the same link are not allowed (see Figure 3.3 and Figure 3.4).

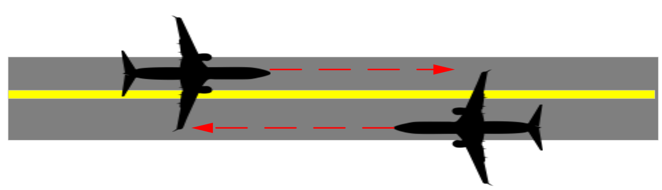


Figure 3.3: Passing in the Opposite Direction

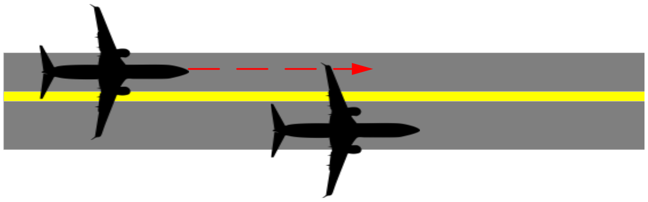


Figure 3.4: Overtaking in the Same Direction

- It is assumed that there is only one link between every two nodes, which can be used in both directions.
- It must be pointed out that each node on the airport's taxi-path has a surface with a specific area, and each arc has a length and a width. Hence, when an aircraft needs to pause before entering an intersection, the required space is considered on the graph (see Figure 3.5 and Figure 3.6).

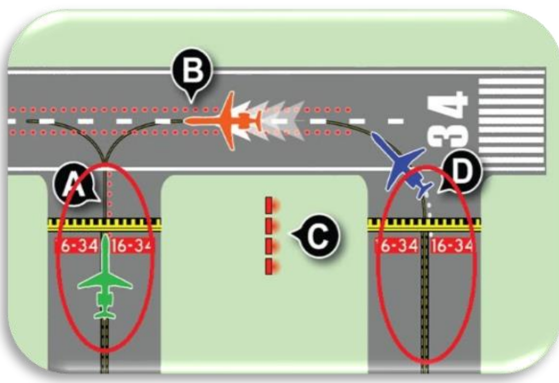


Figure 3.5: An Example of a Holding Position Between a Taxiway and a Runway (Charles De Gaulle Airport, 2019)

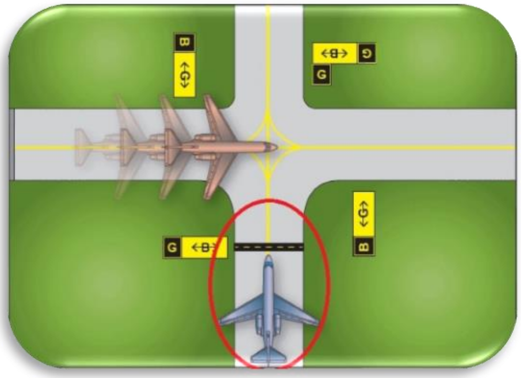


Figure 3.6: A Holding Position on an Intersection of Two Taxiways (Flight Literacy, 2017)

3.2.2 Timing Assumptions

- The time of installing/uninstalling towing vehicles is considered negligible.
- For the towed departing aircraft, the warm-up time occurs in the last two minutes of taxiing while the engine is on idle status since a jet engine usually needs 2-5 minutes for warm-up after turning-on (Ithnan et al., 2013).
- For the towed arriving aircraft, the cool-down time occurs in the first two minutes of taxiing while the engine is on idle status since a jet engine usually needs 2-5 minutes for cool-down before turning-off (Ithnan et al., 2013).
- It assumes that empty trucks take the shortest path (shortest travel time).

3.2.3 Speed Assumptions

- The speed of all towing trucks is equal.
- The speed of all airplane sizes is the same.
- The following speeds are considered for different situations:
  - Speed of taxiing by a jet engine (self-towing): 36 km/h.
  - Speed of taxiing using an electric towing truck: 24 km/h.
  - Speed of an empty vehicle travelling from an aircraft to another aircraft: 30 km/h.

- The speed of push-back operation and taxiing are considered to be equal since the entire ground operation is considered as a single service.
- The speed of aircraft and vehicles during the operation is a constant parameter given that the considered speed is an average of operation speed.

3.2.4 Collision Assumptions

- As long as two aircraft, either on the same arc or different links, respect the safety distance, they will not be involved in a collision on links and nodes.
- We ignored the collision between the trucks and the airplanes.

3.2.5 Assumptions for Towing vehicles

- At the first moment of running the model (time = 0), all trucks are assumed to be in the dummy origin node.
- After finishing the last task by a vehicle, it has to go to the dummy sink node.
- The travel distances from the dummy origin node to the first task and from the last task to the dummy sink node are insignificant.
- A truck is allowed to leave the dummy origin node and go to the dummy sink node only once.
- A truck that has left the dummy origin node should not go back there.
- A truck that has entered the dummy sink node should not leave there.
- At most, one vehicle should serve an aircraft in the entire taxiing, which means that it is not possible to share a towing task between two or more vehicles.
- A vehicle is capable of carrying at most one aircraft at the same time.
- An assigned vehicle to an aircraft should finish its task in the destination node of that plane, and it is not allowed to leave a towed airplane from anywhere except its target location.
- A vehicle is available if and only if it is in the dummy origin node or has finished serving an airplane.
- All towing trucks have the same features.
- It is assumed that all unassigned aircraft use the single-engine taxi method.

3.3 Notations

3.3.1 Sets

F	Set of aircraft, indexed as $f \in F$.
K	Set of towing vehicles, indexed as k $\in K$.
N	Set of all nodes.
N^-	Set of all transition nodes.
N^G	Set of all nodes on gates.
N^R	Set of all nodes on runways.
L	Set of links to connect nodes indexed as $l \in L$. Also, $l(ij)$ represents a link from node i to node j, which $l(ji)$ is the opposite direction of $l(ij)$.
$L(n)^+$	Set of outgoing links through node n (Figure 3.7).
$L(n)^-$	Set of incoming links to node n (Figure 3.7).

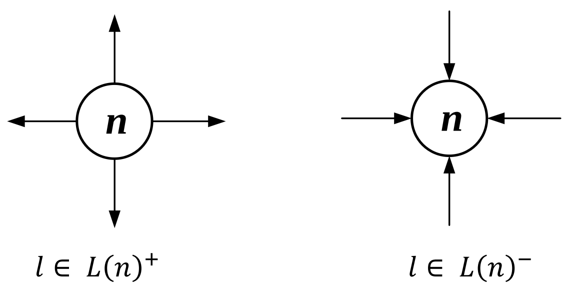


Figure 3.7: Set of Outgoing and Set of Incoming Links to a Node

3.3.2 Parameters

EDT^f_{ORG}	The earliest Scheduled departure time from the origin node.
LDT^f_{ORG}	The latest Scheduled departure time from the origin node.

LAT_{DES}^{f}	The latest Scheduled arrival time to the destination node.
FS^f	Size of aircraft f, such that: small: 1, Midsize: 2, Large: 3.
FT^f	Type of aircraft f, such that: Arrival: 1, Departure: 2.
ORG^f	The entry node for flight f to the network.
DES^f	The exit node for flight f $from$ the network.
$from_l$	The entering node to the link l.
to_l	The exit node from the link l.
Len_l	Length of the link l in meters.
$TTD_{nn'}$	Travelling distance for the towing vehicle when travelling empty between two nodes (n, n'), such that: n is the destination node of f and n' is the origin node of f'. Assume that vehicles always travel on the shortest path between given nodes (n, n').
$ST_{FS^f FS^{f'}}$	The minimum required separation time between two aircraft.
UFC_{FS^f}	Fuel cost per minute according to the aircraft's size.
DC_{FS^f}	Cost of delay per minute according to the aircraft's size.
$TINSC$	Cost of a single minute of ground operation (cost of existing in the system).
ETS	Empty truck's speed (meter/min).
STS	Self-towing's speed (meter/min).
CVS	Coefficient of vehicle's slowness.
M	A large real number.

3.3.3 Decision Variables

X_l^f $\begin{cases} 1, & \text{if aircraft } f \text{ travels on link } l \\ 0, & \text{otherwise} \end{cases}$

Y_k^f $\begin{cases} 1, & \text{if towing vehicle } v \text{ is assigned to serve flight } f \\ 0, & \text{otherwise} \end{cases}$

$Z_k^{ff'}$ $\begin{cases} 1, & \text{if vehicle } v \text{ is assigned to } f \text{ immediately after } f' \\ 0, & \text{otherwise} \end{cases}$

DON_k^f $\begin{cases} 1, & \text{if vehicle } k \text{ leaves dummy origin node to serve flight } f \\ 0, & \text{otherwise} \end{cases}$

DSN_k^f $\begin{cases} 1, & \text{if vehicle } k \text{ goes to dummy destination node after serving } f \\ 0, & \text{otherwise} \end{cases}$

a_l^f The arrival time of aircraft f to the link $l \in L(n)^+$.

d_l^f The departure time of aircraft f from the link $l \in L(n)^-$.

$\alpha_l^{ff'}$ $\begin{cases} 1, & a_l^{f'} - a_l^f \geq ST^{ff'}, d_l^{f'} - d_l^f \geq ST^{ff'} \\ 0, & \text{otherwise} \end{cases}$

$\beta_l^{ff'}$ $\begin{cases} 1, & a_{l'(ij)}^{f'} - d_{l(ji)}^f \geq \Delta^{ff'} \\ 0, & \text{otherwise} \end{cases}$

φ_l^{fk} $\begin{cases} 1, & \text{if truck } k \text{ carries aircraft } f \text{ on link } l. \\ 0, & \text{otherwise} \end{cases}$

TD^f Total delay time of aircraft f = {Delay at Origin + Delay at Destination}.

DIN^f Delay in leave the origin node.

$DOUT^f$ Delay in arriving at the destination node.

FCL_l^f The fuel cost of self − towing aircraft f on link l.

FC^f The fuel cost of self − towing aircraft f.

$TINS^f$ The total time duration that aircraft f is in the system.

EIN^f The earliness slack value of DIN^f.

$EOUT^f$ The earliness slack value of $DOUT^f$.

3.4 Mathematical formulation

In this part, a new and realistic mathematical formulation is offered to solve the problem mentioned above. The model attempts to find the best time scheduling and path planning solutions for a multi-aircraft taxiing system. All safety and incident avoidance issues are ensured. Also, it has been endeavored to take into account all real-world details such as various types of airplanes, both arrival and departure flights, and all kinds of delay during ground maneuvering.

3.4.1 Objective Function

Typically, in the multi-objective decision-making process, the objective function is a trade-off between different available alternatives. It assesses the suitability of each option and estimates its value. Commonly, a multi-objective function is composed of the summation of two or more criteria. Generally, the purpose of each objective function is to find the least amount (cost) or the most value (benefit) of the noted summation. Hence, in this research, the objective function of the proposed MILP formulation is defined to minimize all airport taxiing operation costs, including general operation cost (cost of existing in the system), fuel cost, and delay cost.

$$Minimize \sum_{f \in F} ((TINS^{f} \times TINSC) + (FC^f \times UFC^f) + (TD^f \times DC^f)) \tag{1}$$

As is evidenced, three financial components create the above-indicated multi-objective function. The first part corresponds to the cost of running in the system. For each aircraft, the total time of existing in the system ($TINS^{f}$) is multiplied by the cost of a one-minute presence in the system ($TINSC$). This part helps to minimize the total taxiing time for each airplane. The second component of this formalization is related to the cost of burnt fuel by the jet engine during taxiing, which is a multiplication of the total time that jet power is used for the ground operation (FC^f) and the cost of kerosene (UFC^f). It is notable that the UFC^f is matched to the rate of fuel consumption for different sizes of aircraft. In the last part, the total cost of delay is minimized. Obviously, the delay is an undesirable occurrence during the airport surface operation, and almost all researches in this field tried to decrease it to the least amount. In current work, the cost of each minute delay (DC^f) as a penalty is multiplied by the total delay TD^f. The TD^f is an aggregate of two kinds of delays, including delay in entering the network, and delay in exiting from the network. Also, the DC^f varies according to the size of each aircraft. The main reason for this difference in delay cost is the passenger/cargo capacity of each airplane. It is evident that the cost of a one-minute delay for a heavy aircraft is higher than the cost for a light aircraft with fewer passengers. In brief, the objective function (1) pushes the aircraft taxiing system to have less total taxi times with lower fuel consumption, also to remove all unnecessary ground delays.

3.4.2 Constraints

In this section, all applied constraints are modelled and categorized into different constraint sets. After introducing each equation, the importance and description of each formulation are explained.

3.4.2.1 Aircraft Routing Constraints

The following constraints ensure that a given aircraft moves from its origin node (entering node to the network) to the destination node by passing through available taxiways and intersections.

$$\sum_{l \in L(n)^+} X_l^f \leq 1 \qquad \forall f \in F;\ \forall n \in N^- \tag{2}$$

$$\sum_{l' \in L(n)^-} X_{l'}^f \leq 1 \qquad \forall f \in F;\ \forall n \in N^- \tag{3}$$

$$\sum_{l \in L(n)^+} X_l^f = \sum_{l' \in L(n)^-} X_{l'}^f \qquad \forall f \in F;\ \forall n \in N^- \tag{4}$$

$$\sum_{l \in L(nm)} X_l^f + \sum_{l' \in L(mn)} X_{l'}^f \leq 1 \qquad \forall f \in F;\ \forall n,m \in N \tag{5}$$

$$\sum_{l \in L(n)^+} X_l^f + \sum_{l' \in L(m)^-} X_{l'}^f = 1 \qquad \forall f \in F;\ \forall n,m \in N^G \tag{6}$$

$$\sum_{l \in L(n)^+} X_l^f + \sum_{l' \in L(m)^-} X_{l'}^f = 1 \qquad \forall f \in F;\ \forall\, n, m \in N^R \qquad (7)$$

Inequalities (2) and (3) make sure that each link or transition node is taken at most once by each aircraft. In fact, constraint (2) limits the outgoing links (Figure 3.8) from a transition node, and likewise, constraint (3) bounds the incoming edges (Figure 3.9) to an intermediate vertex.

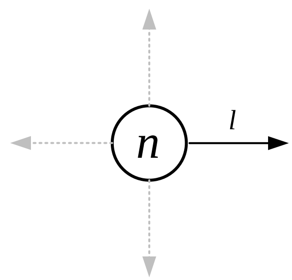


Figure 3.8: Limiting Outgoing Links from a Node

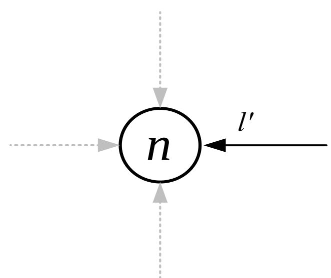


Figure 3.9: Limiting Incoming Links to a Node

The equation (4) guarantees that each entering aircraft to a transition node must leave it (see Figure 3.10). In other words, a taxiing task should not end in a transition point.

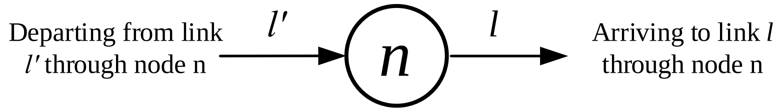


Figure 3.10: Passing Through a Transition Node

Based on equation (*5*), airplanes can only take one direction on the same link (see Figure 3.11). In this way, it is avoided to pass on the same link in both directions by each aircraft.

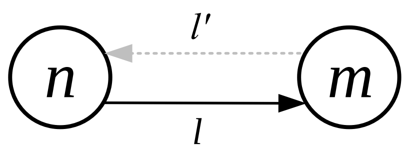


Figure 3.11: Travel Directions between Two Specific Nodes

The constraint (6) restricts travelling through the connected links to the gates (see Figure 3.12), which means an aircraft must take only one of the connected links to the set of gates in both directions. Therefore, arrival flights take the path to their assigned destination gate, and departing flights leave their origin node. It also guarantees that every departing airplane leaves its origin, and every arrival flight enters its destination.

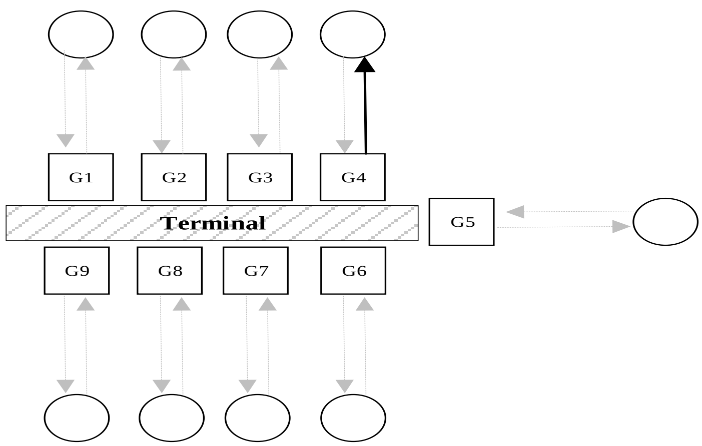


Figure 3.12: An Example of a Connector Link to the Terminal

Similarly, equation (7) ensures that only one of the connected arcs to the runways is taken by each aircraft (see Figure 3.13). This constraint also makes sure that every departing flight reaches its destination, and every arriving aircraft enters its origin node.

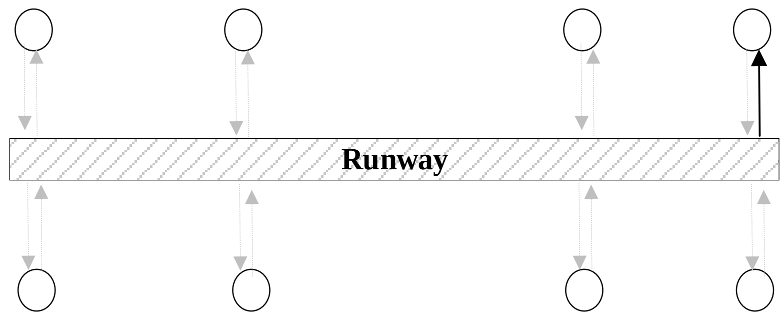


Figure 3.13: An Example of a Connector Link to a Runway

3.4.2.2 Flights Timing Constraints

The below constraints are added to handle the movements in the system. The most common way to control these events is to create a relationship between arrivals and departures.

$$a_l^f \leq MX_l^f \qquad \forall f \in F;\ \forall\, l \in L \tag{8}$$

$$d_l^f \leq MX_l^f \qquad \forall f \in F;\ \forall\, l \in L \tag{9}$$

$$a_l^f \geq EDT_{ORG}^f \qquad \forall f \in F;\ \forall\, l \in L(ORG^f)^+ \tag{10}$$

$$d_l^f \geq a_l^f + \left(\left(X_l^f + (\varphi_l^{fk} \times CVS)\right) \times \left(\frac{Len_l}{STS}\right)\right) \qquad \forall f \in F;\ \forall\, l \in L;\ \forall\, k \in K \tag{11}$$

$$TINS^f \geq d_l^f - EDT_{ORG}^f \qquad \forall f \in F;\ \forall\, l \in L(DES^f)^- \tag{12}$$

$$\sum_{l \in L(n)^+} a_l^f = \sum_{l' \in L(n)^-} d_{l'}^f \qquad \forall f \in F;\ \forall\, n \in N^- \tag{13}$$

$$a_{l'}^{f'} \geq d_l^f + \left(\frac{TTD_{nn'}}{ETS}\right) - M\left(1 - Z_k^{ff'}\right) \qquad \begin{array}{l} \forall f \neq f' \in F;\ \forall\, k \in K \\ \forall\, l \in L(DES^f)^-; \\ \forall\, l' \in L\left(ORG^{f'}\right)^+; \\ \forall\, n, n' \in N - N^-: \\ n = DES^f, n' = ORG^{f'}; \end{array} \tag{14}$$

The first two constraints, (8) and (9), assure that the arrival and departure of an aircraft to a link is equal to zero if the aircraft is not taking the link. The equation (10) is to let an aircraft become available only after its earliest arrival time to the network. Inequality (11) makes a relation between the arrival and departure of an aircraft to a link by applying the travel time. The travelling time is calculated with regard to the truck assignments (see Figure 3.14 and Figure 3.15). In simple terms, the difference of travel time between the self-towing method and vehicle towing will be added if the airplane is assigned to be served by a towing truck. The constraint (12) is responsible for computing the total existing time in the system.

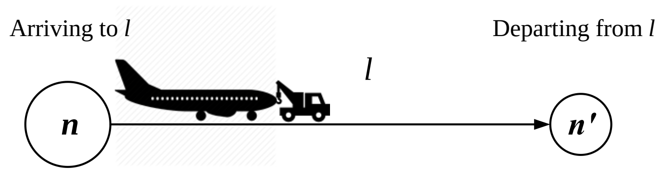


Figure 3.14: Truck Towing on Link l: $X_l^f = 1, \varphi_l^{fk} = 1$

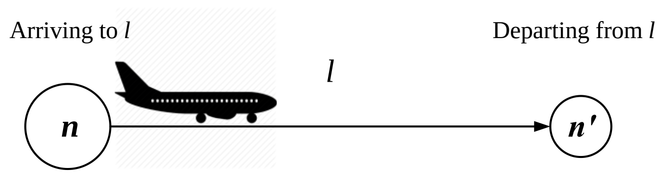


Figure 3.15: Aircraft Self-Towing on Link l: $X_l^f = 1, \varphi_l^{fk} = 0$

In inequality (13), it is guaranteed that the aircraft will not be stuck or delayed in the intersection nodes (Figure 3.16). It emphasizes this fact that an exit node of a link is an entry node of the next arc.

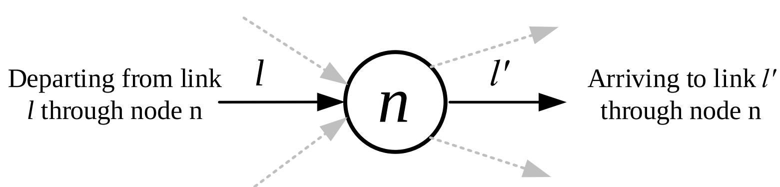


Figure 3.16: Pictorial Description of Passing through an Intersection

With the aid of equation (14), the travel time of an empty truck from a finished task to a new task is calculated (see Figure 3.17). For example, consider f and f' as departure and arrival flights, respectively. Assume that the same towing vehicle serves both flights, and f departs the network before f' enters to it ($Z_k^{ff'} = 1$). In this situation, the vehicle k should take f from its origin (which is a gate) and carry it until its destination (which is a node on the runway). Then truck k needs to travel from the destination of flight f to the origin of f' (which is a node on the runway) to start its next task. All possible truck travel paths are indicated in the following figure. The matrix of distances between every two knots (on gates and runways) uses based on the shortest path method.

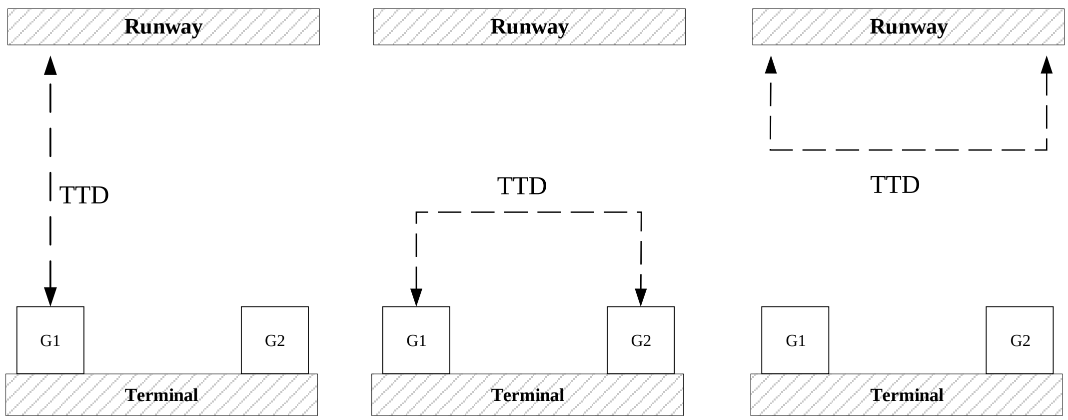


Figure 3.17: Possible Travel Paths for an Empty Truck

3.4.2.3 Delay Calculation Constraints

This set of constraints provides an assessment of two types of ground delays. In each type, the difference between the scheduled and the actual time computes the delay. Equality (15) has the responsibility of estimating delay in entering the network according to the entering time window. Accordingly, if an aircraft leaves its origin node after the latest departure time from the origin (LDT_{ORG}^{f}), it means that this plane has entered the mesh with a delay. In the same way, constraint (16) measures the delay in leaving the network by comparing the actual and expected departing times from the system. Equation (17) computes the total delay for each airplane.

$$DIN^f - EIN^f = a_l^f - LDT_{ORG}^f \qquad \forall f \in F;\ \forall\, l \in L(ORG^f)^+ \qquad (15)$$

$$DOUT^f - EOUT^f = d_l^f - LAT_{DES}^f \qquad \forall f \in F;\ \forall\, l \in L(DES^f)^- \qquad (16)$$

$$TD^f \geq DIN^f + DOUT^f \qquad \forall f \in F \qquad (17)$$

3.4.2.4 Truck Assignment and Routing Constraints

Obviously, to offer an accurate solution to a problem, every single component of the system should be taken into account. After providing a formulation to manage aircraft during their movements, it is required to make contributing formulations to control trucks during their tasks and paths.

$$\sum_{k \in K} Y_k^f \leq 1 \qquad \forall f \in F \tag{18}$$

$$Y_k^f \leq \sum_{f' \in F} DON_k^{f'} \qquad \forall f \in F;\ \forall k \in K \tag{19}$$

$$\sum_{f' \in F} Z_k^{ff'} + DSN_k^f = Y_k^f \qquad \forall f \in F;\ \forall k \in K \tag{20}$$

$$\sum_{f' \in F} Z_k^{f'f} + DON_k^f = Y_k^f \qquad \forall f \in F;\ \forall k \in K \tag{21}$$

$$\sum_{f \in F} DON_k^f \leq 1 \qquad \forall k \in K \tag{22}$$

$$\sum_{f \in F} DON_k^f = \sum_{f' \in F} DSN_k^{f'} \qquad \forall k \in K \tag{23}$$

$$\varphi_l^{fk} \leq Y_k^f \qquad \forall f \in F;\ \forall k \in K;\ \forall l \in L \tag{24}$$

$$\varphi_l^{fk} \leq X_l^f \qquad \forall f \in F;\ \forall k \in K;\ \forall l \in L \tag{25}$$

$$\varphi_l^{fk} \leq Y_k^f + X_l^f - 1 \qquad \forall f \in F;\ \forall k \in K;\ \forall l \in L \tag{26}$$

Constraint (18) limits each airplane to be served at most by one towing vehicle. Inequality (19) ensures that a vehicle is available to serve an aircraft only if it has left the dummy origin node. By equality (20), we demonstrate that a truck has two options after serving an aircraft (see Figure 3.18). One choice is to serve the next assigned airplane, and the second option is going to the dummy sink node after carrying *f*. Correspondingly, equation (21) delimits truck-serving options of a flight. In other words, a truck can assist a flight from the dummy origin node or after serving a previous aircraft (see Figure 3.19).

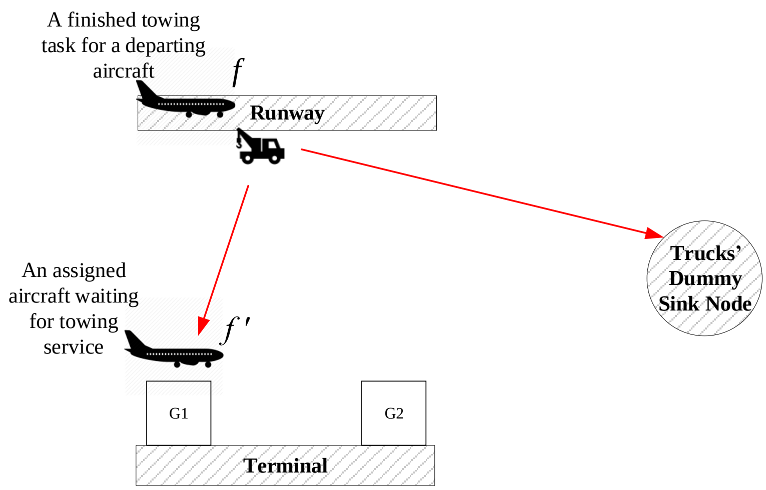


Figure 3.18: Possible Options for a Truck after Serving a Flight

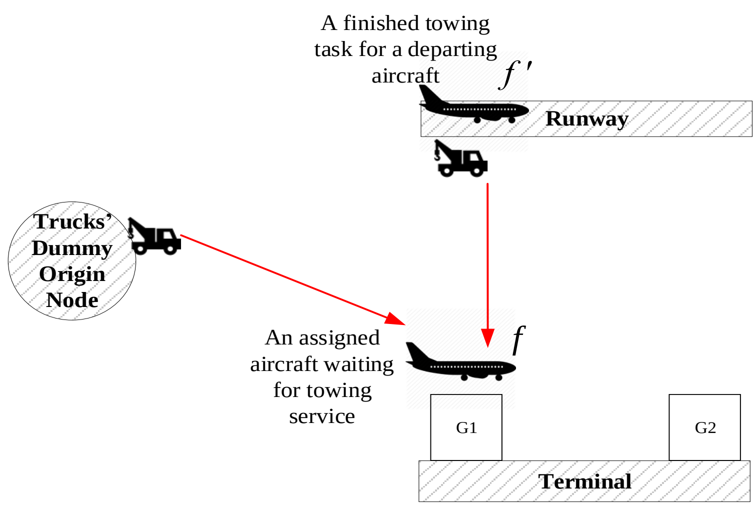


Figure 3.19: Possible Options to Serve an Assigned Airplane

Constraints (22) and (23) are to guarantee that a vehicle leaves its origin or enters its sink node at most once. Also, a truck that has left its origin node should go to its destination node at the end of a day. Equalities (24), (25), and (26) have been created to control the decision variable φ_l^{fk}. In such a way that, φ_l^{fk} becomes equal to one if a towed aircraft takes a specific link; otherwise, it remains equal to zero.

3.4.2.5 Fuel Consumption Constraints

Clearly, in such an above-described problem, it rarely happens that trucks can serve all of the aircraft. Therefore, some of them need to use their power to do taxiing, which means they burn kerosene. In this section, a set of mathematical formulations is presented to calculate the burnt energy.

$$FCL_l^f \geq \left(\frac{Len_l}{STS}\right) - M\left((\sum_{k\in K} Y_k^f) - X_l^f + 1\right) \qquad \forall f \in F;\ \forall\, l \in L \tag{27}$$

$$FC^f \geq \sum_{l\in L} FCL_l^f \qquad \forall f \in F \tag{28}$$

In equation (27), the amount of fuel that an aircraft burns to travel on an arc is estimated. Consequently, constraint (28) obtains the total consumed fuel of a self-towing operation by aggregating the amount of fuel used on all links.

3.4.2.6 Collision Avoidance Constraints

The last part of the mathematical method appertains to safety rules. This set is provided to ensure that all components of the system can move safely through the map. Technically, two different situations may happen for two successive flights, which are supposed to use the same arc at the same moment. They may follow each other in a similar orientation (Figure 3.20) or may see each other running in the opposite direction (Figure 3.21). Both cases are high-risk threats for the safety of airport surface operation. The proposed approach offers a solution for both of these critical issues.

Figure 3.20: Two Airplanes on the Same Arc Following Each Other

Figure 3.21: Two Airplanes on the Same Arc and in the Opposite Direction

$$\alpha_l^{f'} \geq \alpha_l^{f} + ST^{ff'} - M\left(1 - \alpha_l^{ff'}\right) - M\left(2 - X_l^{f} - X_l^{f'}\right) \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{29}$$

$$\alpha_l^{f} \geq \alpha_l^{f'} + ST^{f'f} - M\,\alpha_l^{ff'} - M\left(2 - X_l^{f} - X_l^{f'}\right) \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{30}$$

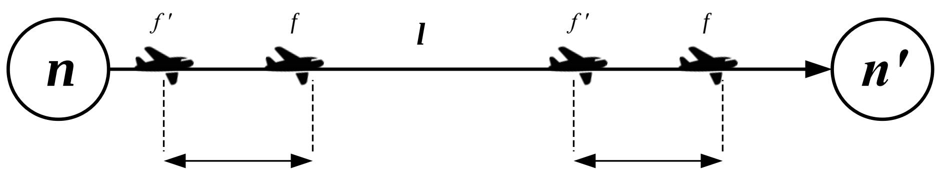
$$d_l^{f'} \geq d_l^{f} + ST^{ff'} - M\left(1 - \alpha_l^{ff'}\right) - M\left(2 - X_l^{f} - X_l^{f'}\right) \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{31}$$

$$d_l^{f} \geq d_l^{f'} + ST^{f'f} - M\,\alpha_l^{ff'} - M\left(2 - X_l^{f} - X_l^{f'}\right) \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{32}$$

$$\alpha_l^{ff'} + \alpha_l^{f'f} \leq X_l^{f} \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{33}$$

$$\alpha_l^{ff'} + \alpha_l^{f'f} \leq X_l^{f'} \quad \forall f, f' \in F : \mathrm{f} \neq f'; \quad \forall\, l \in L \tag{34}$$

Equations (29) – (32) are the main constraints that avoid the incidents on links. The idea is to handle flights with their arrival and departure times. This set guarantees a safe ground maneuvering by applying an aircraft-size-dependent time distance between every two-consecutive aircraft, which are using the same link and in the same direction (see Figure 3.22). In consequence, planes can travel securely through every arc. The following figure clearly illustrated the concept of separation distance on a link. Constraints (33) and (34) restrict the possible values for the decision variable $\alpha_l^{ff'}$.



$a_l^{f'} - a_l^{f} \geq ST^{ff'}$ $\quad$ $d_l^{f'} - d_l^{f} \geq ST^{ff'}$

Figure 3.22: Applying the Separation Distance for Two Following Airplanes

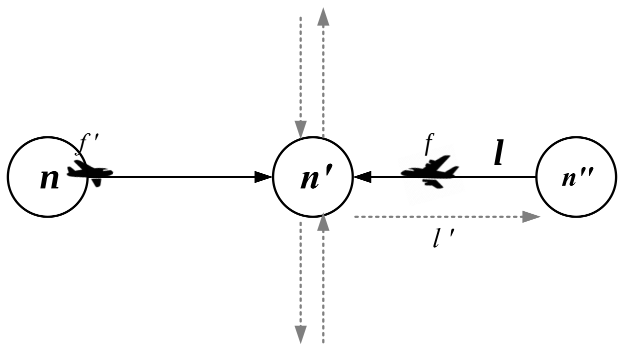
$$a_{l'}^{f'} \geq d_l^{f} + ST^{ff'} - M\left(1 - \beta_l^{ff'}\right) - M\left(2 - X_l^{f} - X_{l'}^{f'}\right) \qquad \begin{array}{l} \forall f, f' \in F : \text{f} \neq f'; \\ \forall l, l' \in L: l(ij), l'(ji) \end{array} \tag{35}$$

$$d_l^{f} \geq a_{l'}^{f'} + ST^{f'f} - M\,\beta_l^{ff'} - M\left(2 - X_l^{f} - X_{l'}^{f'}\right) \qquad \begin{array}{l} \forall f, f' \in F : \text{f} \neq f'; \\ \forall l, l' \in L: l(ij), l'(ji) \end{array} \tag{36}$$

$$\beta_l^{ff'} \leq X_l^{f} \qquad \begin{array}{l} \forall f, f' \in F : \text{f} \neq f'; \\ \forall l, l' \in L: l(ij), l'(ji) \end{array} \tag{37}$$

$$\beta_l^{ff'} \leq X_{l'}^{f'} \qquad \begin{array}{l} \forall f, f' \in F : \text{f} \neq f'; \\ \forall l, l' \in L: l(ij), l'(ji) \end{array} \tag{38}$$

Besides the above-stated constraints, equation (35) and (36) are added to prevent head-on collisions. The same time controlling strategy is considered. Therefore, the consecutive flights which using the same link in the opposite direction is required to respect a time distance for entering/departing from that edge. The last two constraints (37) and (38) are responsible for controlling decision variable $\beta_l^{ff'}$. Accordingly, it changes to one, if and only if two successive flights use an edge in opposite ways (see Figure 3.23).



$$a_{l'}^{f'} - d_l^f \geq ST^{ff'}$$

Figure 3.23: Avoiding Head-On Collision by Applying the Separation Time

CHAPTER FOUR

4 CASE STUDY

In this part of the thesis, the Montréal-Pierre Elliott Trudeau International Airport is chosen as a sample to experiment with the suggested model. First, a brief of general information about the Montreal airport is provided. Then, all influential factors and essential details about the airport's layout are discussed. After that, the parameters of the formulation are estimated. In the end, the achieved results are used to analyze the correctness of the model.

4.1 Introduction to Montréal-Pierre Elliott Trudeau International Airport

The Montréal-Pierre Elliott Trudeau International Airport serves the Greater Montreal Region and is located in a short distance from the center of Montreal. Generally, there are two types of codes to identify an airport, including the ICAO code, which is determined by the International Civil Aviation Organization, and the IATA code, which is defined by the International Air Transport Association. The ICAO code and the IATA code of the Montreal Airport are CYUL and YUL, respectively. In North America, the IATA code is more common. Hence, in this research, YUL is used to name Montreal's Airport.

The YUL ranked as the third busiest Canadian airport (19.4 million passengers) after Toronto Pearson International Airport (YYZ) and Vancouver International Airport (YVR), in 2018. (Statista, 2019). In 2017, YUL recorded a total of 18.2 million travelers with a growth of 9.5% compared to 2016 after the continuous increase in the number of yearly handled passenger and flight traffic, consisting of 39.3% from the international sector, 38.1% from domestic flights and, 22.6% from US segment. This growth was the largest one during the past ten years. The following graphs (Figure 4.1 and Figure 4.2) illustrate the process of increasing the number of YUL passengers over the years (YUL Annual Financial Report, 2018). A simple estimation of the total number of the YUL passengers in 2019 can be obtained based on the number of enplaned/deplaned passengers in the first quarter of the past five years and compared with the recorded rise in these three months of 2019. As can be seen in the below graph, the number of boarded travelers has increased by 6.4% from 2018 to 2019. Accordingly, the total number of YUL travelers is expected to grow by up to 20.66 million people until the end of 2019.

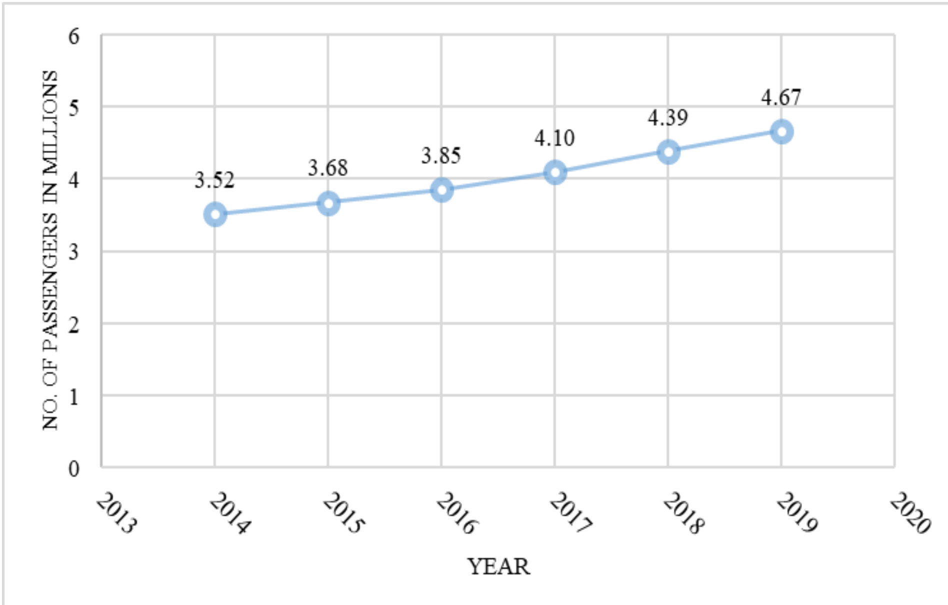


Figure 4.1: YUL Passenger’s Traffic in the First Quarter of Each Year (Statistics, 2019)

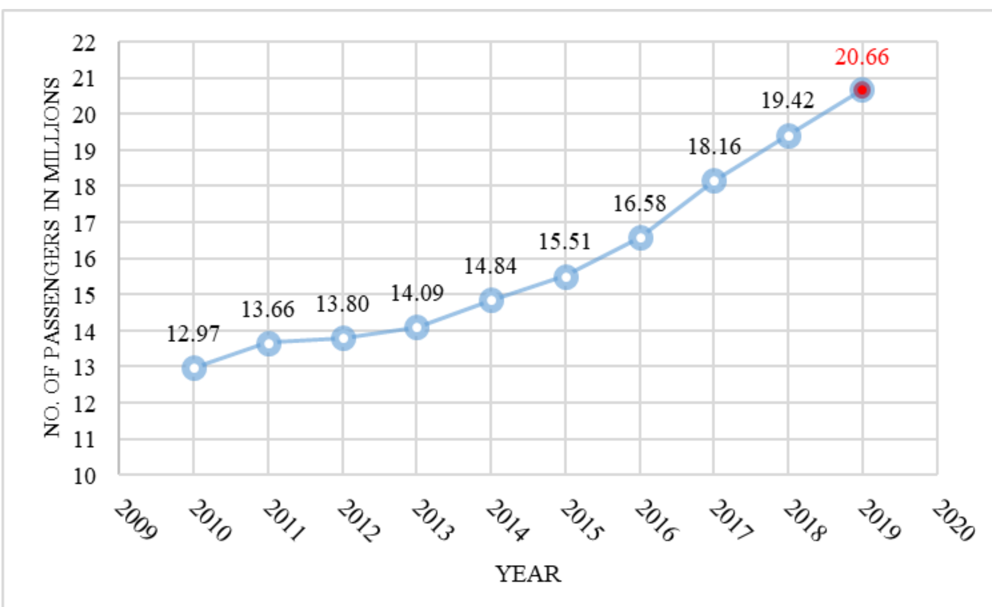


Figure 4.2: YUL Yearly Passenger’s Traffic 2010-2020 (Statistics, 2019)

Certainly, this continuing increase in the number of trippers leads to high-density airport ground traffic at YUL. These facts are some of the obvious reasons to think about a new airport surface handling strategy at Montreal's main aerodrome. Commonly, residential areas surround the airports, and Montreal's airport is not an exception. The noise level of the Montreal airport is evaluated by noise measurement stations which are placed at different distances from the airport. A study by the Aéroports de Montréal (ADM) shows that in recent years, fewer regions of the city are affected by the sound pollution from the YUL (see Figure 4.3). In 2013, the area of affected regions by YUL noises had decreased by almost 60% compared to 1995.

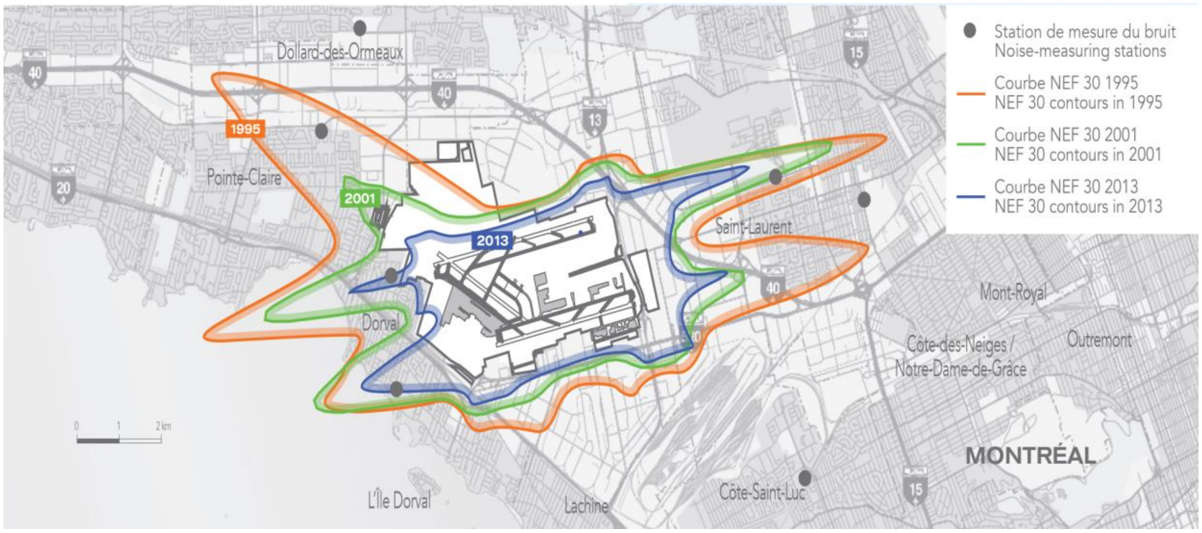


Figure 4.3: Affected Regions of The City of Montreal by The Airport Noises Over Years (AéroEco, 2015)

The jet engine improvement is the main reason for this reduction. Although these days fewer parts of the town are influenced by the noise from the YUL, there are still many people who live in the airport's neighborhood. On the other hand, this continues sound pollutions are a health threat for the airport's personnel. Therefore, replacing the jet-engine-on taxiing methods with the new taxiing strategies is presented as a solution. Before exerting the mathematical technique in case research, it is required to review its particular features in detail.

4.2 Technical Characteristics of the YUL

Some of the most significant features of the YUL are investigated in this section. The Montreal airport serves a wide range of aircraft with different sizes. The ATR 42-500, DHC-8-100, CRJ-100, and DHC-8-300 are some examples of light aircraft, Boeing 737-800, Boeing 757-200, and

Airbus A321 are instances for medium weight planes, the Boeing 747-400, Boeing 777-300ER, and Airbus A330-200 are examples of heavy airplanes that land or take-off every day to or from YUL (YUL aircraft Spotting Guide, 2016).

The YUL has three asphalt runways, which can be used in both directions. The longest one is (06L/24R) with 11,000 ft. length, which is parallel with (06R/24L) with 9,600 ft. length, intersected by (10/28), which is 7,000 ft. The width of all three runways is the same and equal to 200 ft. On the next page (Figure 4.5), a diagram of the YUL with all details is provided. In the current work, the network of the YUL taxiways is drawn based on the following diagram and the Google Map (Satellite), which is including 125 nodes and 282 arcs (see Figure 4.4). An airplane may enter/depart to or from the network through the nodes on gates or runways. In this research, we considered 60 gates, 16 vertices on runways, 49 intersections between taxiways.

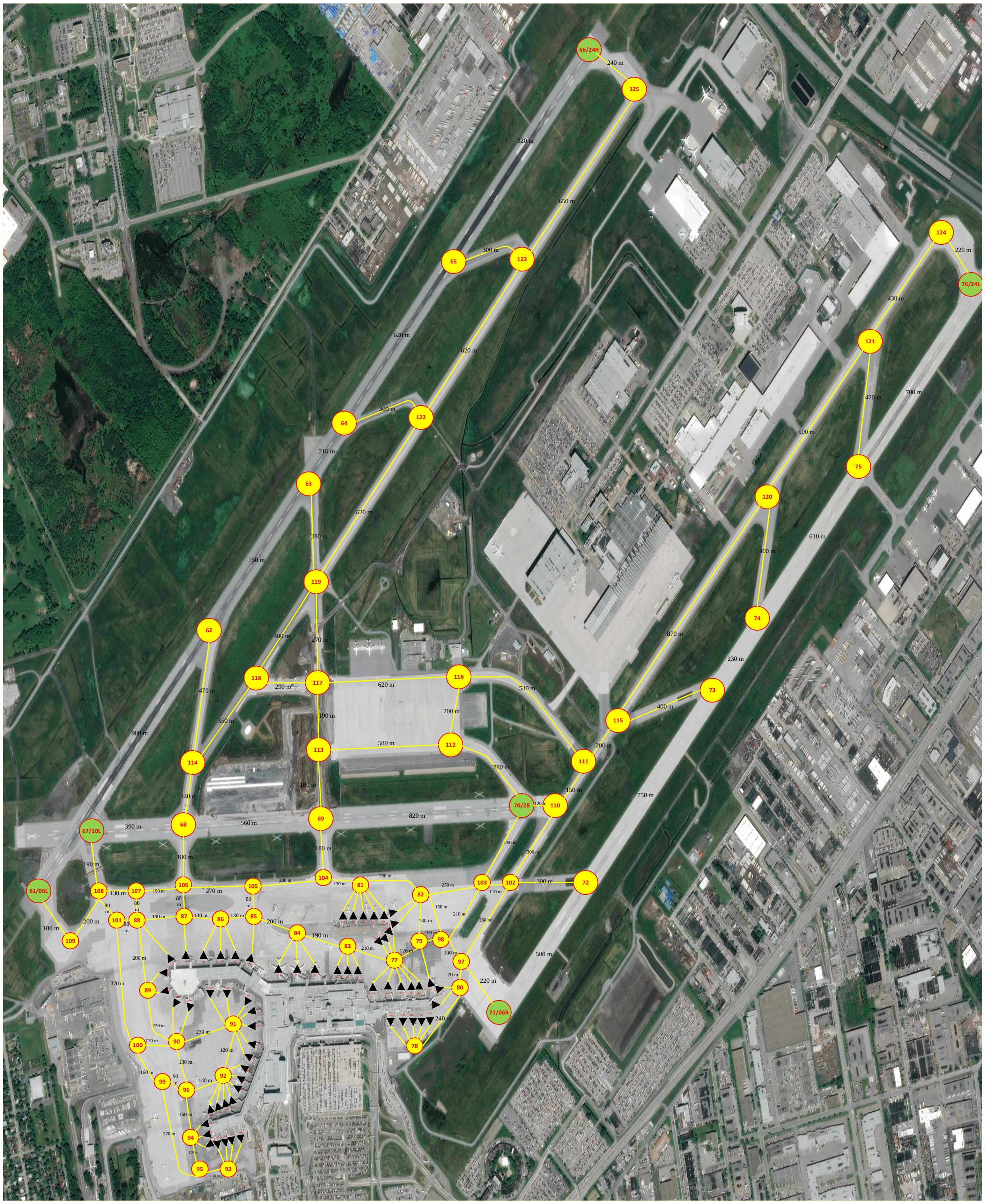


Figure 4.4: High-Resolution Network of Taxiways on the Map of YUL

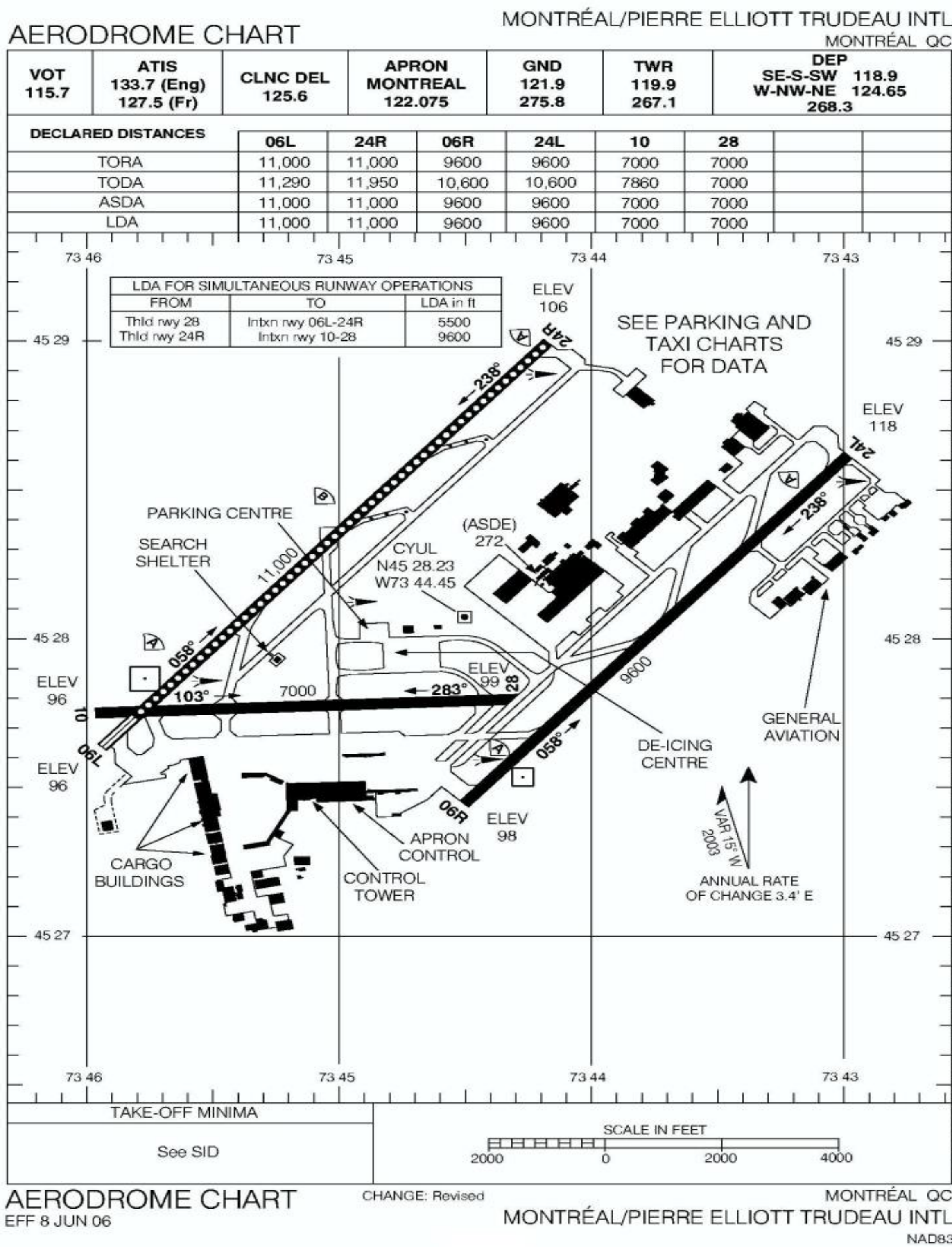


Figure 4.5: The Montréal Pierre Elliott Trudeau International Airport's Diagram ((CA-QC) et al.)

4.3 Evaluating the Current Situation at YUL

Released data by the Government of Canada (2018) demonstrate that during five months, the highest flights' traffic in the peak hours has occurred on 14 April 2019 around 5 P.M., which it is recorded that 65 aircraft arrived at or departed from the YUL during this interval of time. The following table (Table 4.1) indicates a summary of this information. It is notable that both overseas' flights and local flights are considered in this assessment.

Table 4.1: A Summary of Flights' Movements at YUL

Title of Feature / Date	December 2018	January 2019	February 2019	March 2019	April 2019
Day in month that peak day occurs	20th	25th	22th	27th	25th
Day in month that peak hour occurs	10th	6th	25th	18th	14th
Hour in day that peak hour occurs	17	17	18	17	17
No. of movements during peak day	704	695	712	721	718
No. of movements during peak hour	61	56	63	61	65
No. of movements during month	19,023	18,503	17,076	20,044	19,000

Technically, taxi-out is the procedure of travelling a departing plane (towed by a truck or not) from the terminal to a runway, and reversely running an arriving aircraft from a runway to a gate called taxi-in. In general, taxi-out is longer than taxi-in, since keeping the departing flights in the terminal is an old strategy for airport's surface handling. The point is that the control tower usually gives the priority of using the taxiways to the arriving flights. Due to the high risk of safety issues around the runways, it is more preferred to avoid keeping the airplanes close to the runways.

In accordance with the presented data by the FAA, the taxi time at YUL has increased over the years (see Figure 4.6). As can be observed in the below graph, this increase has continued with a higher intensity after 2014. Figure 4.2 describes this distinction clearly, which indicates that the total number of travelers to or from the YUL has risen with a sharp rate between 2014 and 2018 rather than in previous years. On average, 7.78 minutes and 24.3 minutes were recorded for taxi-in and taxi-out at YUL in 2018, respectively. Moreover, the average of taxiing time has increased by 37.2 percent in the last two decades (FAA, 2019).

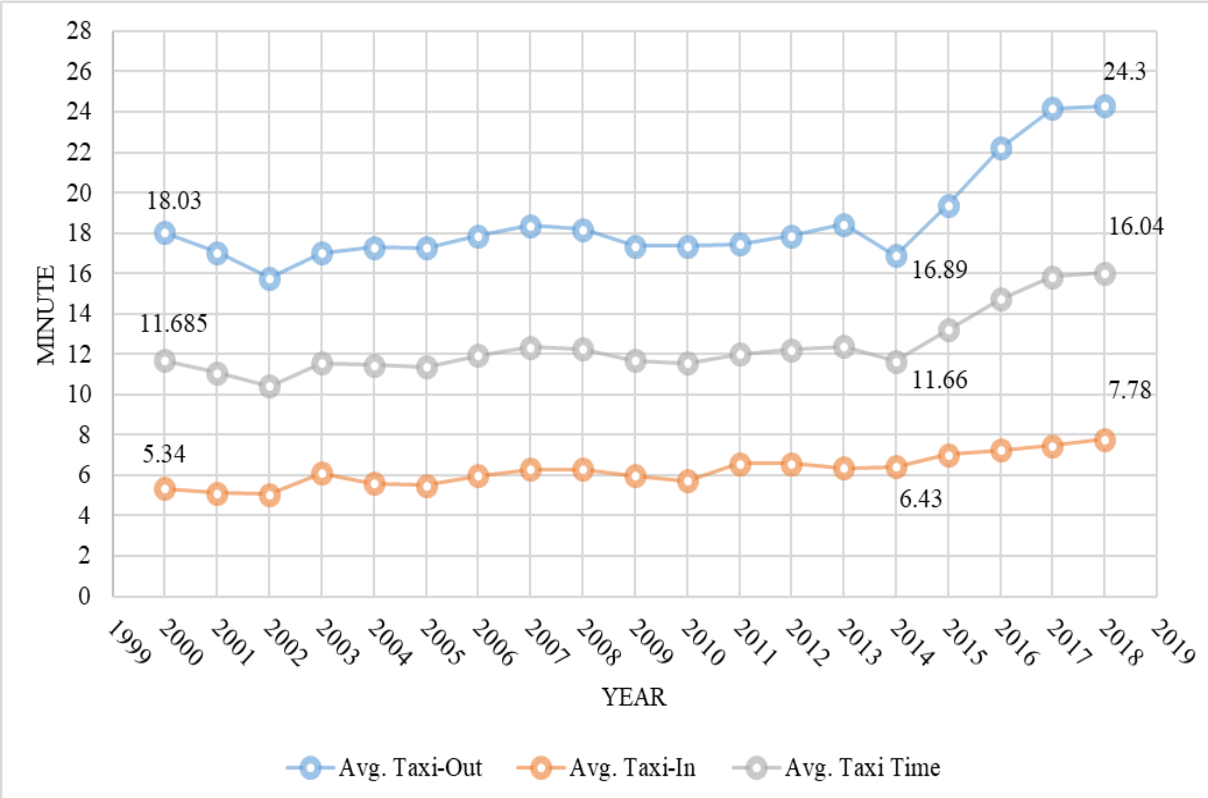


Figure 4.6: Taxi Time at YUL Over Years (FAA, 2019)

According to Figure 4.7, almost 50 percent of departing flights had a long taxi time (20 – 39 minutes) in 2018, while only 20 percent of leaving aircraft had the same taxi time length in 2014. The increase in the number of long taxi-Out operations can be another result of the passengers' traffic growth between 2014 and 2018 (FAA, 2019).

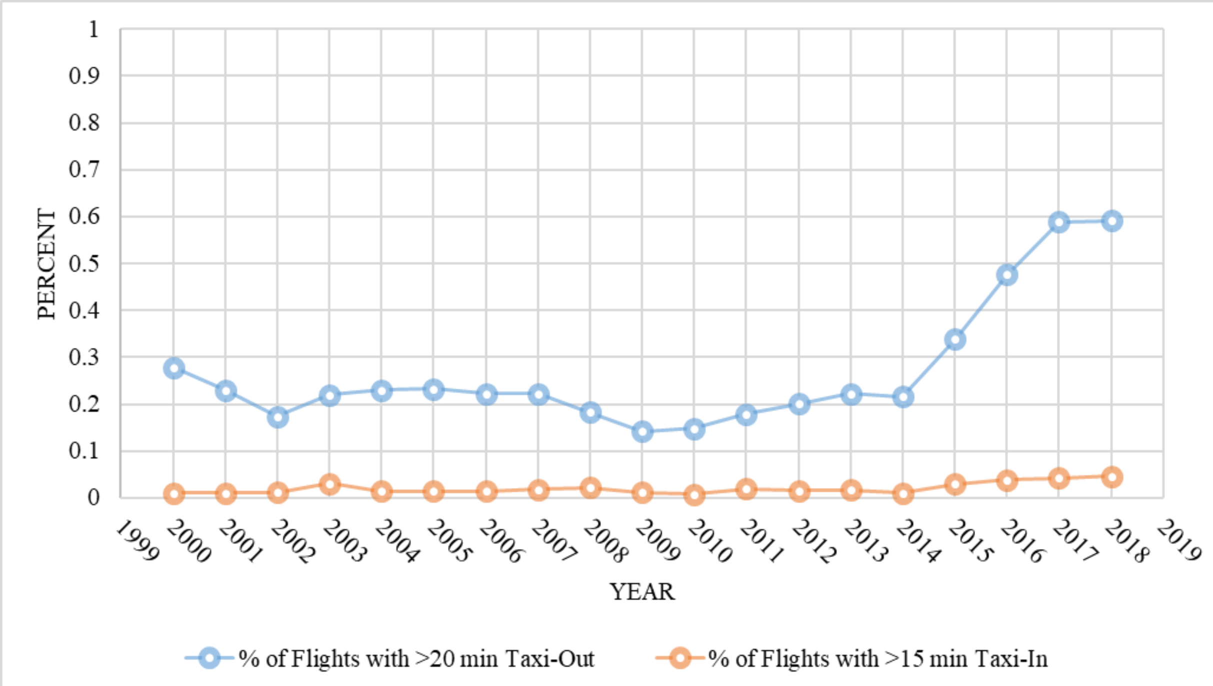


Figure 4.7: Long Taxi Times at YUL Over Years (FAA, 2019)

Based on the presented estimations in the Introduction Chapter, the global passenger traffic is on the increase in future years. Accordingly, the YUL, as a member of the global aviation industry, is expected to serve more passengers every year. Undoubtedly, this situation leads to many problems at the airport, such as longer taxi time, more and longer delays, and increasing the risk of aircraft's conflict. All these mentioned facts about the current situation and the predictions of the future of the airplanes' traffic at YUL draw attention to the importance of developing a modern ground handling strategy.

CHAPTER FIVE

5 SOLUTION AND RESULTS

In this chapter, we show the results validating the accuracy of the proposed model in chapter three. We considered two approaches for applying the offered optimization method to the problem. In the first approach, all airplanes take their optimum plan without considering their entering time to the system. However, the second method takes flights individually to offer the optimal plan.

In the current thesis, the first approach is named centralized, and the second one is called decentralized. Given taxiing data from YUL, it is utilized to examine both approaches. The same mathematical model is used for both cases, and they only differ from the planning strategy. The goal is to create a conflict-free aircraft taxiing solution with minimizing the taxi time, ground delays, fuel consumption, and airport air pollutions.

The centralized method was able to offer a solution for small size problems. Thus, we generated the decentralized approach, which is capable of solving large-scale problems in a short time. Considering the complexity of the presented mathematical model and the size of the problem, we examine the model using the decentralized approach. However, in the following sections, a numerical example of the centralized method has been brought. We took advantage of IBM ILOG CPLEX Optimization Studio 12.9.0 to solve the presented mathematical models, 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.

5.1 Data Collection and Estimating the Value of Parameters

Both strategies are implemented on the network of YUL taxiways, which was provided in the previous chapter. For the centralized method, we use a small part of the network, but in the decentralized, we run the model for the entire YUL airport. The data that we use in these experiments contains information about the exact airport layout, the positions and the number of gates, the quantity and the location of runways, the actual measures of runways and taxi-paths.

Moreover, it includes the times for the aircraft which used the airport. As we discussed before, the peak traffic at YUL typically occurs at 5 P.M. Therefore, to examine the presented model, we take the rush-hour of the ground operation on Monday, August 26, 2019, between 5 P.M. and 6 P.M. plus one hour before and one hour after this period as tolerance. The observations show that the airport has served 150 flights during this specific time, consisting of 91 arrival flights and 59 departing planes. It should be mentioned that the entering node and the exit vertex for both arriving and departing flights are randomly generated, due to the lack of real information. For example, an arriving plane randomly takes a node on a runway to enter the network, and a destination gate is randomly defined for it. Also, the size of airplanes is selected at random, including 48 light, 58 medium, 44 heavy airplanes. We have tested both approaches with various numbers of towing vehicles in the system to demonstrate the capability of the suggested optimization method.

As we discussed in chapter three, an aircraft-size-dependent separation distance between every two consecutive aircraft is required. Hence, in this case, airplanes are categorized into three classes, including light, medium, and heavy planes. Then, the matrix of the safety distances is defined based on research by Li et al. (2019) as below (Table 5.1):

Table 5.1: The Separation Distances between Two Consecutive Aircraft in Meter (Li et al., 2019)

	The Rear Aircraft		
The Front Aircraft	Light	Medium	Heavy
Light	200	200	200
Medium	200	200	200
Heavy	300	300	300

All of these distances are in meter, and it is needed to convert them to a time unit to take advantage of them in the formulation. For this reason, we should divide the distances by speed parameter. In the suggested formulation, two different towing speeds are defined, since the vehicles operate slower than the planes, including of the self-towing speed and the vehicle-towing speed. In accordance with the aviation regulations and standards presented by the ICAO and the IATA, the highest taxiing speed is limited to 50 km/h (830 m/min). Hence, in this study, the speed of the jet-engine taxiing method and the truck-towing are determined by 600 m/min and 400 m/min, respectively. We use the slower speed value for calculating the separation times. Consequently, the model guarantees the minimum separation distances between all types of airplanes. The separation distances are expressed in the time scale. Therefore, the safety requirements will be considered between all airplanes' sizes regardless of the method of taxiing.

It should be noted that the speed of an empty truck while moving from a finished task to the next assigned task is 500 m/min. The matrix of separation times between planes (in minutes) is achieved as below (Table 5.2):

Table 5.2: The Separation Time between Two Consecutive Aircraft in Minute

	The Rear Aircraft		
The Front 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

In both cases, a three-minute time window to leave the stand is considered for departing flights. This value is corresponding to the difference between EDT_{ORG}^{f} and LDT_{ORG}^{f}. The delay penalty will not be applied if the airplanes leave the stands within this period. The corresponding value for arriving airplanes is zero since we prefer that airplanes do not wait around runways. Also, LAT_{DES}^{f} is estimated according to the longest taxiing path on the network. In other words, this value is the greatest number in the truck travelling matrix. In this case study and according to the drawn networks, this parameter for the centralized and the decentralized strategies is 4.175 and 13.24 minutes, respectively. In other words, this means that when the length of taxi time exceeds LAT_{DES}^{f} the model exerts the delay penalty.

After determining the taxiing speed and the separation time, the cost parameters should be assessed. Based on an investigation, the average of total direct operating costs to airline companies is declared about \$74.20 per minute, which \$27.01 of this amount is associated with the cost of the kerosene. On the other hand, the average value of a traveler's time is presumed \$49 per hour (Airlines For America, 2019). According to the statistics mentioned above and considering three sizes of airplanes, the expense of one-minute aircraft's fuel consumption can be estimated at \$20 for light, \$27 for medium, and \$50 for heavy planes. Also, by assuming 50, 120, 200 passengers as the plane's capacity for light, medium, and heavy aircraft, respectively, the total passengers' value of time for these three classes will be around \$41, \$98, and \$164 per minute. It should be mentioned that, in this study, the travelers' value of time specifies the cost of delay. On the other side, the expense of one-minute existing in the system can be obtained from the total operation cost minus the cost of fuel, which almost for all classes of aircraft is equal. Therefore, time in the system's cost is assumed to be $47 per minute of operation.

As we discussed before, there are various types of tow tractors, but in this thesis, we considered that the most advanced towing trucks serve the airport. Hence, the current study has been done to aid in the programming automated guided tow tugs. MOTOTOK produces a model of these vehicles, which is one of the most modern tugs among its kind. It was challenging to find a resource for the price of these towing trucks. Basically, due to the marketing policies of manufacturing companies, they do not release their products' prices. We only could find the price of a secondhand MOTOTOK tug model 2015 twin 6500. This used vehicle costs about USD 61,000 and has a maximum towing capacity of 50 Tones, which is able to carry lightweight airplanes. Ground personnel conducts this electric tug through wireless remote control. On the other hand, the price of a large diesel towing tractor is around USD 350,000. This truck is the former generation of towing vehicles and has an onboard driver. Consequently, we guess the large-size electric towing tugs cost at least USD 700,000. We assume that all vehicles are large-size and the same, so they are able to serve all kinds of airplanes. It is worth mentioning that the high-tech tugs do not need a conductor or a driver since they are fully automated guided. This situation brings direct financial benefits to the aviation industry. Thus, airlines can decrease their operating costs drastically by hiring less crew. Recent evaluations show that the average salary for airport ground personnel in Canada is approximately CAD 33,000 annually (Ground crew salary, 2019). The following parameters have been used to achieve the results for both models:

$ST_{FS^f FS^{f'}}$: $\begin{bmatrix} 0.50 & 0.50 & 0.50 \\ 0.50 & 0.50 & 0.50 \\ 0.75 & 0.75 & 0.75 \end{bmatrix}$; separation distances in minute.

UFC_{FS^f}: $[20 \quad 27 \quad 50]$; in USD per minute.

DC_{FS^f}: $[41 \quad 98 \quad 164]$; in USD per minute.

$TINSC$: 47; in USD per minute.

TTS: 400 meters per minute.

ETS: 500 meters per minute.

STS: 600 meters per minute.

CVS: $\frac{STS - TTS}{STS}$= 0.34

M: 10,000.

Both cases are developed with the aim of offering an optimal taxi plan consisting of the identification number of the flight, taken taxiways, arrival/departure time to/from each link, method of taxiing (self-towing or truck towing), the identification number of the assigned vehicle in case of using the truck towing method.

5.2 Centralized Method

The centralized strategy takes all existing aircraft in the system during a time window and attempts to find the best solution. In this way, all airplanes will be compared with each other to make the optimal global solution for the problem as well as to take their optimum plan considering the availability of resources. In such a system, the equipment will be scheduled to serve the highest number of flights. Therefore, it is expected that trucks serve the heavier planes more than light-size aircraft and be more active during high traffic hours.

Due to the complexity of the model and the size of entities in the real case study, we face a significant problem. As we experimented, it is difficult to run the model for more than 25 aircraft using this method. Therefore, the centralized strategy is not able to solve the real problem, which is a large-scale problem. Hence, we have defined the other scenario, which is significantly more potent than the centralized method. A picture of the network that we used for the centralized method is presented on the next page (see Figure 5.1). Besides, a small sample of the achieved results by the centralized strategy is brought in the following pages (see Table 5.3). We have used the following features of the network to examine the centralized model:

The number of nodes in set N: 19, including 12 transition nodes, three gates, and four nodes on runways.

The number of links in the set L: 46

$TTD_{nn'}$: distances are in meters.

[	0	200	200	1500	220	1040	820	]
[	200	0	200	1500	220	1040	820	]
[	200	200	0	1500	220	1040	820	]
[	1500	1500	1500	0	690	1250	2000	]
[	220	220	220	690	0	920	1670	]
[	1040	1040	1040	1250	920	0	1110	]
[	820	820	820	2000	1670	1110	0	]

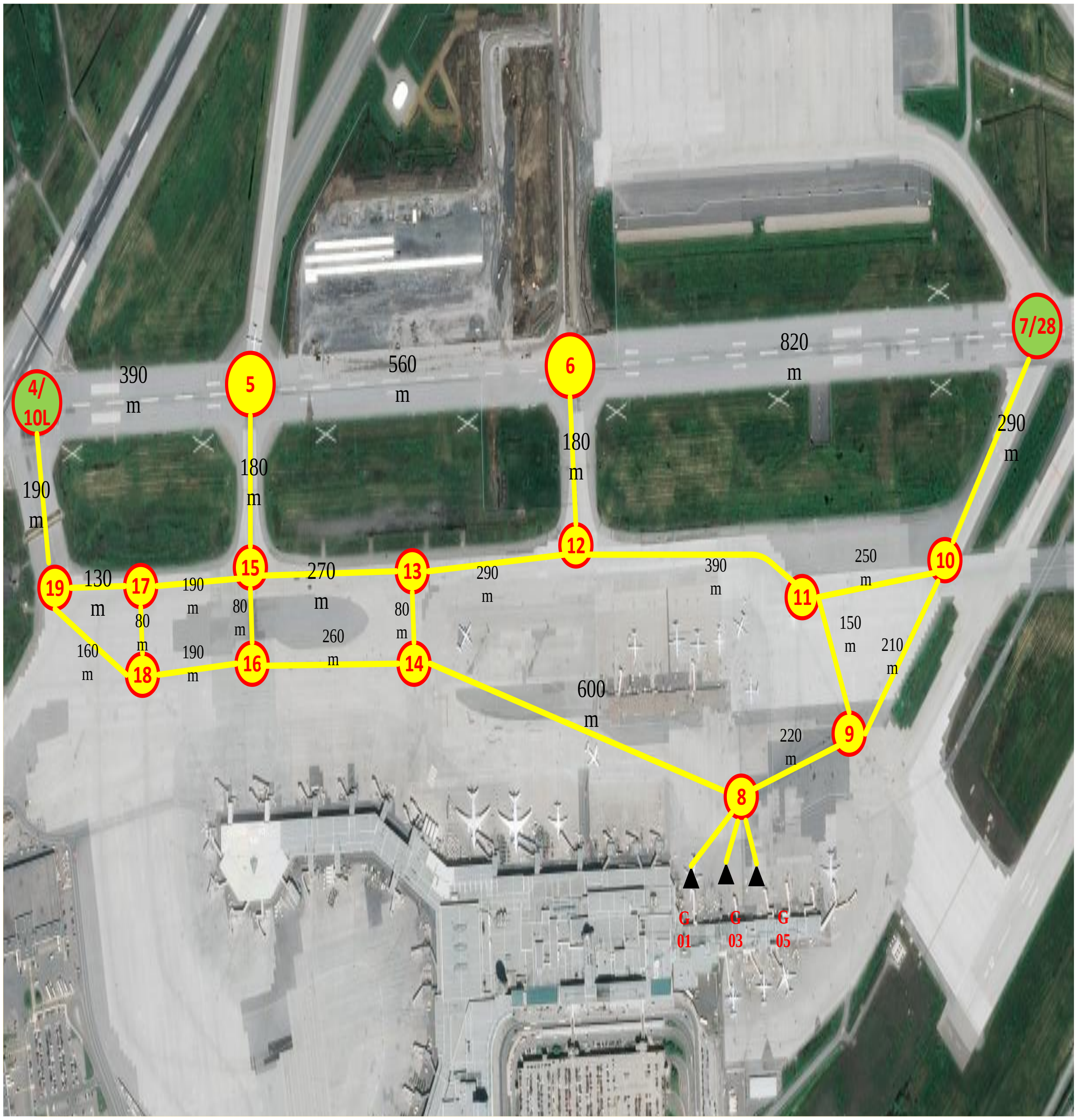


Figure 5.1: A Small Sample of Taxi-Path Network on the Map of YUL

Table 5.3: A Sample of Results of the Centralized Method

Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link	Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link
1	3	3	8	0.10	0.27	11	2	2	8	15.00	15.17
1	9	8	14	0.27	1.27	11	8	8	9	15.17	15.53
1	25	14	16	1.27	1.70	11	11	9	10	15.53	15.88
1	31	16	18	1.70	2.02	11	46	10	7	15.88	16.37
1	37	18	19	2.02	2.28	12	3	3	8	15.00	15.17
1	43	19	4	2.28	2.60	12	9	8	14	15.17	16.29
2	2	2	8	0.20	0.42	12	25	14	16	16.29	16.96
2	8	8	9	0.42	0.91	12	31	16	18	16.96	17.27
2	11	9	10	0.91	1.38	12	37	18	19	17.27	17.54
2	46	10	7	1.38	2.03	12	43	19	4	17.54	17.86
3	6	6	12	4.25	4.65	13	1	1	8	15.00	15.67
3	18	12	11	4.65	5.52	13	8	8	9	15.67	16.16
3	15	11	9	5.52	5.86	13	11	9	10	16.16	16.63
3	10	9	8	5.86	6.35	13	46	10	7	16.63	17.27
3	42	8	3	6.35	6.57	14	5	5	15	19.00	19.30
4	7	7	10	5.00	5.65	14	26	15	13	19.30	19.75
4	13	10	9	5.65	6.36	14	21	13	14	19.75	19.88
4	10	9	8	6.36	6.85	14	23	14	8	19.88	21.67
4	41	8	2	6.85	7.07	14	41	8	2	21.67	21.83
5	5	5	15	10.00	11.27	15	5	5	15	20.00	20.40
5	27	15	16	11.27	11.40	15	26	15	13	20.40	21.01
5	29	16	14	11.40	12.33	15	21	13	14	21.01	21.18
5	23	14	8	12.33	13.33	15	23	14	8	21.18	22.52
5	42	8	3	13.33	13.50	15	40	8	1	22.52	22.75
6	4	4	19	10.00	10.32	16	1	1	8	20.75	20.92
6	39	19	18	10.32	10.58	16	9	8	14	20.92	21.92
6	35	18	16	10.58	10.90	16	25	14	16	21.92	22.65
6	29	16	14	10.90	11.33	16	31	16	18	22.65	22.97
6	23	14	8	11.33	12.33	16	37	18	19	22.97	23.23
6	42	8	3	12.33	12.50	16	43	19	4	23.23	23.55
7	2	2	8	10.00	10.22	17	1	1	8	20.00	20.17
7	9	8	14	10.22	11.83	17	8	8	9	20.17	20.53
7	25	14	16	11.83	12.41	17	11	9	10	20.53	20.88
7	31	16	18	12.41	12.84	17	46	10	7	20.88	21.37
7	37	18	19	12.84	13.20	18	4	4	19	21.00	21.32
7	43	19	4	13.20	13.62	18	39	19	18	21.32	21.58
8	6	6	12	12.00	12.40	18	35	18	16	21.58	21.90
8	18	12	11	12.40	13.27	18	29	16	14	21.90	22.67
8	15	11	9	13.27	13.61	18	23	14	8	22.67	23.67
8	10	9	8	13.61	14.10	18	41	8	2	23.67	23.83
8	40	8	1	14.10	14.32	19	5	5	15	22.00	23.27
9	7	7	10	12.00	12.48	19	27	15	16	23.27	23.40
9	13	10	9	12.48	12.83	19	29	16	14	23.40	23.83
9	10	9	8	12.83	13.20	19	23	14	8	23.83	24.83
9	41	8	2	13.20	13.37	19	42	8	3	24.83	25.00
10	4	4	19	15.00	15.42	20	7	7	10	24.00	24.48
10	39	19	18	15.42	15.78	20	13	10	9	24.48	24.83
10	35	18	16	15.78	16.21	20	10	9	8	24.83	25.20
10	29	16	14	16.21	16.79	20	40	8	1	25.20	25.37
10	23	14	8	16.79	18.13						
10	42	8	3	18.13	18.35						

5.3 Decentralized Method

In the decentralized method, each aircraft will be planned individually with respect to previously scheduled airplanes. It means that the model allocates the resources to the earliest entering flight to the system. The availability of the resources is the common point between all planes. In the explained problem, the taxi-paths and towing trucks are the resources. Therefore, the airplanes will be processed in a way that a tug does not serve two different aircraft at the same time, and besides, every two consecutive flights will not occupy the same path at the same time either in the same or opposite direction. Thus, the truck assignment and collision avoidance problems are solved properly. In terms of the execute time, this method is much stronger and faster than the centralized approach. Therefore, this strategy is able to run a large-scale problem conveniently and in a shorter time than the centralized method. The decentralized strategy is examined using the following features of the network:

The number of nodes in set N: 125, including 49 transition nodes, 60 gates, and 16 nodes on runways.

The number of links in the set L: 282.

$TTD_{nn'}$: A 76×76 distance matrix is defined similarly to the matrix for the small sample, which is mentioned in the previous part.

5.4 Numerical Results

In this part, all numerical results have been taken using the decentralized strategy to validate the developed mathematical programming model. We categorized the results into three segments. In each part, a specific approach is defined. Finally, we compare the results of each section with the existing real data from YUL. All the estimated parameters in the previous section are considered as realistic as possible. We define three different scenarios and indicate the results of each case.

5.4.1 Scenario One: No Truck in the System

In the first scenario, we assumed that all airplanes use jet power as their taxiing method. This case can be named as the worst scenario from the ecological point of view since fuel consumption and GHG emissions are on the highest amount. It should be mentioned, at the time being the YUL airport takes advantage of the diesel towing vehicles only for the push-back process, and the airplanes use their jet power for the ground taxi operation. Moreover, the control tower is responsible for guiding planes on the ground manually. Therefore, we ran the model for all 150 flights and forced them to choose the self-towing method. The purpose of this scenario is to compare the efficiency of the manual aircraft taxi guide with the automated airplane movement controlling system. Based on the current ground handling records at the YUL and the achieved results under the assumptions of the first scenario, correct judgment about the excellences of each method can be made.

As we mentioned before, we are using a three-hours-period of the YUL flight operations' data occurred on Monday, August 26, 2019, between 4 P.M. and 7 P.M. To make an accurate comparison, we collected the flights' information of the same period for the previous 13 weeks (May to July 2019). Henceforth, the corresponding data to this interval will be named as real data in this study.

According to the below graph, we divided the taxi time into two separate classes to investigate the impact of the proposed method on the time of aircraft ground movements, including Taxi-In and Taxi-Out (see Figure 5.2 and Figure 5.3). Undauntedly, the first point in both graphs that draw attention is the big difference between taxi-out of the manual method and our offered strategy. The reason behind this long taxi-outs in the existing system is directly related to the inefficiency of the manual controlling system. In such a system, the control tower keeps the departing airplanes in the stand to clear the way for the arriving planes. The average taxi-out achieved by the suggested method is 5.40 minutes, whereas the shortest taxi-out in the present method is more than 20 minutes. On the other hand, the taxi-in in the manual controlling technique has a range from 5.58 minutes to 10.74 minutes and in most cases, is more than seven minutes, while the average observed taxi-in in the automated system is only 5.31 minutes.

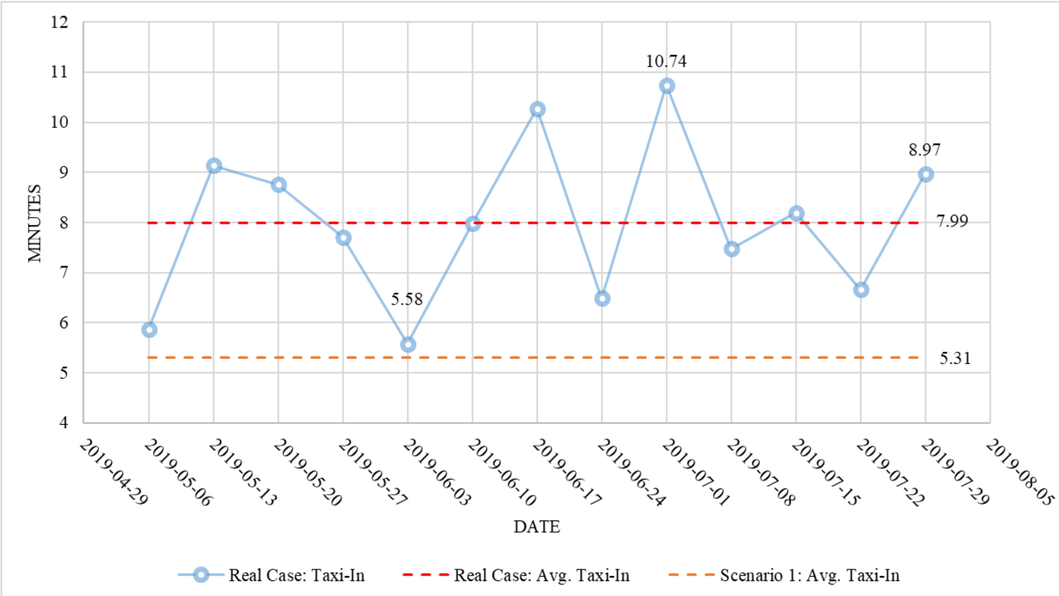


Figure 5.2: Comparing the Taxi-In of the Existing Aircraft Controlling System and The Results of The Scenario One

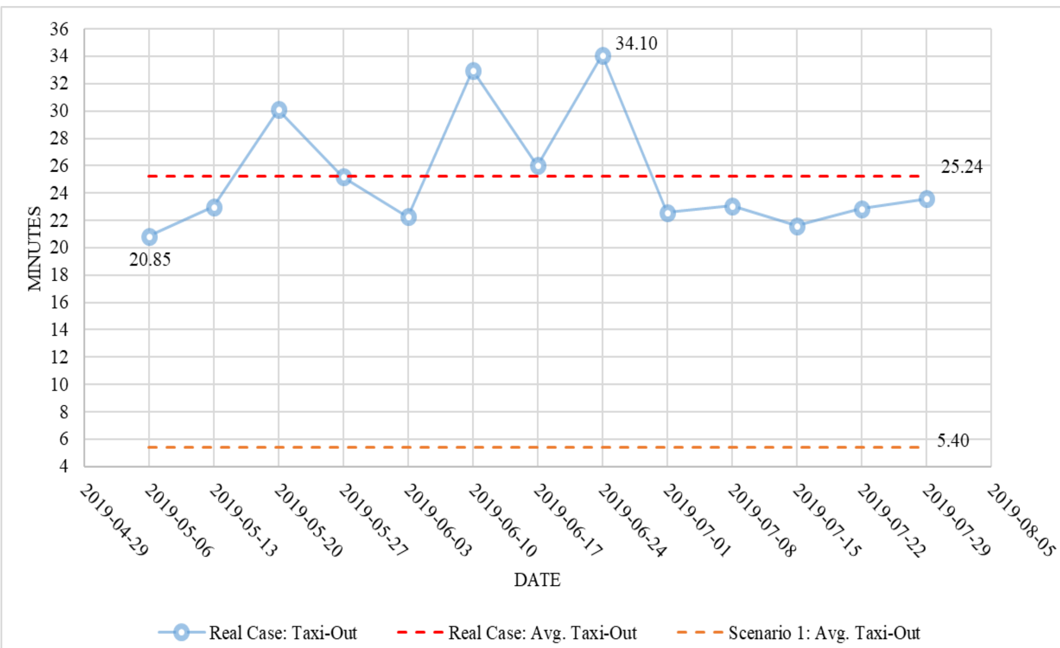


Figure 5.3: Comparing the Taxi-Out of the Existing Aircraft Controlling System and The Results of The Scenario One

The other remarkable effect of applying the automated controlling system on aircraft taxiing operation is that the percent of the long taxi time has decreased drastically (see Figure 5.4 and

Figure 5.5). As it is shown in the following graphs, we investigated the long taxi times of the manual guidance system and found out that, on average, 70 percent of cases have a taxi-out more than 20 minutes. Likewise, nine percent of the arrivals have recorded a taxi-in higher than 15 minutes. Whereas, the results of the presented strategy indicate that 99 percent of arriving airplanes and 98 percent of the departures have a taxi time less than 15 minutes.

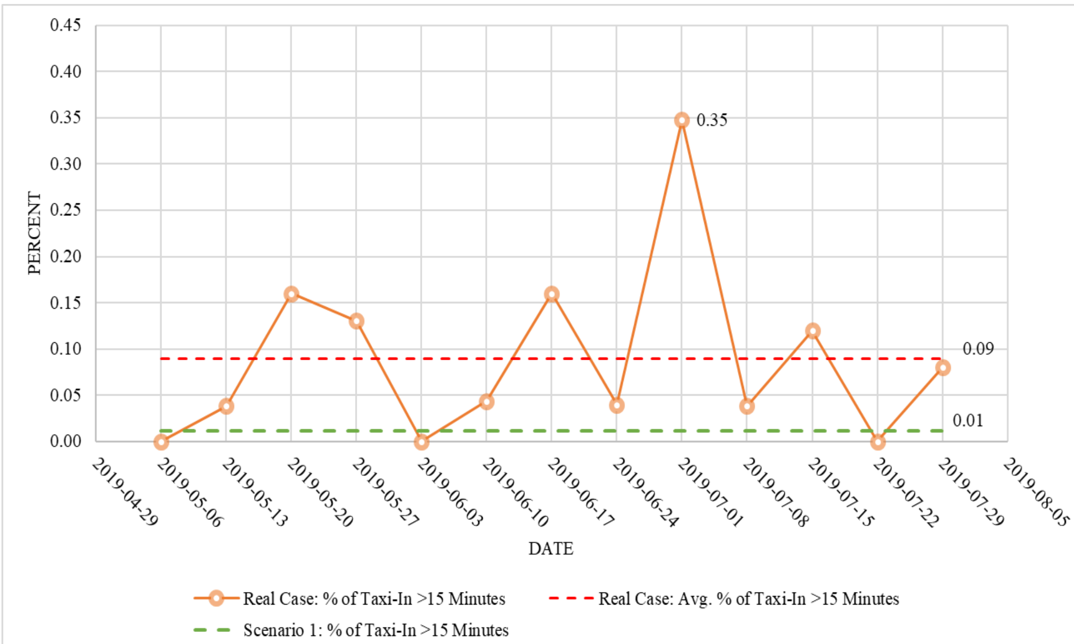


Figure 5.4: Comparing the Percent of The Long Taxi-In in Manual and Automated Taxi Control Systems

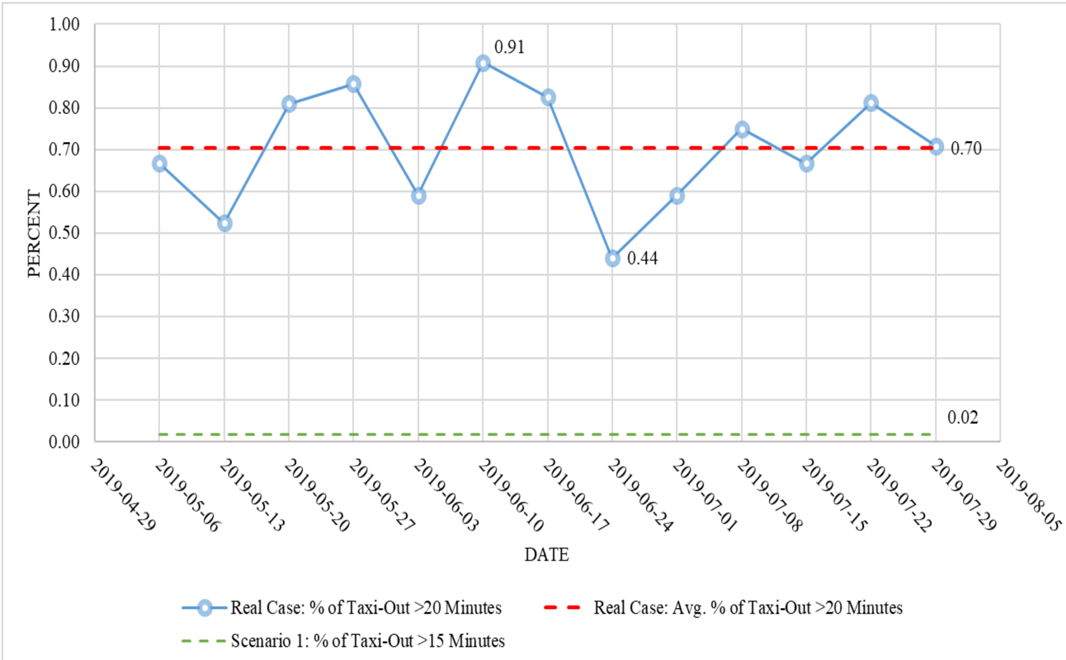


Figure 5.5: Comparing the Percent of The Long Taxi-Out in Manual and Automated Taxi Control Systems

All the above-obtained results demonstrate how an automated system can increase the efficiency of the airport ground handling operation. Although, by only implementing this strategy, we can partially reduce the total taxi time and the total fuel consumption, we eager to replace the old taxiing methods with more environmentally friendly systems. In the two next parts, we will discuss this important subject. It is notable that all safety requirements have been considered, which in the next sections, we describe them thoroughly. A summary of results achieved from the first scenario (Table 5.4) and a sample of aircraft movements is shown (Table 5.5).

Table 5.4: Summarized Numerical Results of Scenario One

Title	Value
Objective Function (USD)	62726.68
Total Taxi Time (Min)	801.32
Avg. Taxi Time (Min)	5.34
Avg. Taxi-in (Min)	5.31
Avg. Taxi-out (Min)	5.40
Longest Taxi Time (Min)	16.95
Fuel Cost (USD)	21886.15
Total Delay (Min)	21.85
No. of towed airplanes	0

Table 5.5: A Sample Result of Offered Scheduling Solution Under Assumption of Scenario One

Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link
1	37	37	89	0.00	0.27
1	239	89	88	0.27	0.60
1	237	88	87	0.60	0.92
1	236	87	86	0.92	1.13
1	234	86	85	1.13	1.35
1	94	85	105	1.35	1.48
1	261	105	104	1.48	1.97
1	229	104	81	1.97	2.18
1	87	81	82	2.18	2.62
1	90	82	103	2.62	3.03
1	259	103	102	3.03	3.22
1	119	102	110	3.22	3.72
1	125	110	111	3.72	3.97
1	126	111	115	3.97	4.30
1	132	115	120	4.30	5.75
1	138	120	121	5.75	6.75
1	139	121	124	6.75	7.47
1	221	124	76	7.47	7.83
2	55	55	93	0.00	0.37
2	107	93	95	0.37	0.58
2	249	95	94	0.58	0.75
2	109	94	96	0.75	1.00
2	111	96	99	1.00	1.15
2	115	99	100	1.15	1.42
2	116	100	101	1.42	2.03
2	117	101	108	2.03	2.17
2	208	108	67	2.17	2.48
3	65	65	123	4.00	4.50
3	281	123	122	4.50	5.53
3	278	122	119	5.53	6.57
3	276	119	117	6.57	7.02
3	274	117	116	7.02	8.05
3	268	116	111	8.05	8.93
3	266	111	110	8.93	9.18
3	260	110	102	9.18	9.68
3	118	102	103	9.68	9.87
3	231	103	82	9.87	10.28
3	228	82	81	10.28	10.72
3	88	81	104	10.72	10.93
3	120	104	105	10.93	11.42
3	235	105	85	11.42	11.55
3	93	85	86	11.55	11.77
3	95	86	87	11.77	11.98
3	96	87	88	11.98	12.30
3	98	88	89	12.30	12.63
3	101	89	90	12.63	13.00
3	102	90	91	13.00	13.38
3	183	91	42	13.38	13.55
4	61	61	109	5.00	5.30
4	265	109	108	5.30	5.63
4	258	108	101	5.63	5.77
4	257	101	100	5.77	6.38
4	256	100	99	6.38	6.65
4	252	99	96	6.65	6.80
4	247	96	92	6.80	7.03
4	188	92	47	7.03	7.20
5	78	74	120	10.00	10.67
5	273	120	115	10.67	12.12
5	267	115	111	12.12	12.45
5	266	111	110	12.45	12.70
5	260	110	102	12.70	13.20
5	118	102	103	13.20	13.38
5	231	103	82	13.38	13.80
5	228	82	81	13.80	14.23
5	88	81	104	14.23	14.45
5	120	104	105	14.45	14.93
5	235	105	85	14.93	15.07
5	171	85	30	15.07	15.23
6	63	63	119	10.10	10.57
6	276	119	117	10.57	11.02
6	274	117	116	11.02	12.05
6	268	116	111	12.05	12.95
6	266	111	110	12.95	13.20
6	260	110	102	13.20	13.70
6	118	102	103	13.70	13.88
6	231	103	82	13.88	14.30
6	228	82	81	14.30	14.73
6	88	81	104	14.73	14.95
6	120	104	105	14.95	15.43
6	235	105	85	15.43	15.57
6	93	85	86	15.57	15.78
6	95	86	87	15.78	16.00
6	96	87	88	16.00	16.32
6	98	88	89	16.32	16.65
6	101	89	90	16.65	17.02
6	103	90	96	17.02	17.23
6	250	96	94	17.23	17.48
6	108	94	95	17.48	17.65
6	248	95	93	17.65	17.87
6	198	93	57	17.87	18.03
7	49	49	92	10.20	10.37
7	106	92	96	10.37	10.60
7	244	96	90	10.60	10.82
7	242	90	89	10.82	11.18
7	239	89	88	11.18	11.52
7	100	88	107	11.52	11.65
7	263	107	106	11.65	11.97
7	238	106	87	11.97	12.48
7	236	87	86	12.48	12.70
7	234	86	85	12.70	12.92
7	233	85	84	12.92	13.25
7	232	84	83	13.25	13.57
7	223	83	77	13.57	13.92
7	81	77	79	13.92	14.12
7	85	79	98	14.12	14.28
7	114	98	103	14.28	14.63
7	213	103	70	14.63	15.12

5.4.2 Scenario Two: Forcing all Airplanes to be Towed

In this scenario, one towing truck will be assigned to each aircraft. In this way, we intend to assess the impact of using electric tractors on taxi time and fuel consumption. As we discussed in the previous chapters, the truck-taxiing method has a slower operation speed than the aircraft self-taxiing. Therefore, we expect a greater taxi time in total. Similar to the previous part, the flights' information of the same period for the past several weeks is a good resource to estimate the effect of using tugs on the airport ground operation. In addition, an overall comparison between the results of both scenarios demonstrates the cons and pros of each approach.

As it is indicated in Figure 5.6 and Figure 5.7, the taxi time of the current scenario is not as short as the first strategy, although it is still obviously lower than the ground operation’s time of the manual guiding system. Both taxi-in and taxi-out times of the second approach are standing on a higher value than the taxi times of scenario one. The average taxi-in and the average taxi-out has increased up to 7.34 minutes and 7.02 minutes, respectively. Also, the total taxi time is approximately 280 minutes greater, which means 35 percent more than the total taxi time of the first scenario. This longer taxi time is precisely related to the reason that is explained in the first sentences of this section. This slowness issue can be answered by the ratio of the truck operation speed than the self-towing speed, which is 34 percent slower. In addition, a comparison between these two scenarios shows that the proportion of flights with a taxi-in and a taxi-out greater than 15 minutes is increased by four percent and six percent, respectively (see Figure 5.8 and Figure 5.9).

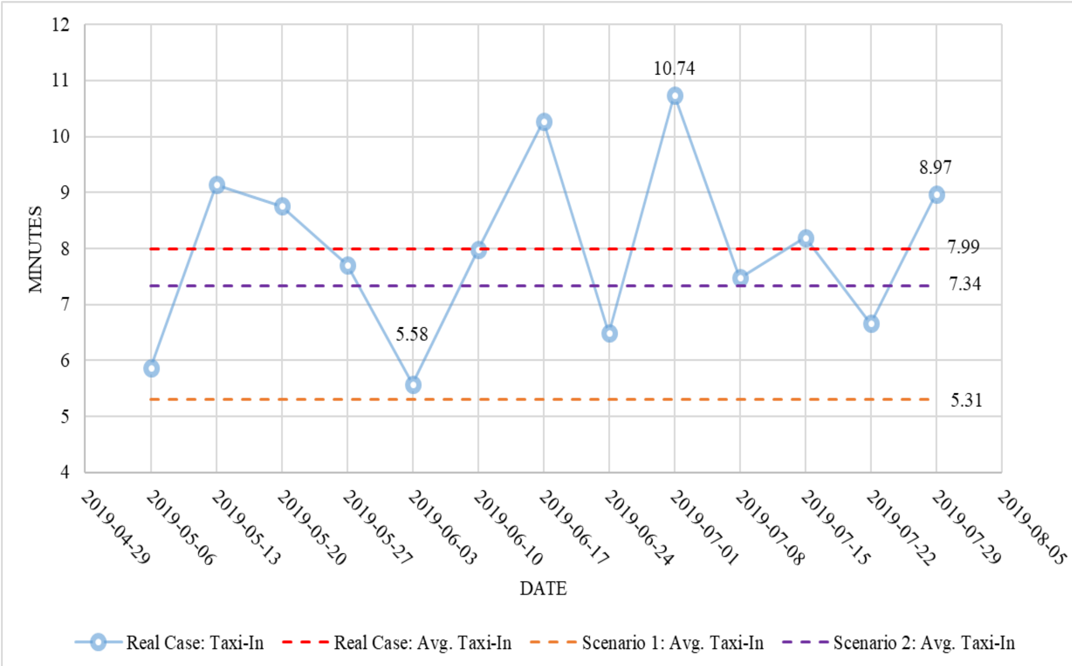


Figure 5.6: Comparing the Taxi-In of the Existing Aircraft Controlling System and The Results of Scenario Two

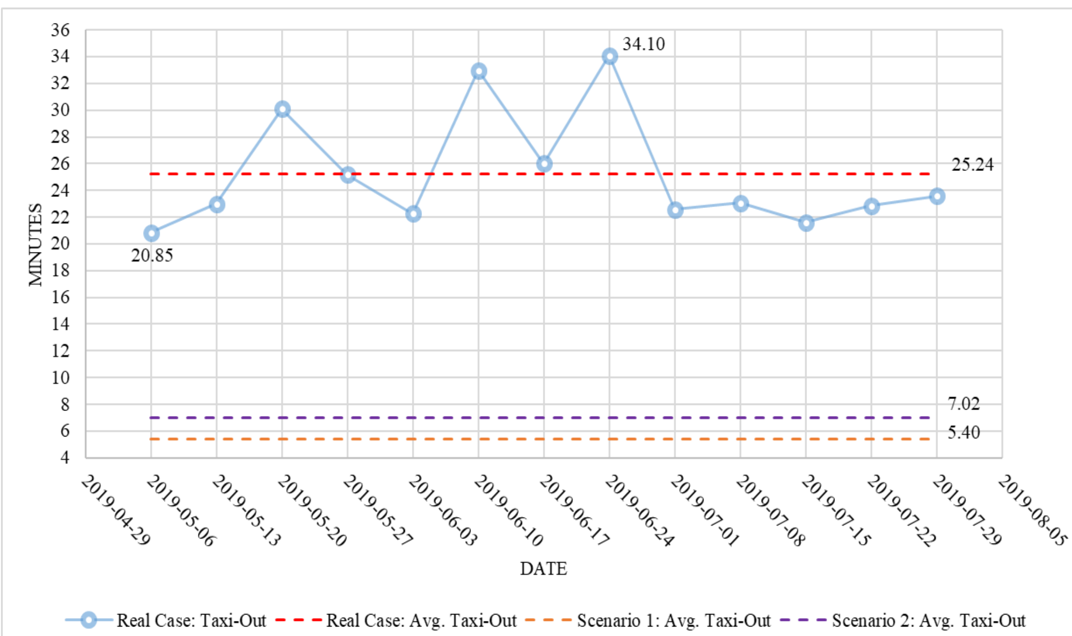


Figure 5.7: Comparing the Taxi-Out of the Existing Aircraft Controlling System and The Results of Scenario Two

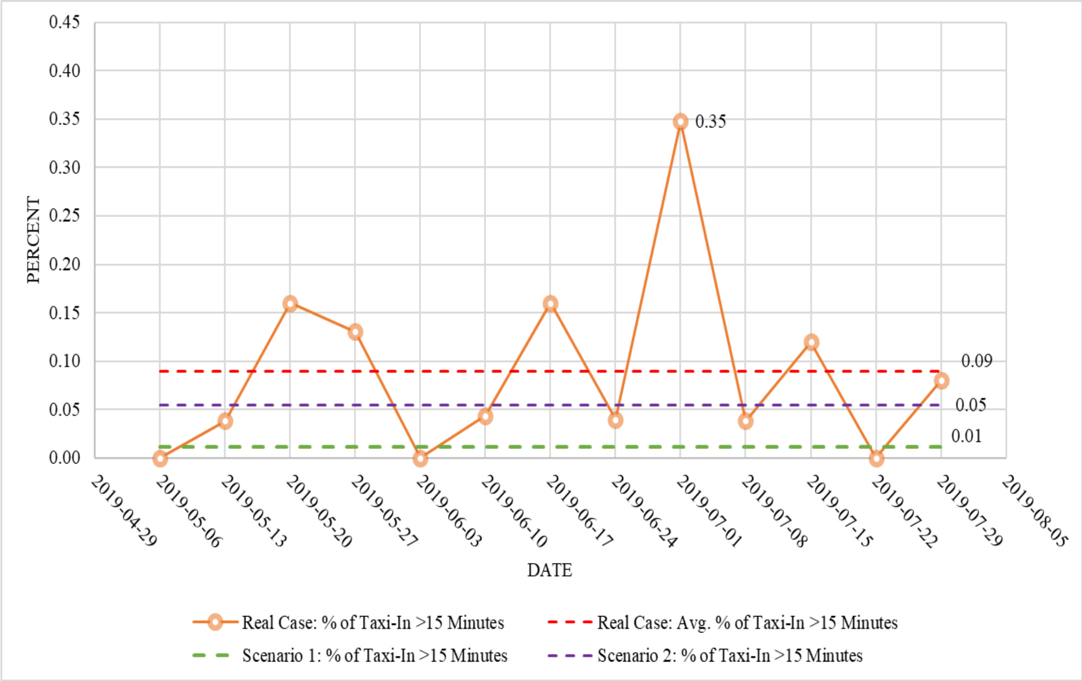


Figure 5.8: Comparing the Percent of The Long Taxi-Ins in Scenario One and Scenario Two

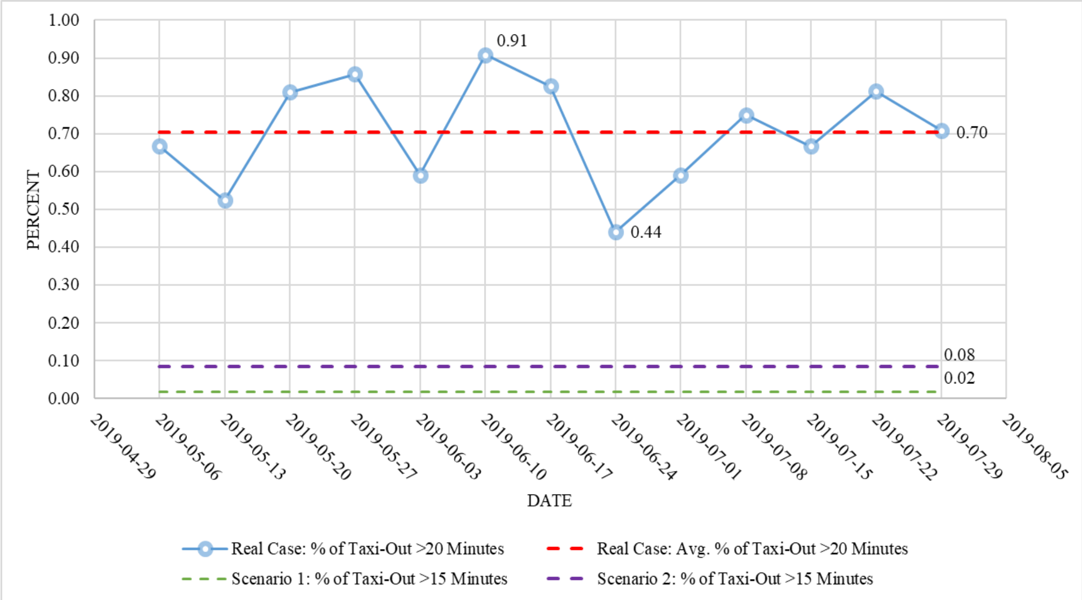


Figure 5.9: Comparing the Percent of The Long Taxi-Outs in Scenario One and Scenario Two

Although tug taxiing is not as fast as the single-engine-towing method, we estimated that more than USD 21,000 of fuel is saved in this three-hour operation. Moreover, one of the significant advantages of applying this strategy is that the air pollution caused by aircraft ground movement will be eliminated. Overall, considering the provided strategies and the analysis of the results, we have gained a correct opinion regarding the efficiency of the automated taxiing system and using new towing powers instead of the old taxi methods. All these works have been done to show the cons and pros of each method. In the first strategy, the taxiing time was improved, but decreasing the fuel consumption, and the emission reduction targets were ignored.

Conversely, in the second scenario, the aircraft fuel consumption was reached to zero, but the taxi time was not as good as the first approach. Apart from this issue, it is not realistic to have a towing vehicle available for being assigned to a taxiing task at all times. The reason is that high-tech trucks are costly, and it is difficult for an airline to purchase several tugs at the same time. Hence, in the next section, we present a new and realistic answer to this problem. On the next two pages, the results of the second scenario are summarized in a table (Table 5.6). Besides, a sample of aircraft's taxi routes is provided in Table 5.7.

Table 5.6: Summarized Numerical Results of Scenario Two

Title	Value
Objective Function (USD)	59366.28
Total Taxi Time (Min)	1081.81
Avg. Taxi Time (Min)	7.21
Avg. Taxi-in (Min)	7.34
Avg. Taxi-out (Min)	7.02
Longest Taxi Time (Min)	20.47
Fuel Cost (USD)	0.00
Saved Fuel (USD)	22962.20
Total Delay (Min)	70.66
No. of Trucks in the System	150
No. of Towed Airplanes	150
$\frac{\text{Truck Taxi Time}}{\text{Total Taxi Time}}$	1.00

Table 5.7: A Sample Result of Offered Scheduling Solution Under Assumption of Scenario Two

Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link	Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link
20	80	76	124	24.00	24.49	24	37	37	89	25.30	25.97
20	280	124	121	24.49	25.45	24	101	89	90	25.97	27.23
20	279	121	120	25.45	26.79	24	104	90	100	27.23	30.94
20	273	120	115	26.79	28.73	24	116	100	101	30.94	31.76
20	267	115	111	28.73	29.18	24	240	101	88	31.76	31.94
20	266	111	110	29.18	29.52	24	237	88	87	31.94	32.37
20	260	110	102	29.52	30.19	24	236	87	86	32.37	32.66
20	118	102	103	30.19	30.43	24	234	86	85	32.66	32.95
20	255	103	98	30.43	30.90	24	233	85	84	32.95	33.39
20	226	98	79	30.90	31.12	24	232	84	83	33.39	33.82
20	222	79	77	31.12	31.39	24	223	83	77	33.82	34.29
20	145	77	4	31.39	31.62	24	81	77	79	34.29	34.56
21	77	73	115	25.00	26.48	24	85	79	98	34.56	34.78
21	267	115	111	26.48	26.93	24	253	98	97	34.78	35.00
21	266	111	110	26.93	27.27	24	113	97	102	35.00	35.58
21	260	110	102	27.27	27.94	24	119	102	110	35.58	36.25
21	118	102	103	27.94	28.18	24	125	110	111	36.25	36.59
21	231	103	82	28.18	28.74	24	127	111	116	36.59	37.77
21	228	82	81	28.74	29.32	24	133	116	117	37.77	39.16
21	88	81	104	29.32	29.61	24	135	117	119	39.16	39.76
21	120	104	105	29.61	30.26	24	137	119	122	39.76	41.14
21	235	105	85	30.26	30.44	24	140	122	123	41.14	42.53
21	93	85	86	30.44	30.73	24	141	123	125	42.53	43.98
21	95	86	87	30.73	31.02	24	207	125	66	43.98	44.52
21	96	87	88	31.02	31.44	25	64	64	122	27.00	27.67
21	98	88	89	31.44	31.89	25	278	122	119	27.67	29.05
21	101	89	90	31.89	32.38	25	276	119	117	29.05	29.66
21	103	90	96	32.38	32.67	25	274	117	116	29.66	31.04
21	250	96	94	32.67	33.01	25	268	116	111	31.04	32.23
21	201	94	60	33.01	33.23	25	266	111	110	32.23	32.56
22	65	65	123	25.10	25.77	25	260	110	102	32.56	33.23
22	281	123	122	25.77	27.15	25	118	102	103	33.23	33.48
22	278	122	119	27.15	28.54	25	231	103	82	33.48	34.04
22	276	119	117	28.54	29.14	25	228	82	81	34.04	34.62
22	274	117	116	29.14	30.53	25	88	81	104	34.62	34.91
22	268	116	111	30.53	31.71	25	120	104	105	34.91	35.55
22	266	111	110	31.71	32.05	25	235	105	85	35.55	35.73
22	260	110	102	32.05	32.72	25	93	85	86	35.73	36.02
22	118	102	103	32.72	32.96	25	95	86	87	36.02	36.31
22	231	103	82	32.96	33.52	25	96	87	88	36.31	36.74
22	228	82	81	33.52	34.10	25	98	88	89	36.74	37.18
22	88	81	104	34.10	34.39	25	101	89	90	37.18	37.68
22	120	104	105	34.39	35.04	25	103	90	96	37.68	37.97
22	235	105	85	35.04	35.22	25	250	96	94	37.97	38.30
22	93	85	86	35.22	35.51	25	199	94	58	38.30	38.52
22	174	86	33	35.51	35.73	26	68	68	106	28.00	28.40
23	80	76	124	25.20	25.69	26	122	106	107	28.40	28.83
23	280	124	121	25.69	26.65	26	241	107	88	28.83	29.01
23	279	121	120	26.65	27.99	26	98	88	89	29.01	29.45
23	273	120	115	27.99	29.93	26	101	89	90	29.45	29.94
23	267	115	111	29.93	30.38	26	103	90	96	29.94	30.23
23	266	111	110	30.38	30.72	26	250	96	94	30.23	30.57
23	260	110	102	30.72	31.39	26	199	94	58	30.57	30.79
23	118	102	103	31.39	31.63						
23	231	103	82	31.63	32.19						
23	228	82	81	32.19	32.77						
23	156	81	15	32.77	32.99						

5.4.3 Scenario Three: Various Number of Trucks in the System

The first strategy was introduced to increase the efficiency of the airport surface handling process, and the second one was presented with environmentally friendly purposes. However, a successful solution should be financially efficient and eco-friendly at the same time. In the current section, we intend to suggest a practical solution for the aircraft taxi operation by suggesting the truck-towing as the optional taxiing method in the system. Thus, for each aircraft, a three-objective trade-off will be made among the cost of delay, fuel cost and the cost of existing in the system. The same input data as the previous scenarios for three-hour ground operation at YUL has been used. Several economic, financial, and technical assessment criteria have been considered in analyzing the results. We categorized our investigations into three subdivisions.

5.4.3.1 Determination of the Optimal Number of Trucks

In this part, we examine the proposed model with a different number of trucks in the system. In this way, we aim to offer a realistic solution by combining previous strategies. The first scenario from the practical point of view and the second scenario from the financial aspect aid in evaluating each iteration. All determinative factors will be compared in order to find the best solution. First of all, we require to know when the lowest total cost and the shortest total taxi time happen. According to the following graph (Figure 5.10), the first point on the left side shows the results of the first strategy, which we assumed that there was not any towing vehicle in the system. Likewise, the results of the second scenario are shown by the point which is marked by a star (*).

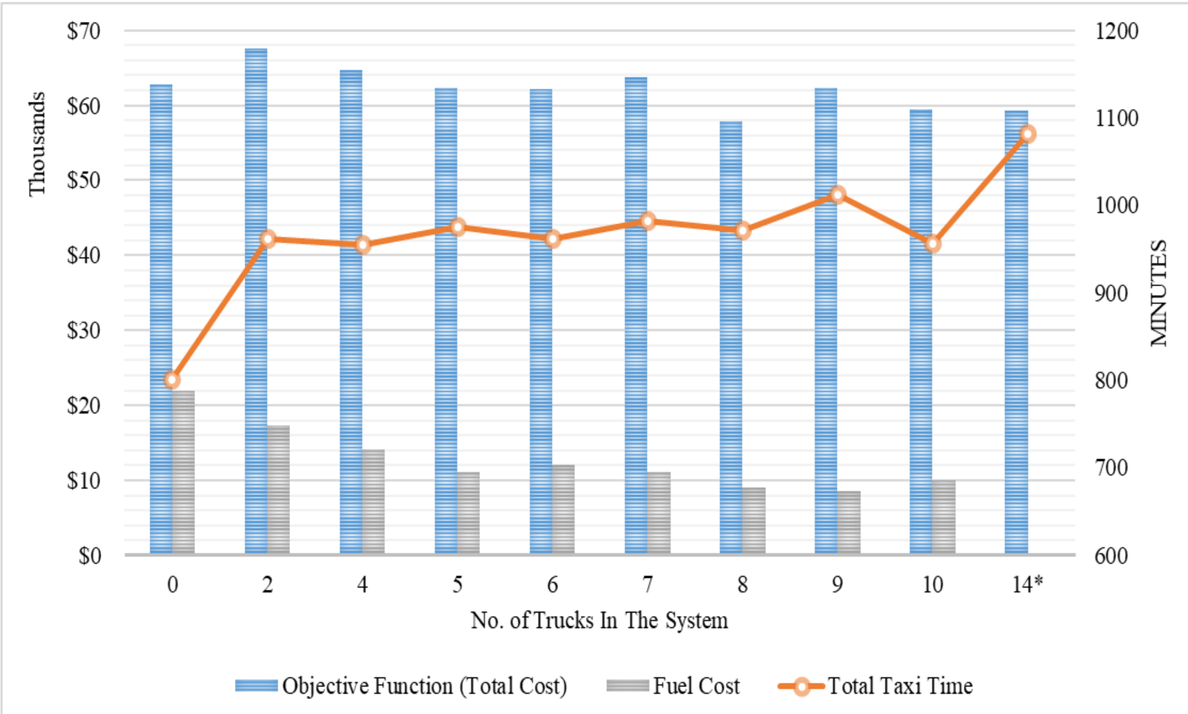


Figure 5.10: Comparing the Main Features of Different Scenarios

As it can be observed on the graph, the first scenario offers a solution with the best service quality, since the total taxi time is on the lowest value, while the total cost is high. On the other hand, the second scenario provides the best environmentally friendly solution since the kerosene's cost is wholly removed, but it is impractical. Hence, we intend to investigate the points that exist between these two strategies and compare their total cost and the total taxi time to find the best solution. In an overall view of this graph, we realize that the total taxi time for different points is almost the same except in points, five, seven, and nine, which have recorded a higher taxi time. Also, only in points eight and ten, the objective function has a remarkable reduction compared to the other situations.

Moreover, the fuel cost in the cases that eight and nine tractors are hired has the lowest amount. It is clear that from each aspect, there is more than one candidate for the best solution. Thus, we should look for the best solution somewhere between these spots, but we need more details to make a more accurate comparison.

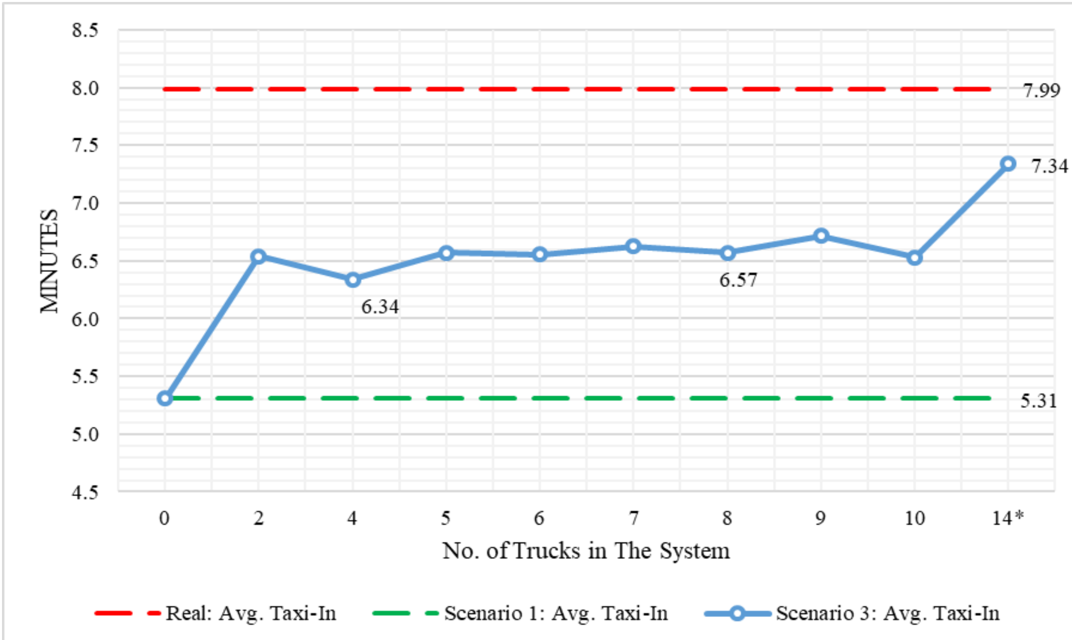


Figure 5.11: Comparing Taxi-In of Different Scenarios

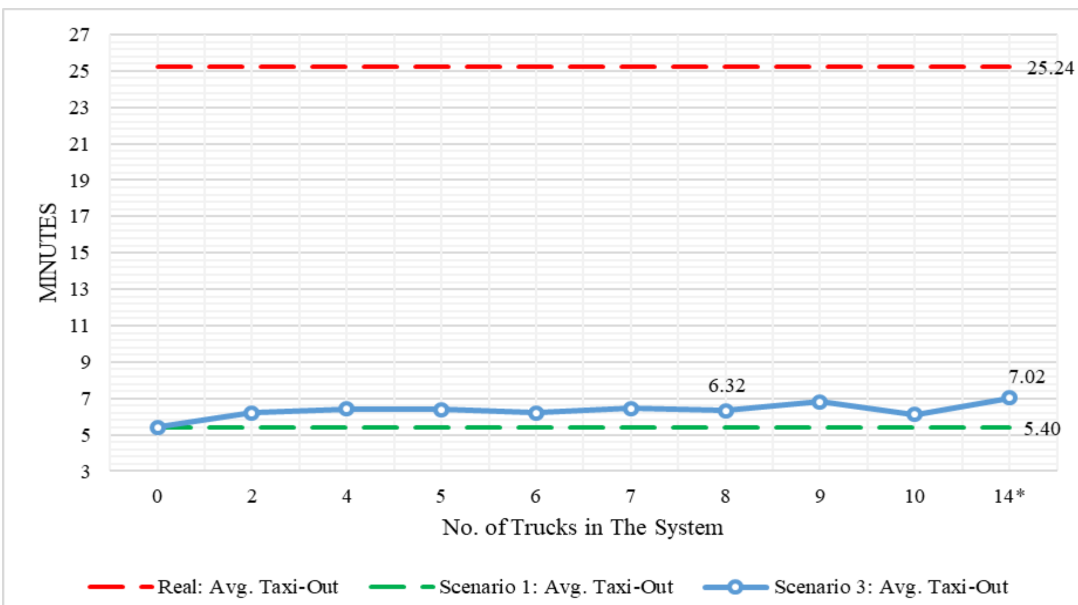


Figure 5.12: Comparing Taxi-Out of Different Scenarios

The above-given diagrams (Figure 5.11 and Figure 5.12) show that although the average taxi-in and taxi-out of the current scenario are not as short as the first scenario, in all cases, they are considerably less than the average real taxi times. Therefore, if we could find a case with a slightly higher taxi time than the first scenario but, with a less total cost, that point can be a candidate for the best solution.

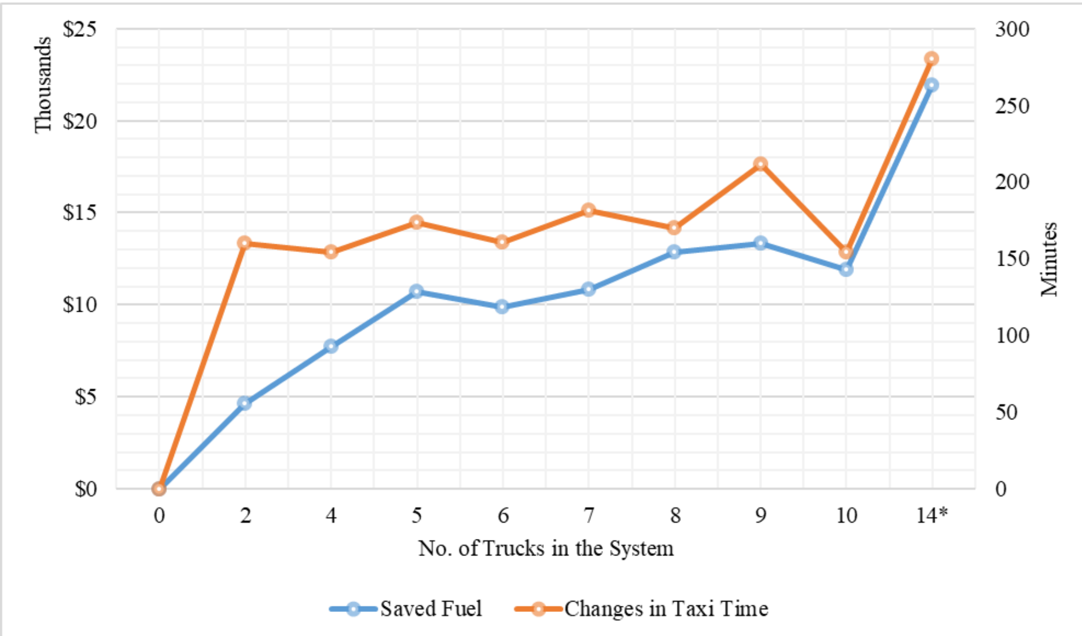


Figure 5.13: Comparing the Saved Fuel and Taxi Time's Changes in Different Situations

In addition, we considered the taxi time of scenario one as the base scale to calculate the changes of total operation time for each iteration (see Figure 5.13). Likewise, its fuel cost has been assumed as the bottom line of costs to estimate the differences in the cost of each case. As is evident in Figure 5.13, the taxi time does not have a rapid change in any of the cases except when the number of existing vehicles in the system is nine. At the same time, the value of saved fuel has risen moderately and finally reached its peak at point nine. Hence and according to the presented evidence, points eight and ten are the candidates for the best solution, one with a shorter taxi time, and the other one with less total cost. At this step, we need to look into the other factors that affect making the decision.

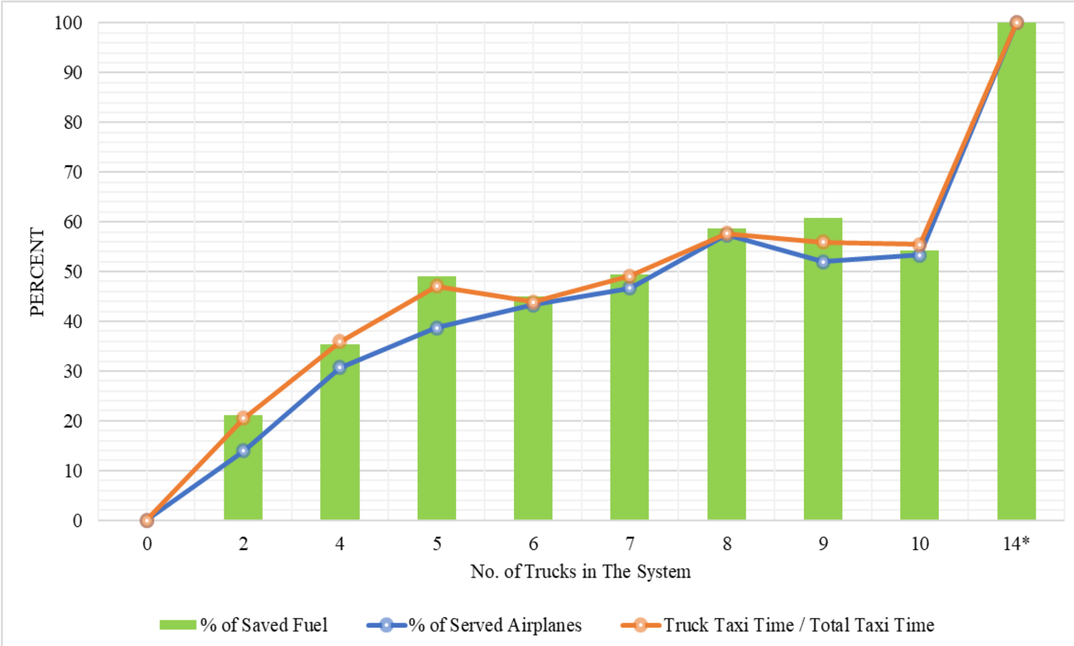


Figure 5.14: Comparing the Other Key Factors of Different Scenarios

In view of Figure 5.14, in the case that eight vehicles serve the airport, approximately 60 percent of flights will be carried by electric tractors, which leads to saving about 60 percent of kerosene. Besides, in this case, almost 60 percent of total taxi time has been done by towing trucks. Therefore, this graph shows that hiring eight tugs is more efficient than using ten trucks. Furthermore, the delay is another key factor in assessing the quality of the routing system. Based on achieved records (see Figure 5.15), the total delay at point eight is almost equal to delay at point zero, which, compared to the other cases, has the shortest cumulative delay.

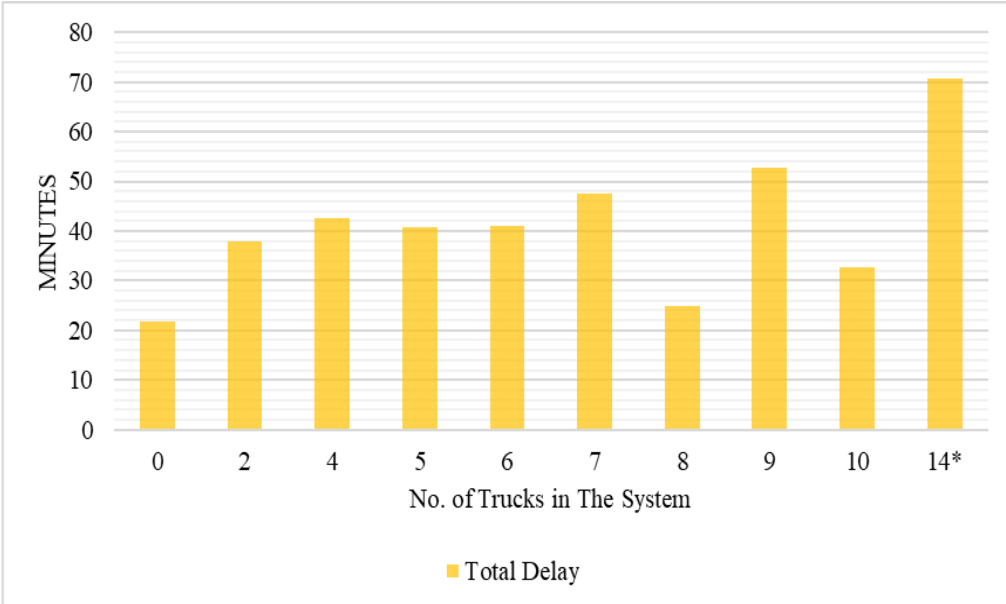


Figure 5.15: Comparing the Cumulative Delay in Different Scenarios

Consequently, all the above evaluations provide enough evidence to hire eight electric tractors. Therefore, a large percentage of airplanes will be towed by trucks, and a massive amount of kerosene will be saved. This decrease in fuel consumption brings great financial and ecological benefits to the aviation industry. In the next part, we discuss these advantages in detail. The results of the third scenario sum up in the below tables (Table 5.8 and Table 5.9). Also, a sample of aircraft taxi traffic schedule is brought in the following pages (Table 5.10).

Table 5.8: Summarized Numerical Results of Scenario Three – Part One

Title	**No. of Trucks in the System**				
	0	**2**	**4**	**5**	**6**
Objective Function (USD)	62726.68	67632.76	64680.75	62251.32	62101.20
Total Taxi Time (Min)	801.32	961.39	955.34	975.11	962.32
Avg. Taxi Time (Min)	5.34	6.41	6.37	6.50	6.42
Avg. Taxi-in (Min)	5.31	6.54	6.34	6.57	6.56
Avg. Taxi-out (Min)	5.40	6.21	6.42	6.40	6.20
Longest Taxi Time (Min)	16.95	17.30	16.45	20.12	17.03
Fuel Cost (USD)	21886.15	17266.20	14131.88	11171.73	12036.22
Saved Fuel (USD)	0.00	4619.95	7754.27	10714.42	9849.93
% of Saved Fuel	0.00	21.11	35.43	48.96	45.01
Total Delay (Min)	21.85	37.95	42.72	40.78	41.10
No. of Towed Airplanes	0	21	46	58	65
% of Towed Airplanes	0.00	14.00	30.67	38.67	43.33
$\frac{\textbf{Truck Taxi Time}}{\textbf{Total Taxi Time}}$	0.00	20.48	35.93	47.10	43.89
% of Arrivals with Taxi-In >15 Min	1.10	0.00	2.20	1.10	1.10
% of Departures with Taxi-Out >15 Min	1.69	8.47	5.08	5.08	1.69

Table 5.9: Summarized Numerical Results of Scenario Three – Part Two

Title	**No. of Trucks in the System**				
	7	**8**	**9**	**10**	**14***
Objective Function (USD)	63684.32	57918.85	62323.75	59423.66	59366.28
Total Taxi Time (Min)	982.77	970.98	1012.75	955.78	1081.81
Avg. Taxi Time (Min)	6.55	6.47	6.75	6.37	7.21
Avg. Taxi-in (Min)	6.63	6.57	6.72	6.53	7.34
Avg. Taxi-out (Min)	6.44	6.32	6.81	6.13	7.02
Longest Taxi Time (Min)	18.14	16.59	17.37	17.37	20.47
Fuel Cost (USD)	11061.60	9047.42	8585.43	10013.10	0.00
Saved Fuel (USD)	10824.55	12838.73	13300.72	11873.05	21886.15
% of Saved Fuel	49.46	58.66	60.77	54.25	100.00
Total Delay (Min)	47.51	24.91	52.69	32.68	70.66
No. of Towed Airplanes	70	86	78	80	150
% of Towed Airplanes	46.67	57.33	52.00	53.33	100.00
$\frac{\textbf{Truck Taxi Time}}{\textbf{Total Taxi Time}}$	49.14	57.65	55.96	55.49	100.00
% of Arrivals with Taxi-In >15 Min	1.10	0.00	1.10	0.00	5.49
% of Departures with Taxi-Out >15 Min	6.78	3.39	5.08	5.08	8.47

Table 5.10: A Sample Result of Offered Scheduling Solution Under Scenario Three’s Assumption (Eight Trucks in the System)

Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link	Flight No.	Link No.	From Node	To Node	Arrival to the Link	Departure from the Link
110	21	21	77	135.00	135.71	114	21	21	77	140.60	140.76
110	82	77	83	135.71	136.18	114	81	77	79	140.76	140.96
110	91	83	84	136.18	137.10	114	85	79	98	140.96	141.13
110	92	84	85	137.10	137.55	114	253	98	97	141.13	141.30
110	93	85	86	137.55	137.84	114	113	97	102	141.30	141.73
110	95	86	87	137.84	138.13	114	119	102	110	141.73	142.23
110	96	87	88	138.13	138.55	114	125	110	111	142.23	142.48
110	99	88	101	138.55	138.73	114	127	111	116	142.48	143.36
110	117	101	108	138.73	138.91	114	270	116	112	143.36	143.70
110	124	108	109	138.91	139.36	114	128	112	113	143.70	144.66
110	202	109	61	139.36	139.76	114	130	113	117	144.66	144.98
111	68	68	106	136.00	136.30	114	135	117	119	144.98	145.43
111	122	106	107	136.30	136.62	114	137	119	122	145.43	146.46
111	241	107	88	136.62	136.75	114	140	122	123	146.46	147.50
111	98	88	89	136.75	137.08	114	141	123	125	147.50	148.58
111	101	89	90	137.08	137.45	114	207	125	66	148.58	148.98
111	103	90	96	137.45	137.67	115	62	62	114	141.00	141.78
111	250	96	94	137.67	137.92	115	131	114	118	141.78	142.37
111	108	94	95	137.92	138.08	115	275	118	117	142.37	142.85
111	248	95	93	138.08	138.30	115	274	117	116	142.85	143.88
111	196	93	55	138.30	138.47	115	268	116	111	143.88	144.77
112	65	65	123	140.00	140.50	115	266	111	110	144.77	145.02
112	281	123	122	140.50	141.87	115	260	110	102	145.02	145.52
112	278	122	119	141.87	142.90	115	118	102	103	145.52	145.70
112	276	119	117	142.90	143.35	115	231	103	82	145.70	146.12
112	274	117	116	143.35	144.38	115	228	82	81	146.12	146.55
112	268	116	111	144.38	145.27	115	88	81	104	146.55	146.77
112	266	111	110	145.27	145.52	115	120	104	105	146.77	147.25
112	260	110	102	145.52	146.02	115	235	105	85	147.25	147.38
112	118	102	103	146.02	146.20	115	93	85	86	147.38	147.60
112	255	103	98	146.20	146.55	115	95	86	87	147.60	147.82
112	226	98	79	146.55	146.72	115	96	87	88	147.82	148.13
112	222	79	77	146.72	146.92	115	98	88	89	148.13	148.47
112	82	77	83	146.92	147.27	115	101	89	90	148.47	148.83
112	91	83	84	147.27	147.58	115	103	90	96	148.83	149.05
112	92	84	85	147.58	147.92	115	250	96	94	149.05	149.30
112	93	85	86	147.92	148.13	115	108	94	95	149.30	149.47
112	95	86	87	148.13	148.35	115	248	95	93	149.47	149.68
112	96	87	88	148.35	148.67	115	196	93	55	149.68	149.85
112	98	88	89	148.67	149.00	116	28	28	84	141.00	141.22
112	101	89	90	149.00	149.37	116	92	84	85	141.22	141.67
112	103	90	96	149.37	149.58	116	93	85	86	141.67	141.96
112	247	96	92	149.58	149.82	116	95	86	87	141.96	142.25
112	194	92	53	149.82	149.98	116	96	87	88	142.25	142.68
113	61	61	109	140.51	140.91	116	99	88	101	142.68	142.85
113	265	109	108	140.91	141.36	116	117	101	108	142.85	143.03
113	258	108	101	141.36	141.53	116	208	108	67	143.03	143.46
113	257	101	100	141.53	142.36						
113	256	100	99	142.36	142.72						
113	252	99	96	142.72	142.92						
113	250	96	94	142.92	143.25						
113	108	94	95	143.25	143.48						
113	248	95	93	143.48	143.77						
113	197	93	56	143.77	143.99						

5.4.3.2 Economic Justification

In the previous section, we evaluated the efficiency of the airport ground operation with different numbers of vehicles in the system. Then we showed that by engaging eight electric trucks, all of the taxiing service quality criteria would be fulfilled. Also, we indicated that by applying the proposed method, the total cost of aircraft taxiing decreases drastically. After that, in this part, we intend to compute the economic and environmental benefits of the proposed case. As it is shown in the results of the previous part, approximately USD 12,800 fuel is saved. Now, we aim to estimate the amount of saved fuel as well as unreleased emissions. Based on the provided results, 57.65 percent of total taxi time was done by trucks, which is equal to 560 minutes. On the other hand, we assumed that truck taxiing is 0.34 slower than the single-taxiing method. In this way, 560 minutes of the truck taxiing method is equal to 369.6 minutes of the self-towing method. In accordance with the presented literature review, an airplane averagely burns around 11.5 kilograms of kerosene in each minute of taxiing. Furthermore, each gram of aviation gasoline releases 3.16 grams of CO_2. In results, we estimate that approximately 4.25 tons of fuel and in addition to it, over 13,000 tons of CO_2 is saved only in these three hours. Various values have been defined for the social marginal damage cost of CO_2, and based on Ricke et al. (2018), a median of 417 USD per ton of CO_2 is evaluated. Thus, producing less GHG in this duration has over 4.5 million dollars of indirect benefits for the environment. As we stated earlier, it is difficult to find a resource for evaluating the cost and the duration of life of an airplane automated controlled tug, but we estimate that a new generation tug costs approximately 700,000 with a minimum of seven years of useful life.

Certainly, the amount of saved fuel in the cases that the tow-tractors were used shows the direct benefits of hiring these electric trucks. However, the effect of using tractors on the quality of the taxiing service is the other crucial element that should be appraised. In accordance with the results, scenario one can be named as the best strategy from the service quality's point of view, since the shortest value for both total taxi time and the total delay occurred under the assumption of this scenario. Therefore, comparing the total cost of this scenario with the case that eight trucks were hired, can indicate the impact of using tow trucks on the entire system.

On the basis of the presented results, in the case that eight vehicles are hired, the total cost decreases by about 4,800 USD compared to the first scenario. On the other side, according to the mentioned appraisals, if we only consider the direct economic benefits of this three-hour ground operation, 1.75 million dollars annually will be saved, which means that the duration of return on investment for purchasing eight vehicles will be around 3.2 years.

5.4.3.3 Collision Avoidance Feature

In the current section, we demonstrate how the proposed solution guarantees the safety distance between consecutive flights. As we explained in the methodology, the aircraft's conflicts are divided into two classes, including accidents between planes moving in the same direction and incidents between planes running in the opposite path. The time-space graph is a powerful tool to reveal any dangerous occurrence in the system. Therefore, three different examples have been brought to show the aircraft movements on links in various traffic congestions. Each example displays airplane activities during a ten-minutes time interval. The first one represents the airport ground operation from time 20 to 30 minutes (Figure 5.16), the second one from 90 to 100 minutes (Figure 5.17), and the last one between 170 and 180 minutes (Figure 5.18). The size-dependent separation of flights during time easily can be seen on the graph. For instance, in the first graph (see Figure 5.16), two airplanes have followed each other on link number 101. The blue one is flight number 15, which is a light plane, and the yellow line traces the movement of the plane number 14, which is a light-size aircraft too. Obviously, airplane 14 is the leader on the link, and the following aircraft required to keep a 0.5-minute distance. As illustrated, they have regarded this distance both in entering and leaving the arc. In the second sample (see Figure 5.17), flight 85 (shown in light orange), which is a medium-size plane, pursues a heavy-size aircraft numbered 72 (shown in light blue) on link 82. A 0.75-minute separation time in applied on their arriving and departing time to the link. Respecting the required separation’s time distance on link 224 between aircraft 139 and 145 is another example that is shown in the third graph (see Figure 5.18).

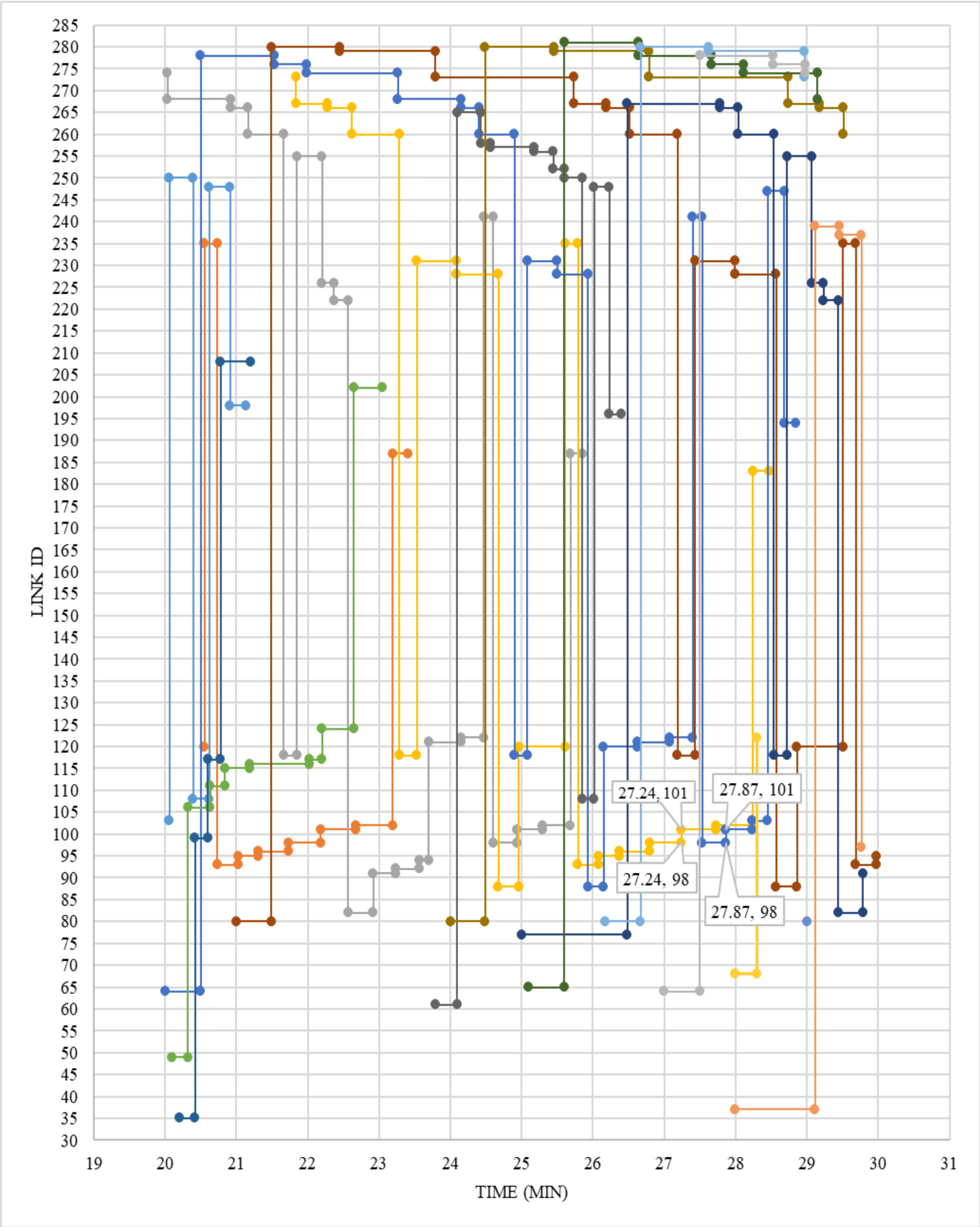


Figure 5.16: Preventing Aircraft's Collisions on Links – Instance One

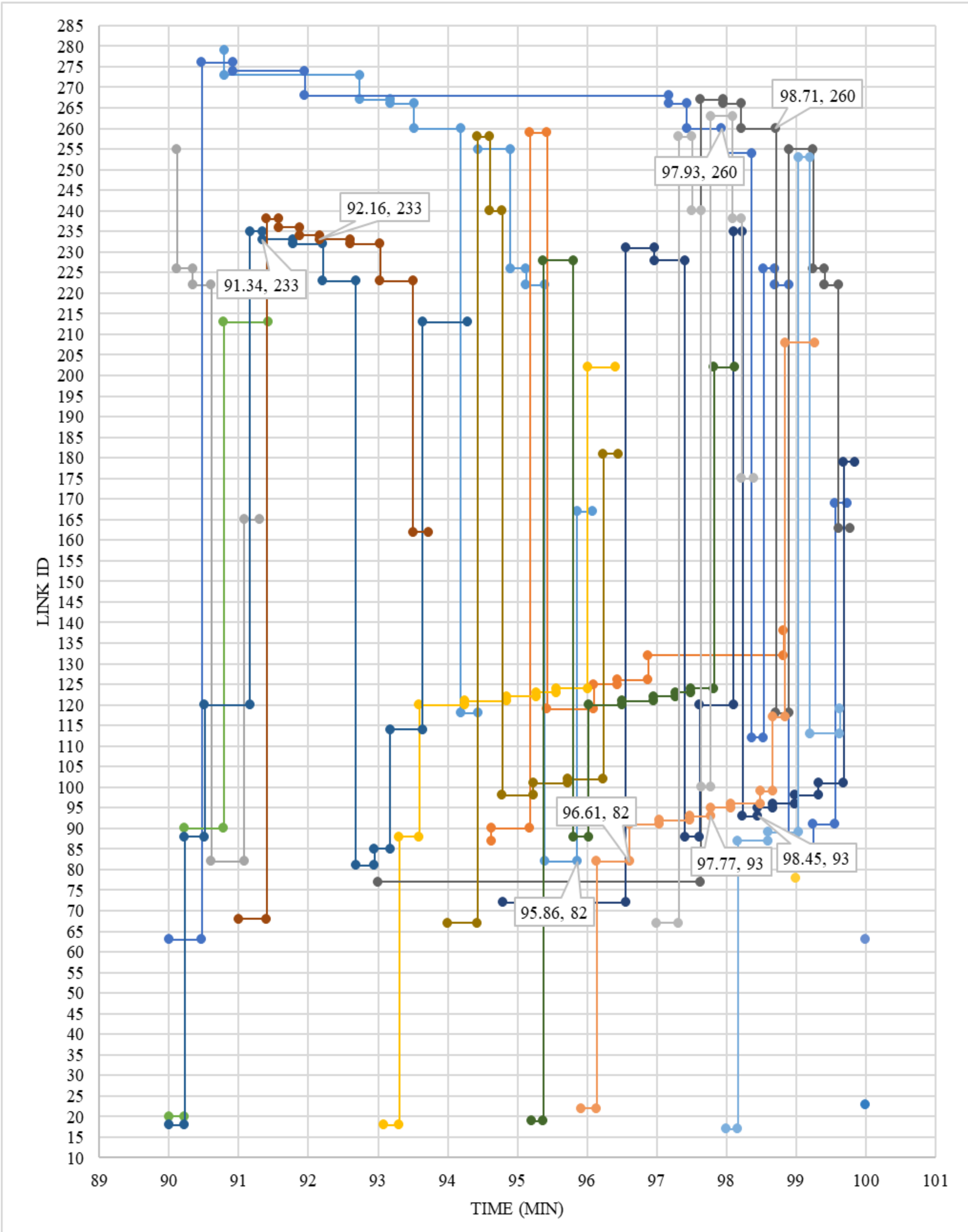


Figure 5.17: Preventing Aircraft's Collisions on Links – Instance Two

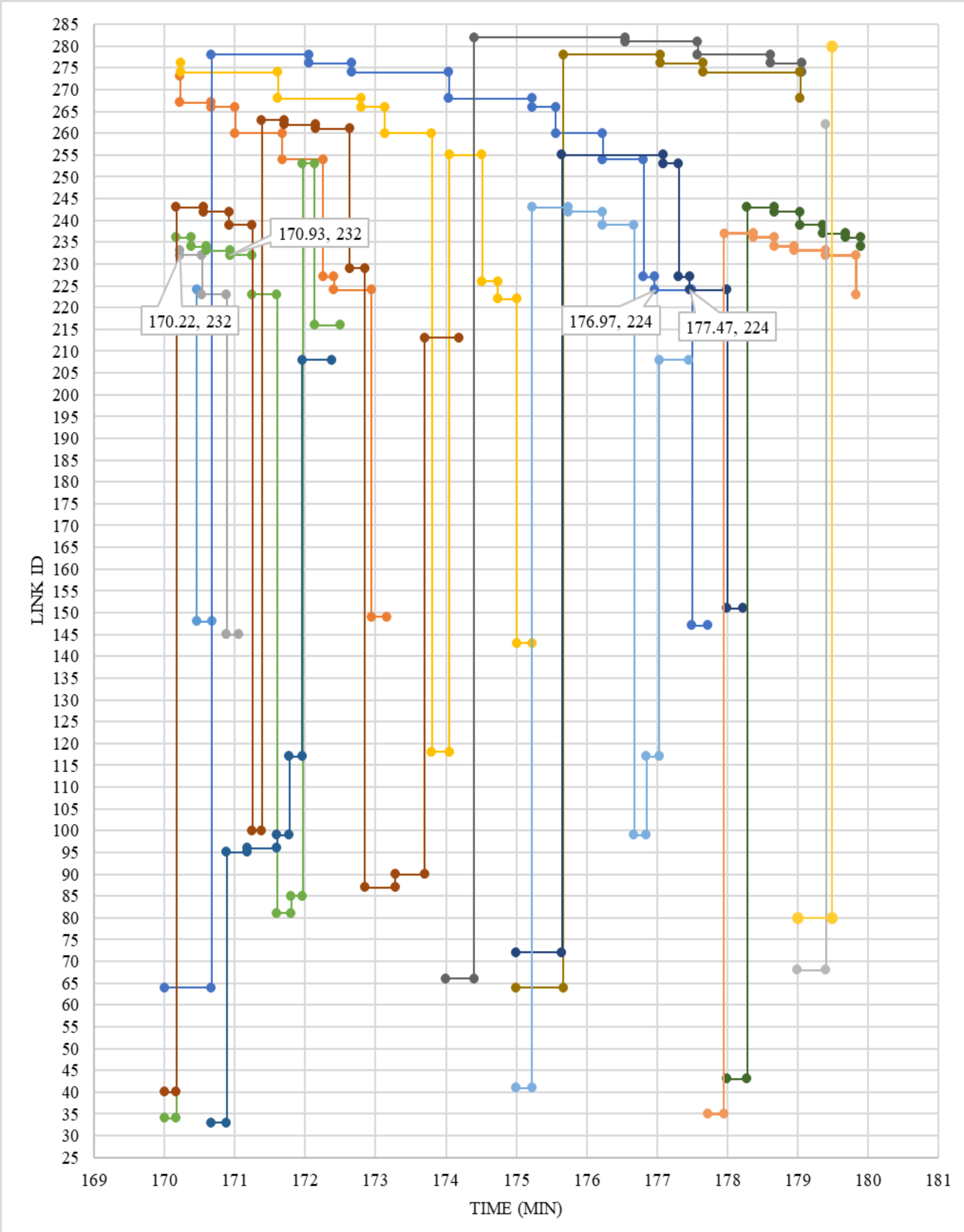


Figure 5.18: Preventing Aircraft's Collisions on Links – Instance Three

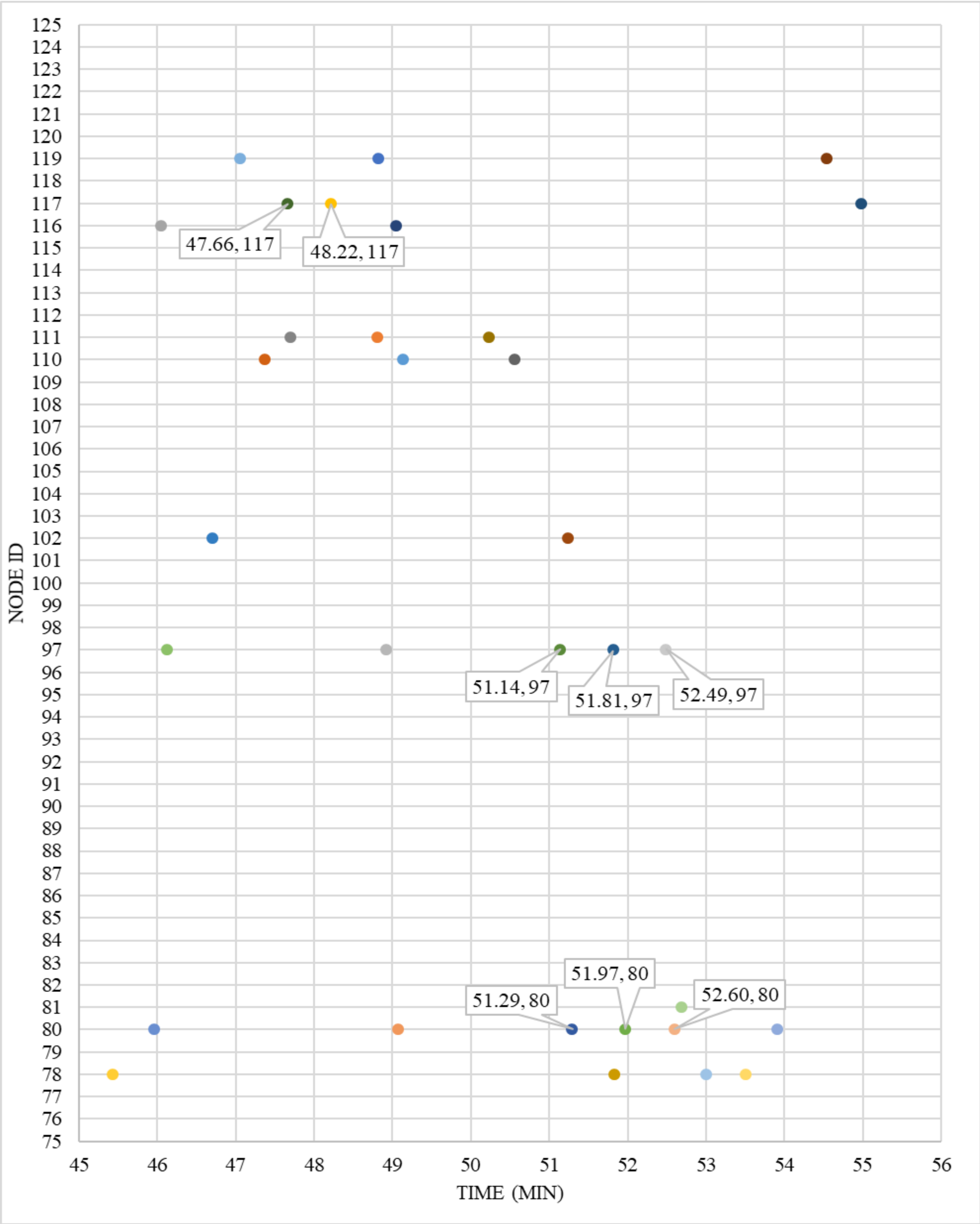


Figure 5.19: Avoiding Aircraft's Collisions on Nodes

Finally, in the above-indicated graph (Figure 5.19), head-on collisions have been analyzed. All nodes on the graph are separated. In this way, there are not any two flights that have travelled on a specific intersection at the same time. For example, three flights have passed through node 97, taking into consideration the minimum safety distance. Also, the flights 40, 37, and 41 have occupied node 80, respectively, considering the minimum separation time. Figure 5.20 indicates a condition that airplanes 36 and 37 travel on the link 117-119 in reverse directions. As illustrated in the picture, a minimum safety distance has been applied between the departing time of aircraft 37 and the entering time of flight 36 from/to node 117. This situation is also demonstrated in the time-space diagram.

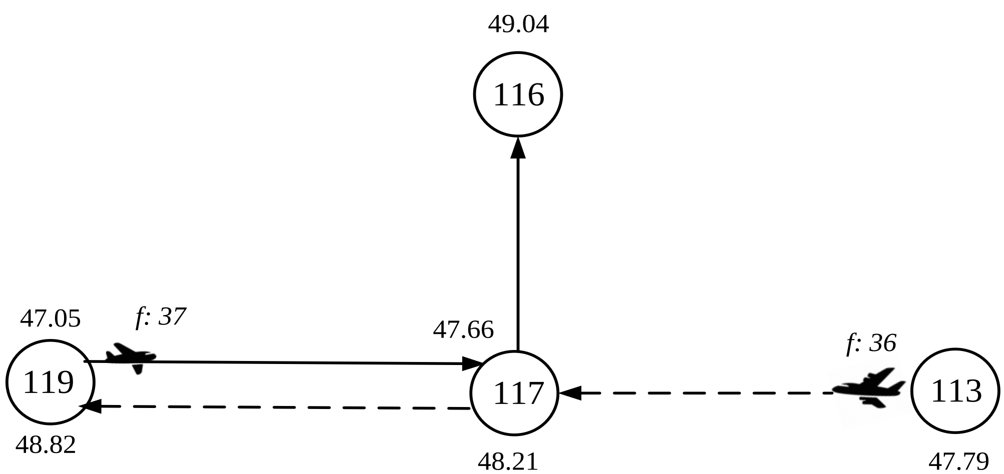


Figure 5.20: An Example of Travelling on a Link in the Opposite Direction

CHAPTER SIX

6 CONCLUSION AND FUTURE WORK

Continuous increase in the number of delayed flights and long taxiing times have drawn attention to the fact that the airports have become more crowded. The main reason for this increase is rapid growth in the number of air-travelers in recent years. Accordingly, the global aviation industry faces severe challenges in the coming years. In this study, we propose a unique mixed-integer linear programming model to optimize the aircraft taxi operation. We minimize the total taxiing time, as well as eliminate unnecessary ground delays. Also, two sets of safety constraints assure that aircraft will not be involved in ground conflicts. One set avoids head to head collisions, and the other one prevents accidents that commonly happen between airplanes running in the same direction. In both cases, we introduce a separation time distance between consecutive aircraft to guarantee the safety of the system.

Two towing methods were considered for taxiing tasks — one taxiing under the power of the jet engine, two, using an electric towing tractor. Tow tugs have significant benefits in not only decreasing total fuel consumption but also reducing air pollution. However, the fact that these trucks have a lower operating speed should be considered. Therefore, the corresponding cost to every plan will be calculated to estimate the final optimum cost of operation.

Several features have been considered to distinguish our study from the previous works. The most significant distinction is that this method is highly practical and easy to implement since it is entirely adaptable to the current equipment of airlines. Hence, to validate the offered model, we performed a case study at YUL. In this case study, we took a three-hour flight schedule at YUL, including the peak traffic hour of a day as well as one hour before and after for tolerance. Although we examined the model on YUL's taxiways, it can be generalized and adapted to the layout of every airport around the world.

In the case study, first, we reviewed the characteristics of taxiing operation at YUL. Then we compared the determinative factors of the current situation with our results to indicate achieved improvements. In the first phase, we showed how the taxiing time could be decreased just by applying mathematical methods. In the next phase, we indicated the effectiveness of green aircraft towing strategies in reducing fuel burn. Finally, based on economic and practical analysis, we proposed that by hiring eight towing trucks and assigning them to tow tasks, a large number of planes will be carried by the vehicles, which leads to saving more than 1.75 million dollars yearly, as well as 1.55 million tons of fuel, and 4.74 million tons of carbon dioxide.

Certainly, air traffic flow management is a vast field, and there are several ways to extend this study in the future. Due to the rapid growth of the aviation industry, it is necessary to attempt to regenerate formulations and propose new solutions for problems. Undoubtedly, this mathematical approach can be expanded for different aircraft types and their specific features such as specific fuel consumption rate, taxiing speed, weight, number of engines, and passenger capacity. Below, we suggest some potential opportunities that can be studied in future works:

- Addition of truck routing issues as a part of the problem.
- Modelling the issue of finding the optimal number of trucks as a resource allocation problem.
- Considering various sizes of electric tugs with different capacities.
- Generating a formulation for continuous taxiing speed.
- Considering other airport surface users as a part of the routing problem.
- Applying gate and runway scheduling problems.
- Adding weather conditions to the problem.

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APPENDICES

The details of the three-hour period of flight's schedules at YUL that has been used to examine the developed model.

Table 0.1: Flights information at YUL-Part One

Flight Number	Actual Arriving / Departing Time	Flight ID	Entering Node	Exit Node	EDT	LDT	LAT	Flight Size	Flight Type
AC7554	04:00:00 PM	1	37	76	0.00	3.00	16.24	1	DEP
AC419	04:00:00 PM	2	55	67	0.00	3.00	16.24	3	DEP
TS867	04:04:00 PM	3	65	42	4.00	4.00	17.24	2	ARR
PD477	04:05:00 PM	4	61	47	5.00	5.00	18.24	3	ARR
AC83	04:10:00 PM	5	74	30	10.00	10.00	23.24	1	ARR
LH478	04:10:00 PM	6	63	57	10.00	10.00	23.24	2	ARR
AC8753	04:10:00 PM	7	49	70	10.00	13.00	26.24	2	DEP
AC8507	04:12:00 PM	8	64	46	12.00	12.00	25.24	2	ARR
UA3986	04:12:00 PM	9	68	41	12.00	12.00	25.24	2	ARR
AC416	04:15:00 PM	10	66	46	15.00	15.00	28.24	3	ARR
AC1942	04:15:00 PM	11	60	67	15.00	18.00	31.24	1	DEP
TU203	04:15:00 PM	12	52	61	15.00	18.00	31.24	2	DEP
WS3531	04:15:00 PM	13	33	71	15.00	18.00	31.24	2	DEP
AC1072	04:19:00 PM	14	74	42	19.00	19.00	32.24	1	ARR
AC893	04:20:00 PM	15	64	53	20.00	20.00	33.24	1	ARR
AC1604	04:20:00 PM	16	49	61	20.00	23.00	36.24	3	DEP
AC8981	04:20:00 PM	17	59	67	20.00	23.00	36.24	3	DEP
AC8685	04:21:00 PM	18	76	56	21.00	21.00	34.24	3	ARR
WQ6800	04:22:00 PM	19	61	55	22.00	22.00	35.24	2	ARR
AC7728	04:24:00 PM	20	76	4	24.00	24.00	37.24	3	ARR
AC865	04:25:00 PM	21	73	60	25.00	25.00	38.24	1	ARR
AC7968	04:25:00 PM	22	65	33	25.00	25.00	38.24	2	ARR
AC2403	04:25:00 PM	23	76	15	25.00	25.00	38.24	3	ARR
AC8842	04:25:00 PM	24	37	66	25.00	28.00	41.24	1	DEP
DL5549	04:27:00 PM	25	64	58	27.00	27.00	40.24	2	ARR
WS3528	04:28:00 PM	26	68	58	28.00	28.00	41.24	2	ARR
AC318	04:29:00 PM	27	76	49	29.00	29.00	42.24	3	ARR
DL5474	04:30:00 PM	28	4	66	30.00	33.00	46.24	1	DEP
AC7971	04:30:00 PM	29	18	71	30.00	33.00	46.24	2	DEP
TS109	04:33:00 PM	30	71	8	33.00	33.00	46.24	2	ARR
AC811	04:35:00 PM	31	69	6	35.00	35.00	48.24	1	ARR
DL5518	04:36:00 PM	32	4	67	36.00	39.00	52.24	2	DEP
WG427	04:40:00 PM	33	71	2	40.00	40.00	53.24	3	ARR
AH2700	04:40:00 PM	34	66	8	40.00	40.00	53.24	3	ARR
AC1652	04:40:00 PM	35	2	76	40.00	43.00	56.24	2	DEP
AC1902	04:40:00 PM	36	1	66	40.00	43.00	56.24	3	DEP
0Q101	04:45:00 PM	37	64	8	45.00	45.00	58.24	2	ARR
AC6	04:45:00 PM	38	67	8	45.00	45.00	58.24	3	ARR
AC781	04:45:00 PM	39	10	76	45.00	48.00	61.24	1	DEP
AC7702	04:47:00 PM	40	68	10	47.00	47.00	60.24	1	ARR

Table 0.2: Flights information at YUL-Part Two

Flight Number	Actual Arriving / Departing Time	Flight ID	Enterin g Node	Exit Node	EDT	LDT	LAT	Flight Size	Flight Type
AC8909	04:47:00 PM	41	68	9	47.00	47.00	60.24	1	ARR
UA4074	04:49:00 PM	42	8	61	49.00	52.00	65.24	2	DEP
TS507	04:50:00 PM	43	64	9	50.00	50.00	63.24	1	ARR
AC478	04:50:00 PM	44	76	5	50.00	50.00	63.24	2	ARR
KL671	04:50:00 PM	45	66	20	50.00	50.00	63.24	3	ARR
LX87	04:50:00 PM	46	10	61	50.00	53.00	66.24	2	DEP
AC8757	04:50:00 PM	47	5	67	50.00	53.00	66.24	3	DEP
AA4845	04:52:00 PM	48	69	15	52.00	52.00	65.24	1	ARR
WS542	04:52:00 PM	49	73	12	52.00	52.00	65.24	1	ARR
YN204	04:52:00 PM	50	63	16	52.00	52.00	65.24	1	ARR
AA3126	04:53:00 PM	51	64	11	53.00	53.00	66.24	1	ARR
AC2401	04:55:00 PM	52	76	15	55.00	55.00	68.24	3	ARR
AC8664	04:55:00 PM	53	61	14	55.00	55.00	68.24	3	ARR
AC8741	04:55:00 PM	54	9	76	55.00	58.00	71.24	2	DEP
AC307	05:00:00 PM	55	5	66	60.00	63.00	76.24	1	DEP
AC835	05:00:00 PM	56	15	61	60.00	63.00	76.24	1	DEP
PD478	05:00:00 PM	57	3	67	60.00	63.00	76.24	1	DEP
WS543	05:00:00 PM	58	50	66	60.00	63.00	76.24	2	DEP
1I550	05:00:00 PM	59	14	76	60.00	63.00	76.24	3	DEP
DL5478	05:03:00 PM	60	13	70	63.00	66.00	79.24	2	DEP
AC747	05:04:00 PM	61	67	19	64.00	64.00	77.24	3	ARR
PD479	05:05:00 PM	62	70	13	65.00	65.00	78.24	2	ARR
0Q103	05:05:00 PM	63	67	15	65.00	65.00	78.24	3	ARR
AF345	05:05:00 PM	64	36	66	65.00	68.00	81.24	3	DEP
AC1684	05:08:00 PM	65	69	30	68.00	68.00	81.24	2	ARR
TS835	05:08:00 PM	66	61	23	68.00	68.00	81.24	3	ARR
AC8463	05:14:00 PM	67	61	29	74.00	74.00	87.24	3	ARR
7F867	05:15:00 PM	68	65	17	75.00	75.00	88.24	2	ARR
AC418	05:15:00 PM	69	69	26	75.00	75.00	88.24	2	ARR
WS3533	05:15:00 PM	70	12	67	75.00	78.00	91.24	2	DEP
AC8768	05:15:00 PM	71	20	76	75.00	78.00	91.24	2	DEP
AC8745	05:28:00 PM	72	76	26	88.00	88.00	101.24	3	ARR
AA3126	05:28:00 PM	73	17	76	88.00	91.00	104.24	3	DEP
DL5494	05:29:00 PM	74	70	24	89.00	89.00	102.24	3	ARR
AA4845	05:29:00 PM	75	18	61	89.00	92.00	105.24	1	DEP
SS900	05:30:00 PM	76	63	28	90.00	90.00	103.24	2	ARR
AC7973	05:30:00 PM	77	20	70	90.00	93.00	106.24	1	DEP
AC8795	05:30:00 PM	78	18	70	90.00	93.00	106.24	2	DEP
AC1689	05:31:00 PM	79	68	21	91.00	91.00	104.24	2	ARR
AA3903	05:33:00 PM	80	73	22	93.00	93.00	106.24	1	ARR

Table 0.3: Flights information at YUL-Part Three

Flight Number	Actual Arriving / Departing Time	Flight ID	Entering Node	Exit Node	EDT	LDT	LAT	Flight Size	Flight Type
AC7525	05:34:00 PM	81	67	40	94.00	94.00	107.24	2	ARR
AC1883	05:34:00 PM	82	70	38	94.00	94.00	107.24	2	ARR
AC7597	05:35:00 PM	83	19	61	95.00	98.00	111.24	1	DEP
AC1636	05:35:00 PM	84	17	76	95.00	98.00	111.24	2	DEP
AC7685	05:35:00 PM	85	22	67	95.00	98.00	111.24	2	DEP
AC8905	05:37:00 PM	86	67	34	97.00	97.00	110.24	3	ARR
AC8471	05:39:00 PM	87	74	32	99.00	99.00	112.24	1	ARR
DL5473	05:40:00 PM	88	63	37	100.00	100.00	113.24	1	ARR
AC8594	05:40:00 PM	89	76	36	100.00	100.00	113.24	3	ARR
WG378	05:40:00 PM	90	23	71	100.00	103.00	116.24	3	DEP
AC8793	05:41:00 PM	91	68	34	101.00	101.00	114.24	1	ARR
TS474	05:45:00 PM	92	23	67	105.00	108.00	121.24	2	DEP
AC8171	05:46:00 PM	93	68	36	106.00	106.00	119.24	1	ARR
AC8827	05:46:00 PM	94	63	35	106.00	106.00	119.24	1	ARR
DL5519	05:46:00 PM	95	64	32	106.00	106.00	119.24	2	ARR
AC884	05:50:00 PM	96	23	66	110.00	113.00	126.24	1	DEP
AC760	05:51:00 PM	97	72	42	111.00	111.00	124.24	2	ARR
AC1519	05:52:00 PM	98	66	41	112.00	112.00	125.24	3	ARR
0Q313	05:54:00 PM	99	75	43	114.00	114.00	127.24	2	ARR
PD481	05:55:00 PM	100	67	50	115.00	115.00	128.24	3	ARR
AC333	05:55:00 PM	101	20	61	115.00	118.00	131.24	1	DEP
AC8904	05:55:00 PM	102	45	66	115.00	118.00	131.24	2	DEP
AC748	05:55:00 PM	103	25	76	115.00	118.00	131.24	3	DEP
AC8033	05:59:00 PM	104	64	45	119.00	119.00	132.24	2	ARR
AC332	06:07:00 PM	105	69	44	127.00	127.00	140.24	1	ARR
3H705	06:10:00 PM	106	74	45	130.00	130.00	143.24	2	ARR
WS3452	06:14:00 PM	107	71	41	134.00	134.00	147.24	2	ARR
AC420	06:15:00 PM	108	64	47	135.00	135.00	148.24	1	ARR
TS778	06:15:00 PM	109	71	46	135.00	135.00	148.24	3	ARR
DL5469	06:15:00 PM	110	21	61	135.00	138.00	151.24	3	DEP
WS592	06:16:00 PM	111	68	55	136.00	136.00	149.24	1	ARR
TS915	06:20:00 PM	112	65	53	140.00	140.00	153.24	2	ARR
AC1987	06:20:00 PM	113	61	56	140.00	140.00	153.24	3	ARR
AC8641	06:20:00 PM	114	21	66	140.00	143.00	156.24	2	DEP
AC8179	06:21:00 PM	115	62	55	141.00	141.00	154.24	2	ARR
DL5524	06:21:00 PM	116	28	67	141.00	144.00	157.24	3	DEP
AC8966	06:24:00 PM	117	64	60	144.00	144.00	157.24	2	ARR
AA3903	06:24:00 PM	118	26	66	144.00	147.00	160.24	3	DEP
AC7972	06:25:00 PM	119	69	55	145.00	145.00	158.24	1	ARR
AC8173	06:25:00 PM	120	67	51	145.00	145.00	158.24	2	ARR

Table 0.4: Flights information at YUL-Part Four

Flight Number	Actual Arriving / Departing Time	Flight ID	Entering Node	Exit Node	EDT	LDT	LAT	Flight Size	Flight Type
FI805	06:35:00 PM	126	74	53	155.00	155.00	168.24	1	ARR
TS789	06:35:00 PM	127	66	46	155.00	155.00	168.24	2	ARR
WS218	06:37:00 PM	128	74	4	157.00	157.00	170.24	1	ARR
AC12	06:40:00 PM	129	68	5	160.00	160.00	173.24	1	ARR
AC7594	06:40:00 PM	130	67	8	160.00	160.00	173.24	3	ARR
AH2701	06:40:00 PM	131	28	61	160.00	163.00	176.24	2	DEP
AC1727	06:43:00 PM	132	76	7	163.00	163.00	176.24	3	ARR
AC1932	06:45:00 PM	133	35	70	165.00	168.00	181.24	1	DEP
OS74	06:45:00 PM	134	34	67	165.00	168.00	181.24	1	DEP
TS594	06:45:00 PM	135	31	61	165.00	168.00	181.24	2	DEP
AC1523	06:46:00 PM	136	75	8	166.00	166.00	179.24	2	ARR
UA6170	06:49:00 PM	137	68	4	169.00	169.00	182.24	1	ARR
AC671	06:49:00 PM	138	63	2	169.00	169.00	182.24	1	ARR
1I738	06:50:00 PM	139	64	6	170.00	170.00	183.24	1	ARR
AC775	06:50:00 PM	140	34	71	170.00	173.00	186.24	1	DEP
KL672	06:50:00 PM	141	33	67	170.00	173.00	186.24	2	DEP
WS3453	06:50:00 PM	142	40	70	170.00	173.00	186.24	3	DEP
AC7641	06:54:00 PM	143	66	3	174.00	174.00	187.24	2	ARR
LH474	06:55:00 PM	144	64	13	175.00	175.00	188.24	1	ARR
3H821	06:55:00 PM	145	70	10	175.00	175.00	188.24	3	ARR
AC1563	06:55:00 PM	146	43	71	175.00	178.00	191.24	2	DEP
AC7628	06:55:00 PM	147	41	67	175.00	178.00	191.24	2	DEP
AC1988	06:55:00 PM	148	35	66	175.00	178.00	191.24	3	DEP
AC326	06:59:00 PM	149	68	13	179.00	179.00	192.24	1	ARR
AA3940	06:59:00 PM	150	76	17	179.00	179.00	192.24	2	ARR