CONFLICT-FREE AIRPORT OPERATIONS PLANNING AND MANAGEMENT

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Abstract

Conflict Free Airport Operations Planning and Management

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This thesis proposes conflict-free mathematical models and solution strategies for both gate scheduling and taxiway scheduling problems by taking account all meaningful airport and flight characteristics into consideration that are not yet extensively studied in current academic literature. Since gate schedule performance has a great impact on the performance of the taxiway, we consider gate scheduling as a bi-objective optimization problem, present mathematical models and propose a two-phase solution approach. We also propose a mixed integer programming (MIP) model that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, the non-time segmented model proposed in this thesis, determines a taxi plan for each aircraft by identifying the sequence of taxiway intersections represented as nodes to be visited and determines the aircrafts' exact arrival and departure times to these nodes, average speed used on the taxiway represented as links between two consecutive nodes while ensuring the safety conditions that avoid aircraft collisions. The cost incurred from arrival and departure delays with total taxiing time is minimized. The model enables collision free airport operations considering both airlines and airport controller's objectives in continuous time where we know the *exact arrival and departure* times which is more accurate in tackling collision issues. However, accuracy comes with a cost of solution time. To overcome the difficulty to solve, strategies are proposed. The first strategy proposed, called the *iterative-TSM,* adopts a batch by batch policy and optimizes the TSM by solving it in an iterative way where in each iteration, schedules of the previous iteration are fixed. The second strategy proposed

motivates from the idea of decomposition the model into two as routing and timing problem and incorporates a genetic algorithms with TSM. All the models proposed are tested on a hypothetical data and the results are presented. Main contributions of this thesis can be listed as follows:

- A MILP model is presented for flight gate scheduling problem. The model is compared to modified version of one of the existing MILP model in literature and efficiency of the proposed model is evaluated. A two phase solution approach making use of the proposed MILP is also presented and the characteristics of the problem are analysed. While utilization of gates is maximized, on time performance is also considered.
- A MILP that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, all safety constraints are modeled with Big-Ms. This enables us to know the exact arrival and departure times for each flight on each link on the ground.
- Collision free taxiway scheduling is achieved. Since the models in the existing literature either assumes arbitrary capacities on the nodes of the network or discretizes time, they do not guarantee collision avoidance.
- Speed changes, rerouting, and holding at gates and taxiway intersections are used as control options.
- Both airlines and airport authorities' objectives are considered. Proposed models have the capability to be adopted as a decision support tool for the ground controllers and they allow airport traffic authorities to do what-if analysis in case of a change in the flight or airport network information. Proposed TSM also minimizes to total taxiing time which results in less costly taxiway schedules for airlines in terms of fuel costs and CO2 emissions.
- Two solution strategies are proposed for the TSM: *iterative TSM* and *GA-TSM.* While *iterative TSM* decomposes the problem into batches of flights, solves each batch by fixing the schedules of the previous batch in each batch, GA-TSM decomposes the problem into routing and timing. While *GA* searches for the best set of routes for the flights, *fixed TSM* solves the timing problem for a given set of routes.

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CHAPTER I

INTRODUCTION

Airline industry has been growing continuously during recent years while airport capacities have been stagnating. Despite the negative impact of September 11 attacks and ongoing global financial turmoil, demand for airline services has been steadily increasing. In most of the major markets including Europe, North America and large part of Asia, since early 90s, both total seat capacity and number of airline companies have increased significantly resulting fierce competition in industry. Emerging market conditions brought many challenges along with its benefits. Overcrowding in airport terminals, airspaces around the airports particularly in North America, airspaces between airports in Europe and frequent delays are some of the challenges for the airline industry as well as for the transportation authorities to tackle. Furthermore, volatility in fuel prices, increasing labor costs and unpredictable weather conditions in most parts of the world are forcing many airline companies to face extreme financial challenges.

Growing airline industry puts serious pressure on Air Traffic Controllers (ATCs) and Airport Ground Traffic Controllers (AGTCs). From taxiing to navigating in open skies, AGTCs and ATCs play crucial roles in delivering on-time service and ensuring the safety of aircrafts and passengers at all times. It is clear that, increasing ground and air traffic is becoming unmanageable for traffic management personnel to effectively determine a flight plan for each aircraft. Due to high traffic volume, traffic controllers frequently ignore economic and service objectives of airlines; rather they mainly focus on safety. Hence, fuel consumption cost, delays and early arrivals are frequently ignored. These traffic delays due to congestion are main sources of unnecessary cost to airlines, passengers, and air transportation dependent businesses. Delays also have significant environmental effects. Sub-optimal flight plans result in unnecessary fuel burn and gaseous emission that give rise to environmental concerns both globally and locally at ground level. The significant magnitude of air traffic delays presently observed is an indication that the current air traffic control infrastructure is not capable of handling present traffic levels.

A significant proportion of the actual travel time can be spent at the airport, especially with short-haul flights. To achieve efficient air transportation, it is crucial to more accurately manage traffic at the surface of airports. Congestion on the airport surface is a major constraint to the available capacity of the air transport system. Economically, congestion reduces the turnaround efficiency, whereas environmentally, the increase in both air pollutants and noise emissions negatively impact the local region. Surface congestion increases the taxi times of flights, leading to increased fuel costs and environmental impacts. Furthermore, congestion causes concerns for controller workload and increased risk of ground incursions.

There are several ways to increase the efficiency of an airport. First, is to build the new facilities in terms of runways, taxiways, and terminal ramp areas. However, such expansion generally will also increase the complexity of the airport configuration. Under most airport configurations, adding runways results in some runways blocking the traffic between the terminal ramp area and other runways further out. As the tower controllers have more flights to control, they also have more taxiway intersections and runway crossings to worry about. Furthermore, it also needs to consider land acquisition and it is costly investment, therefore it is considered to be a long term solution. The other way is to optimize the main airport surface resources: gates, taxiways, and runways. Taxiways connect the gates with the runways. Each runway may have several entry and exit nodes, i.e. nodes that connect the taxiways with the runway. When a flight arrives to the airport, it leaves the runway and taxies to its assigned gate where passengers and luggage are unloaded and loaded, the flight is prepared for its next departing leg. When the flight gets permission to depart from the air traffic controllers, then it taxies to the runway where it takes off. All this turnaround process, the movement of an aircraft on the ground, under its own power, excluding takeoff, landing, and gate utilization is defined as *taxiing*. Therefore, optimization of those airport resources can be categorized into two as gate scheduling and taxiing movement (i.e from the apron gate to the runway, vice versa) scheduling of aircrafts. While *gate scheduling* mainly focuses on assigning a given set of flights legs to a given set of gates available at the airport, as well as arrival and departure times to and from the gate it has been assigned to, *taxiway* *scheduling* considers movement of the aircraft on the ground between the gates and the runways in order to achieve safe and efficient ground plans. All those optimization efforts aim at helping ground controllers, to support them in making better decisions when routing and scheduling aircraft on the taxiways, from the gate or runway exit to the runway entrance or back to the gate. Thereby, total taxi time is aimed to be reduced or, more broadly, it is aimed that the operations serve the other linked airport operations as smoothly as possible. Therefore the problem on hand is scheduling the taxiway plans in an efficient and safe way. In the airport surface taxiing scheduling, there are many different stakeholders involved each with different requirements. The air traffic controllers require ensuring the safety of the movement of aircraft on the airport surface. Airline managers wish for ensuring flights can depart and arrive on time to reduce delays and taxiing costs. Airport authorities want to improve the utilization of airport resources. Therefore, when scheduling aircraft movements on the ground, not only security but also efficiency should be considered.

Airport taxiing scheduling for aircraft on airport surface is to determine aircraft approach time, departure time, and taxiing route for each aircraft under the premise of ensuring safety. The taxi system in the airport is composed of runway passageways, taxiways, and parking aprons. For a departure flight, after finishing the work in an assigned gate, such as cleaning, taking the passengers, and fuelling, the aircraft taxies till it reaches the departure runway. On the other hand, for an arrival flight, after landing on the runway, the aircraft enters the taxiway scheduling system in one of the runway entrance points and taxies till it reaches its assigned gate.

This movement of aircraft between the runways and gates or parking aprons is called taxiing and safe and efficient movement requires some of the decisions to be made for the flights. We can mainly group those decisions into two categories: routing and timing decisions. Routing considers giving a path of taxiways to follow for each flight from their original positions to their destination positions. For a departure flight, this route starts from its assigned gate, includes using predetermined taxiway links, and ends at the runway exit. For an arrival flight, the route starts from the runway and ends at the gate it is assigned to. On the other hand, timing decisions complete the schedule of the aircraft by determining the time to pass on each taxiway link in the route. In doing so, locational and temporal decisions are incorporated. However, there are some operational and technical limitations to consider. The most important one among those is the safety issue. In order to obtain a conflict-free schedules, all aircraft must keep a minimum safety separation during taxiing. According to the aircraft operation management manual, a minimum safety separation is regulated between different types of aircraft (including heavy, medium-size, and light aircraft). During taxiing, only one aircraft is allowed to pass the same location at one time and other aircrafts are required to wait to ensure safety. When two aircrafts need to taxi on the same segment of taxiway from different nodes, one aircraft must hold and wait. Similarly, when two aircraft is trailing each other, minimum separation requirements should be respected. Conflicts occur when two or more flights taxi through a common taxiway intersection without keeping the minimum safety separation, or two or more flights taxi on the same taxiway in opposite directions. In these cases, one aircraft must hold and wait at the entrance of the taxiway. Currently, ground controllers are responsible for all the ground movements and they guide all the aircraft during taxiing. When arriving flight gets permission to land from the runway controllers, the flight exits the runway and then ground controllers takes the responsibility of guiding the flight during taxiing to its gate. Similarly, for a departure flight, under the direction of ground controllers, the flight begins to taxi via the designated route and holds short of runway and then the responsibility is handed over to the runway controllers.

Considering the increasing traffic on the ground, optimization of gates and taxiways in a conflict-free, safe, and efficient way is a challenging task, a task that is performed mainly visually currently. Since it is difficult for controllers to manage taxiing, they are constantly suffering great pressure because of the responsibility they carry and this taxiing process is responsible for most of the flights at airports. In Europe, for example, it is estimated that aircraft spend 10-30% of their flight time taxiing, and that a medium range aircraft expends as much as 5-10% of its fuel on the ground (Deonandan and Balakrishnan, 2010). One way of overcoming the limitations is to design decision support tools/methods to guide controllers and the pilots on the ground.

Most of the studies in taxiway scheduling literature focuses on two decision problems: *routing problem* and *timing problem*. The studies on the routing problem considers finding a taxiway route for each aircraft, some of the studies among them makes route selection from a set of predetermined paths (Clare and Richards, 2011, Balakrishnan and Jung, 2007), and usually assumes that an aircraft taxies at a *constant speed* (Gotteland et al. 2001, Roling and Visser, 2008). While others generates routes (Baik et. al. 2002, Marin 2006, Jiang et. al 2015) by assuming aircraft taxi speed is constant. On the other hand, timing problem considers determining the time for each aircraft to cross a taxiway link based on a predetermined path (Smeltink and Soomer, 2004). Some studies in this category allows for speed changes but a maximum speed is imposed (Rathinam et al, 2008, Lee and Balakrishnan, 2012, Jiang et al. 2013).

Most widely used objective considered is to minimize the total taxiing time (TT) (Jiang et al. 2013, Jiang et al. 2015). The main assumption is that shorter taxi times will result in less fuel burn and less environmental cost. Apart from the TT as an objective, deviations from the scheduled time of departure or arrival and minimization of total waiting time are also considered in some studies (Marin 2006, Balakrishnan and Jung, 2007, Lee and Balakrishnan, 2012). When the studies are compared in terms of the control options they use to achieve conflict free ground traffic, we see three categories: holding aircraft at gates and/or on the taxiways, speed adjustments, and routing.

Limitations of the Literature

Most of the models considers the problem as a network problem with nodes and associated links representing the taxiways. However, they assume an approximate capacity on the nodes and links of the network without considering the real separation times. Although collision is hidden in capacity constraints in each node or link, none of these models consider safety restrictions, thus they do not consider air traffic control issues as resolution of potential conflicts between aircraft. Particularly at airports on the ground, ATFM and collision free flight should be merged. There is no such application yet.

Another common feature of the existing models in literature which is thought to be a shortcoming is that almost all of them (Roling and Visser, 2008, Rathinam et al, 2008, Marin 2006) use time intervals as possible decision making points. Aircraft's relative position during each time interval is not considered. Particularly on airports on the ground, time interval such as 2-5 minutes may lead to significant errors since several aircrafts would enter and leave gates and taxiways during that 5 minutes since taxiway lengths can be as minimum as 300 meters (0.5 minutes assuming 600meters/minute speed). When time is discretized it is impossible to guarantee conflict free schedules. Hence, mathematical models using non-time indexed decision variables that determine exact location aircraft at all times may be more realistic models to be considered in the future. Although there are also some studies modeling the problem in continuous time (Clare and Richards, 2011, Lee and Balakrishnan, 2012) they differ in the control options they use, objectives considered, conflicts they consider. As far as our concern there is no study considering the problem from all aspects to ensure safety and efficiency.

This thesis proposes *conflict-free* mathematical models and solution strategies for both *gate scheduling* and *taxiway scheduling* problems by taking account all meaningful airport and flight characteristics into consideration that are not yet extensively studied in current academic literature. Since gate schedule performance has a great impact on the performance of the taxiway, we consider gate scheduling as a bi-objective optimization problem, present mathematical models and propose a two-phase solution approach. We also propose a *mixed integer linear programming (MILP)* model that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, the non-time segmented model proposed in this thesis, determines a taxi plan for each aircraft by identifying the sequence of taxiway intersections represented as nodes to be visited and determines the aircrafts' exact arrival and departure times to these nodes, average speed used on the taxiway represented as links between two consecutive nodes while ensuring the safety conditions that avoid aircraft collisions. The cost incurred from arrival and departure delays with total taxiing time is minimized. The model enables collision free airport operations considering both airlines and airport controller's objectives in continuous time where we know the *exact arrival and departure* times which is more accurate in tackling collision issues. However, accuracy comes with a cost of solution time. To overcome the difficulty to solve, strategies are proposed. The first strategy proposed, called the *iterative-TSM,* adopts a batch by batch policy and optimizes the TSM by solving it in an iterative way where in each iteration, schedules of the previous iteration are fixed. The second strategy proposed motivates from the idea of decomposition the model into two as routing and timing problem and incorporates a genetic algorithms with TSM. All the models proposed are tested on a hypothetical data and the results are presented. Main contributions of this thesis can be listed as follows:

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- A MILP that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, all safety constraints are modeled with Big-Ms. This enables us to know the exact arrival and departure times for each flight on each link on the ground.
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- Speed changes, rerouting, and holding at gates and taxiway intersections are used as control options.
- Both airlines and airport authorities' objectives are considered. Proposed models have the capability to be adopted as a decision support tool for the ground controllers and they allow airport traffic authorities to do what-if analysis in case of a change in the flight or airport network information. Proposed TSM also minimizes to total taxiing time which results in less costly taxiway schedules for airlines in terms of fuel costs and CO2 emissions.
- Two solution strategies are proposed for the TSM: *iterative TSM* and *GA-TSM.* While *iterative TSM* decomposes the problem into batches of flights, solves each batch by fixing the schedules of the previous batch in each batch, GA-TSM decomposes the problem into routing and timing. While *GA* searches for the best set of routes for the flights, *fixed TSM* solves the timing problem for a given set of routes.

As far as our concern, this is the first study focuses the problem from both aspects: safety and efficiency.

Next chapter provides the literature review on the air traffic flow management problem *(ATFM)*. Chapter 3 proposes a two phase approach for flight gate scheduling problem (*FGSP)*. Mathematical formulation of the problem is also provided. In Chapter 4 we present the taxiway scheduling model (*TSM*), test performance of the model on hypothetical data using commercial solvers, provide strategies to deal with the solution difficulty, and present results of the model. Chapter 5 provides an alternative solution methodology for the *TSM* incorporating routing algorithms with a genetic algorithm. Unfortunately, because of time limitations, we couldn't present the results of the method but it is considered as a future study in Chapter 6 in order to more deeply understand the characteristics of the problem and creating alternative ways to increase the solution speed.

CHAPTER 2

LITERATURE REVIEW

Continuous growth in air traffic as well as problems caused by increased congestion on the ground and in the airspace has motivated researchers all around the world to develop models to support ATFM and FGSP decisions. In the following sections, first we discuss the models presented for ATFM used for airspace traffic schedules, then we discuss the models presented for ground traffic scheduling (GM). The models developed for the airspace are considered to be related with the models developed for the ground since they both share the same problem characteristics such as the limitations, objectives considered, and most importantly very similar network representation. In parallel with the needs of practice, both the ATFM and GM evolved in two leading directions on the basis of time scale relative to flight operations. While the models in the first direction, known as tactical models, are developed to assign ground and airborne delays to flights before they enter the airspace and airport systems, the models in the second direction focuses on developing conflict detection and resolution techniques that covers a shorter time period or even real-time decisions. Although there is a wide body of research on both research directions applying various methodologies such as metaheuristics and heuristics, in this thesis, the focus will be only on deterministic mathematical optimization techniques used for tactical decisions of ATFM and GM.

2.1. AIR TRAFFIC FLOW MANAGEMENT

The seminal work of Odoni (1987) stimulated much of the subsequent work on the first research path. After the problem is introduced, conceptualized, and described in detail in Odoni (1987), several models have been proposed for different versions of the problem. The first and the simplest version, known as the Single Airport Ground Holding Problem (SAGHP) considers only one airport as a congested resource and assigns ground delays to flights in their departure airport if they are directed to the congested airport. On the other hand, multi-airport ground holding problem (MAGHP) considers the network of airports to make ground holding decisions. Both problems assume that only destination airports in the system faces arrival capacity reduction and that all air sectors have either unlimited capacity or do not impose ant capacity restrictions. Because of simplicity and computational tractability they both gained significant traction. Therefore, there are plenty of work on SAGHP and MAGHP (see Terrab and Odoni 1993; Richetta and Odoni 1993; Andreatta and Brunetta 1998, and Mukherjee and Hansen 2007). However, current applicability of these models are somewhat restricted since congestion in air sectors is as significant as the congestion in major airports nowadays. Therefore, the literature is directed to developing models to solve real situations that are much more complex. Given the flight paths, models for Air Traffic Flow management Problem (ATFMP) not only use ground holding but also airborne holding with speed adjustments as control options, thus determine how to control flights throughout their duration. On the other hand, Air Traffic Flow Management Rerouting Problem (ATFMRP) considers rerouting as an option. In this problem, in case of severe weather conditions or any other reason resulting in decreased capacity of airspace resources, a flight might be rerouted through a different path from the path it originally assigned to. In this section, first, we will review the important works on ATFMP and ATFMRP. We will conclude this section by presenting some of the recent trends on these problems and some supplementary work on the subject.

2.1.1. Models for Air Traffic Flow Management Problem

One of the first attempts on ATFMP was in Helme (1992) who formulated the problem as a multi-commodity minimum cost flow problem on a time-space network. Instead of dealing with individual flights, this model deals with aggregate flows and assign airborne and ground delays to aggregate flows since it provides a view of an optimal response at the aggregate level to the future capacity levels. Although the model is straightforward and easy to understand, it is computationally intensive.

One of the first readily solvable large-scale model is presented in Bertsimas and Patterson (1998). In this model, for each flight, a predetermined set of air sectors including the origin and destination airports is specified. The model determines the departure and sector entrance times from a set of feasible times for each aircraft. Since the set of feasible times for arrivals into sectors is computed using the minimum and maximum speed that an aircraft can fly at, the model implicitly determines the speed used by traversing a sector. The uniqueness of the formulation lies on the definition of the decision variables which enables them to specify constraints very easily. The use of feasible time windows also reduces the size of the formulation since decision variables are only defined for feasible time periods. Similar to other works in the literature, the objective function minimizes the total delay costs. Several variants of the formulation is also presented. More specifically, it is shown that if sector capacity constraints are removed, the formulation corresponds to a MAGHP and it is proven that LP relaxation of this MAGHP formulation gives bounds that are at least as strong as those from the LP relaxations of two known MAGHP formulations: formulation in Vranas et. al. (1994) and formulation in Terrab and Paulose (1992). It is also shown how to integrate the interdependency between capacity of arrivals and departures for airports in which aircraft may use the same runways for both arrivals and departures. This interdependency is captured with capacity envelopes which shows all the feasible arrival and departure capacity combinations for a time period with a curve. Another variant of the formulation is obtained by modifying the flight connectivity constraints to address multiple connections at a hub airport. Although the formulation does not consider rerouting as an option, the authors also show two ways to incorporate rerouting option to their model. The first way is specified as the path approach while the second approach is specified as the sector approach. Besides these variants, the authors also show that their formulation is NP-Hard. Moreover, the authors analyze the polyhedral structure of the underlying linear relaxation by showing that several of the constraints provide facets of the convex hull of solutions. This gives insights on the usefulness of the new decision variables. Both the theoretical results and the practical application to real cases point to the advantages of the models as opposed to others used in the literature. Another important work, presented by Lulli and Odoni (2007) highlights the main practical differences between current ATFM systems in US and in Europe and it is also one of the first paper that draws attention to the trade-off between efficiency and fairness which are generally thought as the most overriding objectives of ATFM systems. The authors point out that the basic difference of the ATFM systems in US and in Europe is that while congestion in airports and the airspace around airports is the major concern in US systems, enroute congestion is the primary concern of ATFM in Europe. Moreover, the authors also state the flexibility of rerouting in US systems since it is much more harder in Europe where the number of stakeholders is larger and rerouting of flights through the airspace of several countries require official permission from the corresponding countries. All these reasons results in a more complex decision making environment to control air traffic in Europe. The European ATFM model presented in Lulli and Odoni (2007) can be seen as a macro level model since it disregards some of the control options such as speed adjustments and enroute airborne delays. The authors assume that all aircraft in an air-sector fly with the same speed and airborne delay can be assigned to flights only in their terminal airspace which are not practical in real-life cases. An important characteristic of the model is that it ensures equity of delays assigned to flights. This is achieved by including cost coefficients that are a superlinear function of the tardiness of flights in the objective function. The most important contribution of the paper is that it presents the characteristics of the solutions to European ATFM by an extensive experimental analysis. For this, the model has been applied to several examples based on four generic network configurations to emphasize three important characteristics of solutions of the problem. The first characteristic is that the solutions may have both ground and airborne delays. Second, in some situations, assignment of airborne delays to some flights may decrease total delay cost considerably although cost of airborne delay is much higher than the cost of ground delay. And most importantly third, there is a conflict between efficient solutions and equitable solutions. The authors show that minimizing simply the total delay costs yield unfair solutions in which some of the flights are delayed significantly while the others departs on time. However, fairness between flights is an important issue in practice. The authors show the trade-off between efficiency (in terms of total delay) and equity between flights. Although the cases used in the experiments are inadequate to represent the real network structure in either Europe or US airspace, they capture all the interactions between different flows of traffic that compete for access to common resources, thus they can adequately provide insights on the important characteristics of the solutions.

2.1.2. Models for Air Traffic Flow Management Rerouting Problem

None of the models cited above consider rerouting as a flow control option. They all assume that the flight path is known in advance and is fixed. However, diverting flights from congested air sectors is a very common application in daily operations. Very often, extreme weather conditions force the capacities of some sectors (and airports) in the NAS to drop significantly. Flights are then forced to use alternative routes. Recently, research focus has shifted to the routing problem known as ATFMRP. Rather than using only ground holding and airborne holding, rerouting of flights is became a viable control option for air traffic flow problems.

Bertsimas and Patterson (2000) is the first to study the ATFMRP. In this study, the authors formulate ATFMRP as a multi-commodity integer network flow model with side constraints and determine dynamically how to control flights with rerouting, delaying or adjusting speed between sectors to avoid congestion caused by dynamically changing weather conditions. The objective function minimizes the total cost that include delay costs and rerouting costs due to change in fuel consumption. Their solution approach consists of an integrated mathematical programming approach. Since the size of the problem is very large, to overcome dimensionality problem, instead of dealing with individual flights, they deal with aggregate flows. However, they also use non-aggregate flight variables to deal with connectivity of flights. Aggregate flows are generated by solving a Lagrangian relaxation of the LP model. In this LP relaxation the capacity constraints are relaxed and penalized in the objective function. In each iteration of the Lagrangian Relaxation algorithm, a randomized rounding heuristic is applied to decompose the aggregate flows into a collection of individual flight paths. Then an integer packing problem is solved to obtain feasible, and near-optimal, individual flight routes. They test their solution approach on real problems for three problem instances reflecting three different weather scenarios. Although the results suggest that the solution approach is capable of efficiently solving real problems for a part of NAS, the computational performance of this model was not adequate for addressing problems encountered in realistic, very large-scale instances. Another work worth mentioning is proposed in Churchill et. al. (2009). Although the model is based on the model proposed in Bertsimas and Stock (1998), it differentiates from the models in the literature in the design of the airspace network. They employ a more general airspace constructs, called airspace volumes containing airspace and airports to take the advantage of reduced complexity. They also define set of possibilities for each flight as entry and exit points in each volume. Further, they investigate the potential applicability of aggregate-level flow management problems. They propose a three-level approach for future air traffic flow management systems. Each level in this approach reflects the different planning stages capturing a different time horizon. The first level of the approach, known as the strategic level, is used to generate aggregate flows and suggested to be employed several times during the day. On the other hand, second and third level of the approach suggests making tactical, even real-time decisions to best exploit available resource. While second level spawns regional traffic flow initiatives, third level determines immediate actions using the up-to-date information regarding capacity reductions. However, the definition of airspace volume is an important issue on its own and the level of details in ATFM decisions are restricted. Another important work presented in (Bertsimas et. al., 2011) is the extension of the Bertsimas-Stock formulation (Bertsimas and Stock, 1998) that allows rerouting decisions, thus they use all the control options of flights say; ground holding and air delay, rerouting, and speed control. Their model determines the optimum departure time, set of sectors traversed, the time required to spend in each sector thus the speed used to traverse each sector, and arrival time to the destination airport by considering all the capacitated elements of the system, the trade-off between arrivals and departures in airports and continuity of flights. The originality of the work comes from the definition of the routes which enables the authors to model rerouting of flights without adding any extra decision variables or changing the definition of the decision variables used in Bertsimas- Stock formulation. The routes for any origin-destination (o-d) pair (routes of any flight) is represented by digraphs given that the nodes of the digraph corresponds to all the capacitated elements of the airspace (departure and arrival airports and all the sectors that a flight might traverse) and the arcs corresponds to the sequence relationship between these nodes. Since these digraphs are acyclic in ATFM context, describing all the sectors through a sequence of binary relations and hence regarding the routes as partially ordered sets enables the authors including rerouting options by only adding new sets of constraints. Note that the definition of these decision variables is first introduced in Bertsimas and Stock (1998). Another important note on these decision variables is that they are only defined for feasible (f, j, t) triples where f, j, and t corresponds to flight, sector, and time, respectively. This results in a decrease in the size of the problem. Moreover, since cancellation of flights is not allowed in the formulation, decision variables regarding the departure and arrival airports of flights always takes value of one, thus they are fixed. This restriction seems unrealistic at first, however, in practice, cancellation decision can only be made by airlines after delays are issued by FAA. As in most other models in the literature, the aim of the model is to minimize total delay (TD) costs. Therefore, the objective function minimizes the combination of ground delay (GD) and airborne delay (AD). However, to possess that AD per unit time is more costly than GD and to assure equity of the assigned delays among flights, instead of directly minimizing TD, the objective function uses cost coefficients that are superlinear functions of tardiness both for GD and AD. The use of these cost coefficients will favor the solutions in which delays are assigned to flights in a more balanced way. This approach is similar to the one adopted in Lulli and Odoni (2007). However, the authors state that this objective function has an important problem since it cannot distinguish a solution that assign two units of delay to one flight and zero to the other from a solution that assigns one unit of delay to each flight. They also state that use of this objective function results in favoring the first one. To overcome this problem, the authors suggest an adjustment in the objective function. This feature of the objective function is unique in ATFM literature both in terms of identifying this issue and proposing a solution to overcome the problems caused by this issue.

All the models discussed above tackle tactical decisions related to ATFM. Although it is possible to reset the parameters and solving the model dynamically, they are mainly designed to be solved 1-2 hours before the departure of flights and to provide a baseline air traffic plan. Although mid-air collision is hidden in capacity constraints in each air sector, none of these models consider safety restrictions, thus they do not consider air traffic control issues as resolution of potential conflicts between aircraft, altitude assignments etc. Particularly around airports, ATFM and collision free flight should be merged. There is no such application yet. Although Sherali et. al. (2002) propose a model to decide on delays and routes for a set of flights by considering all safety, efficiency, controller workload, and capacity constraints, its scope is far more local.

2.1.3. Discussion

A common feature of all the models presented in report is that they can be applied in a setting where one controlling entity is authorized to assign delays and reroutes to flights. This is not the case under the CDM paradigm, where airlines actively participate and exchange information during the ATFM decision making process. Moreover, FAA is investigating the “free flight” concept for future ATFM systems. Under free flight paradigm which first conceptualized in Hoekstra et. al. (1998), the aim is to transfer the responsibility of en-route flight planning task to individual aircrafts. All air traffic restrictions are only imposed to ensure safety, to ensure capacity feasibility and to prevent unauthorized flights through special use of airspace. For a recent study on this concept, we refer to Molina et. al. (2014).

Another common feature of the existing models in literature which is thought to be a shortcoming is that all of them use time intervals as possible decision making points. Aircraft’s relative position during each time interval is not considered. Particularly around airports, time interval such as 15 minutes may lead to significant errors since several aircrafts would enter and leave airport and airspace around the airport during that 15 minutes. Hence, mathematical models using non-time indexed decision variables that determine exact location aircraft at all times may be more realistic models to be considered in the future. Furthermore, continuous route planning based on the meteorological data and feedbacks received from nearby aircrafts may comply very well with the objectives of NASA driven Free-Flight-Concept.

Although the literature on ATFM is large and air transport industry is trying to engage with new tools and procedures due to exponential growth in air transport, these optimization models rarely adopted in practice. As mentioned in Leal de Matos and Ormerod (2000), optimization models are often regarded with suspicion by users since these users view the mathematical content as a black-box which is hard to understand. Second reason is that most of the optimization models are computationally intensive limiting especially real-time decisions. Another reason for the discrepancy between theory and practice is that most of the models require intensive data requirements. Moreover, the results of most of the models heavily depend on the parameters chosen. Therefore, selecting the best parameters might be hard for decision makers. Furthermore, since the current ATFM environment in practice is conservatively focuses more on safety than efficiency, adopting new models will be slower than adopting new technologies. Besides these, the research on ATFM is concentrated on centralized decision making. However, beside to the free flight concept FAA is planning to implement a more general concept called NextGen in which the notions of information sharing, common situational awareness and decentralized decision making is emphasized.

2.2.FLIGHT GATE SCHEDULING

FGSP has received a considerable attention and been widely studied. For an extensive review we refer to Dorndorf (2007). Babic et al. (1984), Bihr (1990), Mangoubi and Mathaisel (1985) are some of the authors formulating the problem as a mixed 0–1 linear program with the objective of minimizing the total passenger walking distance inside the terminal. The problem is modelled as a quadratic assignment problem (QAP) and reformulated as a mixed 0–1 linear program by Xu and Bailey (2001), Yan and Huo (2001), Ding et al. (2004a), Ding et al. (2004b), Ding et al. (2005). On the other hand, there are also studies considering multiple objectives. For example, by adopting a multi-criteria approach, Dorndorf (2002) modelled the problem as a multi-mode resource constrained project scheduling problem (RCPSP). Similarly, Nikulin and Drexl (2010) modelled the problem as a multi-mode RCPSP and developed a pareto-simulated-annealing in order to get a representative approximation of the pareto front.

2.3. TAXIWAY SCHEDULING

Most of the studies in taxiway scheduling literature focuses on two decision problems: *routing problem* and *timing problem*. The studies on the routing problem considers finding a taxiway route for each aircraft, some of the studies among them makes route selection from a set of predetermined paths. Balakrishnan and Jung (2007) extend the formulation of Bertsimas and Patterson (1998) that uses gate holding and routing as control options in order to minimize TTT and total delays, however, they lack of claiming safety since they don't consider all types of conflicts. Among the ones that makes route selection, Roling and Visser, 2008 assumes that an aircraft taxies at a *constant speed* and they propose a binary mathematical formulation addressing the safety separation requirements by dividing each taxiway into smaller links and allowing each link to hold only one aircraft at a time, resulting in a conservative estimate of the capacity. Moreover, for a large airport, with long taxiways, the formulation becomes too complex to solve. Some studies on the other hand, generates the routes (Marin 2006, Jiang et. al 2015) by assuming aircraft taxi speed is constant. Marin 2006 models the problem with a linear multicommodity flow network with discrete time variables but their model doesn't include take off separation on the runways. Moreover, they only consider TTT. On the other hand, timing problem considers determining the time for each aircraft to cross a taxiway link based on a predetermined path. Smeltink and Soomer, 2004 present a continuous time formulation of the problem but their model does not account for all the safety requirements excluding the trail constraints. Since they use a sequencing based separation where only nodes, taxiway intersections are taken into account, separation on taxiway links is taken into account indirectly. Some studies on timing problem allows for speed changes but a maximum speed is imposed (Rathinam et al, 2008, Lee and Balakrishnan, 2012, Jiang et al. 2013). Rathinam et al (2008) presents a formulation based on the formulation of Smeltink and Soomer (2004) to include all types of safety constraints with fever variables. Lee and Balakrishnan 2012 proposes a MILP that has both continuous time variables for the passage times for the nodes, and binary sequencing variables or determining the relative order of the flights on the nodes.

Most widely used objective considered is to minimize the total taxiing time (TT) (Lee and Balakrishnan 2012). The main assumption is that shorter taxi times will result in less fuel burn and less environmental cost. Apart from the TT as an objective, deviations from the scheduled time of departure or arrival and minimization of total waiting time are also considered in some studies (Marin 2006, Balakrishnan and Jung, 2007, Lee and Balakrishnan, 2012). When the studies are compared in terms of the control options they use to achieve conflict free ground traffic, we see three categories: holding aircraft at gates and/or on the taxiways, speed adjustments, and routing. Most of the models considers the problem as a network problem with nodes and associated links representing the taxiways. However, they assume an approximate capacity on the nodes and links of the network without considering the real separation times and model the problem in discrete time (Roling and Visser, 2008, Rathinam et al, 2008, Marin 2006). When time is discretized it is impossible to guarantee conflict free schedules. As far as our concern there is no study considering the problem from all aspects to ensure safety and efficiency.

2.4. DISCUSSION

In this thesis we consider conflict-free ground scheduling and focus on the problem from the *safety*, *efficiency* aspects. Proposed (MILP) model that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, the non-time segmented model proposed in this thesis, determines a taxi plan for each aircraft by identifying the sequence of taxiway intersections represented as nodes to be visited and determines the aircrafts' exact arrival and departure times to these nodes, average speed used on the taxiway represented as links between two consecutive nodes while ensuring the safety conditions that avoid aircraft collisions. A common feature of the existing models in literature which is thought to be a shortcoming is that all of them use time intervals as possible decision making points. Aircraft's relative position during each time interval is not considered. Time interval such as 5 minutes may lead to significant errors since several aircrafts would enter and leave airport and during that 5 minutes. Hence, mathematical models using non-time indexed decision variables that determine exact location aircraft at all times may be more realistic models to be considered in the future. The model enables collision free airport operations considering both airlines and airport controller's objectives in continuous time where we know the *exact arrival and departure* times which is more accurate in tackling collision issues. However, accuracy comes with a cost of solution time. To overcome the difficulty to solve, strategies are proposed. The first strategy proposed, called the *iterative-TSM,* adopts a batch by batch policy and optimizes the TSM by solving it in an iterative way where in each iteration, schedules of the previous iteration are fixed. The second strategy proposed motivates from the idea of decomposition the model into two as routing and timing problem and incorporates a genetic algorithms with TSM. All the models proposed are tested on a hypothetical data and the results are presented. Main contributions of this thesis can be listed as follows:

- A MILP model is presented for flight gate scheduling problem. The model is compared to modified version of one of the existing MILP model in literature and efficiency of the proposed model is evaluated. A two phase solution approach making use of the proposed MILP is also presented and the characteristics of the problem are analysed. While utilization of gates is maximized, on time performance is also considered.
- A MILP that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, all safety constraints are modeled with Big-Ms. This enables us to know the exact arrival and departure times for each flight on each link on the ground.
- Collision free taxiway scheduling is achieved. Since the models in the existing literature either assumes arbitrary capacities on the nodes of the network or discretizes time, they do not guarantee collision avoidance.

CHAPTER 3

A TWO-PHASE APPROACH FOR FLIGHT GATE SCHEDULING PROBLEM

Exponential evolution of air transport traffic in recent years, strong competition between airlines and the demand of passengers for more comfort have led to complex planning problems that require new models and developments in airline operations. Scheduling of flights to available gates is a major and challenging issue for daily operations in airports. Flight gate scheduling problem (FGSP) mainly focuses on assigning a given set of flights to a given set of gates available at the airport, as well as arrival and departure times to/from the gate while satisfying some business constraints. In this chapter we consider FGSP as a bi-objective optimization problem and propose a two-phase solution approach. The objectives considered in our solution approach are the minimization of the number of flights assigned to the apron and, minimizing the total deviation of flights' arrival and departure times to and from the gates from their scheduled times. We also propose a new mathematical formulation and a modified version of an existing mathematical formulation for the problem to be employed in the two-phase approach. We compare the performances of the mathematical formulations on randomly generated test instances using the two-phase solution methodology. The results show that our mathematical formulation provides better results in terms of speed and quality within a reasonable time.

3.1. SOLUTION METHODOLOGY

In this section, we introduce two different mathematical formulations of *FGSP* and present a two-phase goal-based solution approach. Since assigning all flights to gates is difficult in congested airports, Phase I of the solution approach minimizes the number of flight legs assigned to the apron. Note that, proposed approach allows flights to enter the gates after their landing and also allows the flights to depart the gate before they depart the airport as long as they stays in the gate during their dwelling times, i.e., a flight may leave its gate and wait in the apron until its departure time. Therefore it is of interest to generate gate assignments with less total deviation to increase flight schedule punctuality. Thus, in Phase II, using the output of Phase I, the aim is to minimize total schedule deviation of flights' arrival and departure times to and from the gates from their scheduled times, respectively. More specifically, in Phase II we search for gate schedules with minimum total deviation among the ones that have the same number of unassigned flights obtained in Phase I. We accomplish this objective basically by fixing the number of unassigned flights with an additional constraint in Phase II. We also propose two different mathematical formulations, *Model-I* and *Model-II*, to be used in the two-phase solution approach. *Model-I* is a modified version of the model developed by Zhu et. al (2003) in order to consider the availability of the apron. In contrary to four-indexed decision variables used *Model-I*, in *Model-II*, we only use two-indexed decision variables. In the following subsections, we present these mathematical formulations with detailed explanations of input parameters, decision variables, objectives and constraints.

3.1.1. MODEL-I

In this section we first introduce the sets and input parameters used in the model with definitions of decision variables then we explain the objective function and constraints of Phase I and Phase II of *Model-I.*

Phase I of Model-I

Sets and Parameters:

$\boldsymbol{F}$: $set\ of\ flights\ indexed\ by\ f = 1, \dots, \lvert F \rvert)$ $\boldsymbol{G}$: $set\ of\ gates\ \ indexed\ by\ g = 1, \dots,\ \lvert G \rvert + 1)$	$\boldsymbol{t_f}$: $safety\ time\ for\ flight\ f\ to\ enter\ the\ gate\ after\ previous\ flight\ leaves\ the\ gate$
$\boldsymbol{T_a^f}$: $scheduled\ arrival\ time\ of\ flight\ f;\ f \in F$	$\boldsymbol{dwell_f}$: $minimum\ dwelling\ time\ of\ flight\ f\ at\ a\ gate$
$\boldsymbol{T_d^f}$: $scheduled\ departure\ time\ of\ flight\ f;\ f \in F$	$\boldsymbol{M}$: $A\ large\ number$

Decision Variables:

$\boldsymbol{a_f}$: $arrival\ time\ of\ flight\ f\ to\ the\ gate\ it\ is\ assigned\ to;\ \ \forall f\ \in F$
$\boldsymbol{d_f}$: $departure\ time\ of\ flight\ f\ from\ the\ gate\ it\ is\ assigned\ to;\ \forall f\ \in F$
$\boldsymbol{x_{fg}}$: $1\ if\ flight\ f\ is\ assigned\ to\ gate\ g, 0\ otherwise;\ \forall f\ \in F$
$\boldsymbol{y_{ff'}}$: $1\ iff\ flight\ f\ departs\ no\ later\ than\ flight\ f'lands, 0\ otherwise;\ \ \forall f, f' \in F$
$\boldsymbol{z_{ff'gg'}}$: $1\ if\ flight\ f\ and\ f'are\ assigned\ to\ gates\ g\ and\ g'; respectively, 0\ otherwise;\ \ \forall f, f' \in F$

Phase I of Model-I:

minimize $\sum_{f \in F} x_{f\ (\lvert G\rvert+1)}$		(1)
Subject to:		
$\sum_{g=1}^{\lvert G\rvert+1} x_{fg} = 1$	$\forall f\ \in F$	(2)
$z_{ff'gg'} \leq x_{fg}$	$\forall f, f' \in F, \forall g, g' \in G$	(3)
$z_{ff'gg'} \leq x_{f'g'}$	$\forall f, f' \in F, \forall g, g' \in G$	(4)
$x_{fg} + x_{f'g'} - 1 \leq z_{ff'gg}$	$\forall f, f' \in F, \forall g, g' \in G - \{\lvert G\rvert + 1\}$	(5)
$a_f \geq T_a^f$	$\forall f\ \in F$	(6)
$d_f \leq T_d^f$	$\forall f\ \in F$	(7)
$d_f - a_f \geq dwell_f$	$\forall f\ \in F$	(8)
$(d_f + t_f) - a_{f'} + y_{ff'} * M \geq 0$	$\forall f, f' \in F$	(9)
$(d_f + t_f) - a_{f'} - (1 - y_{ff'}) * M \leq 0$	$\forall f, f' \in F$	(10)
$y_{ff'} + y_{f'f} \geq z_{ff'gg}$	$\forall f, f' \in F: f \neq f', \forall g \in G - \{\lvert G\rvert + 1\}$	(11)
$y_{ff'} \in \{0,1\}$	$\forall f\ \in F$	(12)
$z_{ff'gg'} \in \{0,1\}$	$\forall f, f' \in F, \forall g, g' \in G$	(13)
$x_{fg} \in \{0,1\}$	$\forall f\ \in F, \forall g \in G$	(14)

The objective function in Phase I of Model-I (1) minimizes the number of flights assigned to the apron. Constraint set (2) forces flights to be assigned exactly to one gate. Constraint set (3) and (4) forces the corresponding z variable to be zero if the flights are not assigned to the gate. Constraint set (5) assures that if both flights f and f' are assigned to the same gate, corresponding z variable must be 1. If they are assigned to different gates, there is no restriction on z variables. Constraint set (7) and (8) assure the time ranges for arrival and departure times to and from gates are respected. Constraint set (9), (10) and (11) together guarantee that the flight couples that has a conflict in arrival and departure times, cannot be assigned to the same gate. Finally constraint set (12)-(14) gives the domain of the decision variables.

Phase II of Model-I

In Phase II, using the schedule obtained in Phase I, we minimize total deviation of flights. In addition to sets and parameters used in Phase I, Phase II has two additional parameters used as inputs in the model. First additional parameter is the number of flights assigned to the apron which is basically the objective function value obtained in Phase I, and second additional parameter is the total deviation of flights in the schedule obtained in Phase I. By restricting the number of flights assigned to the apron, in Phase II, we improve the solution obtained in Phase I such that the total deviation is minimized. We also restrict the total deviation since we want the new schedule to be at least as good as the one obtained in Phase I in terms of flight deviations. Phase II uses the same decision variables as the ones used in Phase I.

Additional Parameters

U: $number\ of\ flights\ assigned\ to\ apron\ in\ Phase\ I$
B: $total\ deviation\ of\ the\ schedule\ obtained\ in\ Phase\ I$

Phase II of Model-I:

min $\sum_{f \in F} (a_f - T_a^f + T_d^f - d_f)$		(15)
Subject to:		
$\sum_{f \in F} x_{f((\lvert G \rvert+1))} = U$		(16)
$\sum_{f \in F} a_f - T_a^f + T_d^f - d_f \leq B$		(17)

In Phase II, the objective function minimizes the total deviation of arrival and departure times of flights from their scheduled times. Constraint set (16) fixes the number of unassigned flights. Constraint set (17) sets and upper bound on the total deviation which is the total deviation of the schedule obtained in Phase I. This Constraint is added just to accelerate the search time giving an additional cut to the feasible region of the problem. Constraint sets from (2) to (14) are exactly the same as in the constraints used in Phase I.

3.1.2. MODEL-II

In Phase I and Phase II of *Model-II*, we use the same sets and parameters used in Phase I and Phase II of *Model-I*, respectively. As in *Model-I*, here in *Model-II*, we try to minimize the number of flights assigned to the apron and total deviation using a two-phase solution approach. It should be noted that in *Model-II*, we only have two-indexed decision variables. There are three sets of additional auxiliary variables used to model the states that each flight couple can have.

Phase I of Model-II

Decision Variables:

$\boldsymbol{a_f}$: $arrival\ time\ of\ flight\ f\ to\ the\ gate\ it\ is\ assigned\ to$; $\forall f \in F$
$\boldsymbol{d_f}$: $departure\ time\ of\ flight\ f\ from\ the\ gate\ it\ is\ assigned\ to$; $\forall f \in F$
$\boldsymbol{x_{fg}}$: $1\ if\ flight\ f\ is\ assigned\ to\ gate\ g, 0\ otherwise$; $\forall f \in F$
$\boldsymbol{\alpha_{ff'}}$: $1\ if\ flight\ f'\ arrives\ after\ flight\ f\ departs, 0\ otherwise$; $\forall f, f' \in F$
$\boldsymbol{\beta_{ff'}}$: $1\ if\ flight\ f\ arrives\ after\ flight\ f'\ departs, 0\ otherwise$; $\forall f, f' \in F$
$\boldsymbol{\gamma_{ff'}}$: $1\ if\ gate\ occupation\ times\ of\ flight\ f\ and\ f'\ conflicts, 0\ otherwise$; $\forall f, f' \in F$

Phase I of Model-II:

Objective function is the same as in Model I (equation 1). Furthermore, constraints (2), (6), (7) and (8) are same as in Model I. Below, new set of constraints that are required for Model II are introduced.

$Minimize \quad \sum_{f \in F} x_{f\,(\lvert G \rvert+1)}$		(1)
s.t.		
$\sum_{g=1}^{\lvert G \rvert+1} x_{fg} = 1$	$\forall f \in F$	(2)
$a_f \geq T_a^f$	$\forall f \in F$	(6)
$d_f \leq T_d^f$	$\forall f \in F$	(7)
$d_f - a_f \geq dwell_f$	$\forall f \in F$	(8)
$a_{f'} \geq d_f + t_f - M(1 - \alpha_{ff'}) - M(2 - x_{fg} -$	$\forall f, f' \in F: f \neq f', \forall g$	(9)
$d_{f'} + t_{f'} \leq a_f + M(1 - \beta_{ff'}) - M(2 - x_{fg}$	$\forall f, f' \in F: f \neq f', \forall g$	(10)
$\alpha_{ff'} + \beta_{ff'} + \gamma_{ff'} = 1$	$\forall f, f' \in F: f \neq f'$	(11)
$x_{fg} + x_{f'g} \leq 2 - \gamma_{ff'}$	$\forall f \in F, \forall g \in G$	(12
$\alpha_{ff'}; \beta_{ff'}; \gamma_{ff'}; x_{fg} \in \{0,1\} \in \{0,1\}$	$\forall f, f' \in F, f \neq f'$	(13)

$a_{f'} \geq d_f + t_f - M(1 - \alpha_{ff'}) - M(2 - x_{fg} - x_{f'g})$	$\forall f, f' \in F: f \neq f', \forall g \in G - \{\lvert G \rvert + 1\}$	(18)
$d_{f'} + t_{f'} \leq a_f + M(1 - \beta_{ff'}) - M(2 - x_{fg} - x_{f'g})$	$\forall f, f' \in F: f \neq f', \forall g \in G - \{\lvert G \rvert + 1\}$	(19)
$\alpha_{ff'} + \beta_{ff'} + \gamma_{ff'} = 1$	$\forall f, f' \in F: f \neq f'$	(20)
$x_{fg} + x_{f'g} \leq 2 - \gamma_{ff'}$	$\forall f, f' \in F: f \neq f', \forall g \in G - \{\lvert G \rvert + 1\}$	(21)
$\alpha_{ff'}; \beta_{ff'}; \gamma_{ff'}; x_{fg} \in \{0,1\}$	$\forall f, f' \in F, f \neq f'$	(22)

Constraint (18), (19), (20) and (21) together guarantee that the flight couples that has a conflict in arrival and departure times, cannot be assigned to the same gate. Finally constraint set (22) gives the domain of the decision variables.

Phase II of Model-II

In Phase II, using the schedule obtained in Phase I, we minimize total deviation of flights. In addition to sets and parameters used in Phase I, Phase II has two additional parameters used as inputs in the model. First additional parameter is the number of flights assigned to the apron which is basically the objective function value obtained in Phase I, and second additional parameter is the total deviation of flights in the schedule obtained in Phase I. By restricting the number of flights assigned to the apron, in Phase II, we improve the solution obtained in Phase I such that the total deviation is minimized. We also restrict the total deviation since we want the new schedule to be at least as good as the one obtained in Phase I in terms of flight deviations. Phase II uses the same decision variables as the ones used in Phase I.

Additional Parameters:

U: $number\ of flights\ assigned\ to\ apron\ in\ Phase\ I$
B: $total\ deviation\ of\ the\ schedule\ obtained\ in\ Phase\ I$

Phase II of Model-II:

We solve the problem with the conditions stated as in Phase I Model I. The objective function of Phase II, equation (15), minimizes the total deviation of arrival and departure times of flights from their scheduled times. Constraint set (16) fixes the number of unassigned flights. Constraint set (17) sets and upper bound on the total deviation which is the total deviation of the schedule obtained in Phase I. This Constraint is added just to accelerate the search time giving an additional cut to the feasible region of the problem. Constraint sets (2), (6-8) and (18-22) are exactly the same as the constraints used in Phase I.

3.2. COMPUTATIONAL ANALYSIS

In this section we provide information on problem instances and we report computational results on these test instances. We compare the results of each mathematical formulation with each other with respect to solution time and quality. The tests are performed on a computer with an Intel i5 1.80 GHz CPU and 12 GB RAM.

3.2.1. Problem Instances

There is a major difference between airports with respect to congestion. For instance, in an uncrowded airport, flights arrive in every five to 15 minutes. On the other hand, in a congested airport, a time window as small as zero to two minutes may separate the arrival of two consecutive flights. Therefore, we generated three different test instances based on the mean interarrival time between flights. In the first data set, mean interarrival time between flights are 10 minutes and scheduled arrival time of flight f (T_a^f) is randomly generated in the interval [10*f*, 10*f*+5]. This interval models a flight landing in every 5-15 minutes. In the second data set, mean interarrival time between flights are 5 minutes and T_a^f is randomly generated in the interval [2*f*, 2*f*+5]. This interval models a flight landing in every 3-7 minutes. In the third data set, mean interarrival time between flights are 2 minutes and T_a^f is randomly generated in the interval [*f*, *f*+2]. This interval models a flight landing in every 0-2 minutes. On the other hand, we assume that the time between a flight's arrival and its departure is a uniform variable randomly generated in the interval [T_a^f+60 - T_a^f +70] minutes. Required time for flight f to enter the gate after previous flight leaves the gate,t_f, is generated in the interval [5-10] minutes. This buffer time assumes that there should be a time window (5 to 10 minutes) between the departure of flight f and the arrival of another flight f' to the same gate. The dwelling time, $dwell_f$, which is the minimum time for a flight to spend on a gate is randomly generated in the interval [40, 60]. This scheme is similar to that used in Xu and Bailey (2001). Following the above-described rules, we generate three sets of test instances. The first data set includes three sets of instances each differs in the number of flights. In the smaller size instances, the number of flights ranges from 20 to 35. In the medium size instances the range is between 40 and 70 and in the large size cases the flights number differ between 80 and 110.

3.2.2. Comparison of Model-I and Model-II

In this section, we compare the results of Phase I and Phase II of the solution approach obtained applying *Model-I* and *Model-II*. Table 1 shows the performance measures obtained in Phase I for each model and Table 2 shows the performance measures obtained in Phase II of the mathematical models for the problem instances with 11 gates. Note that the discussed *FGSP* models are NP-hard, a time limit of 30 minutes is used to terminate search.

Table 1. Results of Phase I obtained with Model-I and Model-II

Flight Number	Gate Number	MODEL-I PHASE I			MODEL-II PHASE I		
		LB on Number	Number of	Time (Seconds)	LB on Number	Number of Flights	Time (Seconds)
20	11	1	1	88	0	1	1800
25	11	1	1	312	0	1	1800
30	11	1	2	1800	0	2	1800
35	11	1	2	1801	1	2	1800
40	11	3	6	1800	0.33	4	1800
50	11	1	6	1800	0	4	1800
60	11	0	10	1800	0	5	1800
70	11	NFSWTL			0	10	1800
80	11	NFSWTL			0	10	1800
90	11	NFSWTL			NFSWTL		
100	11	NFSWTL			0	11	1800
110	11	NFSWTL			0	15	1800
40	21	NFSWTL			0	3	1800
50	21	NFSWTL			0	5	1800
60	21	NFSWTL			0	11	1800
70	21	NFSWTL			0	17	1800
80	21	NFSWTL			0	20	1800
90	21	NFSWTL			0	23	1800
100	21	NFSWTL			0	22	1800
110	21	NFSWTL			0	29	1800
80	51	NFSWTL			NFSWTL		
90	51	NFSWTL			0	0	468
100	51	NFSWTL			0	1	1800
110	51	NFSWTL			0	6	1800

**NSWTL=No Solution within Time Limit*

Table 1 tabulates the results of Phase I obtained with *Model-I* and *Model-II*. It shows that for the first two instances although *Model-I* and *Model-II* gives the same objective values, *Model-I* can state that the given result is optimal within a very short time. It is because *Model-I* provides better lower bounds so identifying a solution's optimality takes less time. However, for the rest of the test instances, neither Model-I nor Model-II can provide optimal schedules within given time limit. Moreover, while *Model-II* gives better upper bound on the number of unassigned flights, no feasible solution can be determined by Model-*I* within the given time limit for most test instances. With these in mind, we can clearly state that for the large sample sizes, *Model-II* is more capable of providing good feasible solutions.

Table. 2. Results of Phase II obtained with Model-I and Model-II

Flight Number	**MODEL-I PHASE II**				**MODEL-II PHASE II**			
	Number of Flights Assigned to	**LB on Total Deviation**	**Total Deviation**	**Total Deviation in Phase I**	**Number of Flights Assigned to**	**LB on Total Deviation**	**Total Deviation**	**Total Deviation in Phase I**
20	1	10.87	184	239	1	0	184	184
25	1	1.04	212	337	1	0	210	363
30	2	0	394	470	2	0	-	373
35	2	0	-	493	2		-	
40	6	0	315	435	4	0	-	470
50	6	0	585	666	4	0	-	708
60	10	0	517	719	5	0	-	830

As shown in Table 2, *Model-II* cannot improve the feasible solutions determined in Phase I. On the other hand, *Model-I* is more capable of improving the solution found in Phase I in terms of total deviation. It should be noted that the solutions found in Phase I are better in terms of total deviation when model-II is used, thus this makes the solution of Phase II harder for the model since the limit on the number of flights assigned to the apron in *Model-II* is more strict. Table 3 shows average deviation of flights in test instances.

Table 3. Average Deviations for Flights

MODEL-I PHASE II			MODEL-II PHASE II		
Number of Flights Assigned to The apron	**Total Deviation (minutes**	**Average Deviation for a Flight (Minutes)**	**Number of Flights Assigned to The apron**	**Total Deviati on (minute s**	**Average Deviation for a Flight (Minutes)**
1	184	9.2	1	184	9.2
1	212	8.48	1	210	8.4
2	301	10.03	2	373	12.43
2	493	14.09	2	-	
6	315	7.88	4	470	11.75
6	585	11.7	4	708	14.16
10	517	8.62	5	830	13.83

3.2.3. Further Analysis

In this section, we analyze the results obtained with *Model-II* in terms of number of flights assigned to the apron and total deviation. Table 4 tabulates the results obtained in Phase I and Phase II with different number of gates and Figure 1 and Figure 2 show how the number of flights assigned to the apron and total deviation change with respect to gate number, respectively. Note that, the results are obtained setting a time limit of 15 minutes for each phase of the solution approach.

Table 4. Results of Phase II and Phase II with Different Gate Capacities

Flight	Gate	Number of	Total
20	**12**	0	184
20	**11**	1	184
20	**10**	2	184
20	**9**	3	178
20	**8**	5	134
20	**7**	7	91
20	**6**	9	63

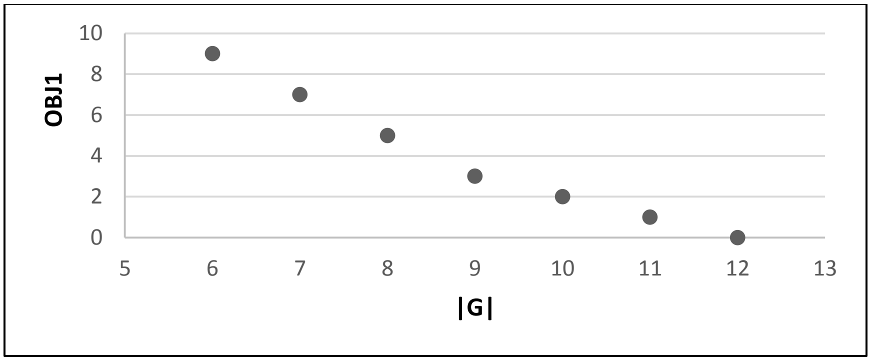

Figure 1. Number of Flights Assigned to The apron for Different Gate Capacities

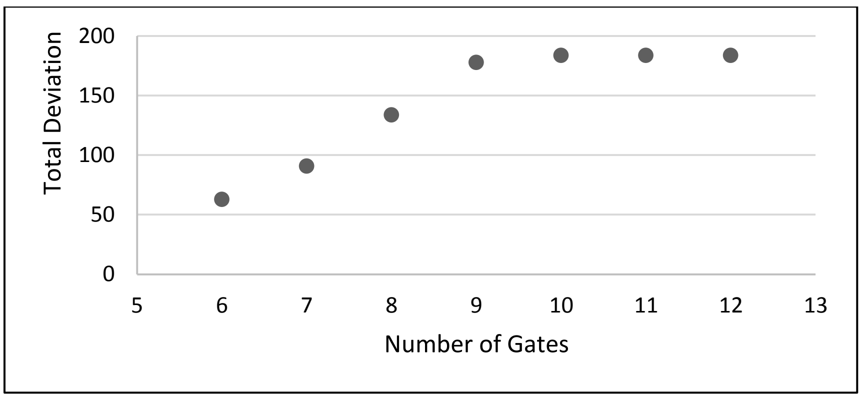

Figure 2. Total Deviation for Different Gate Capacities

When we analyze Table 4, we see that these two objectives are conflicting. While the number of flights assigned to the apron increases, total deviation of the resulting schedule decreases with the decrease in gate numbers. Figure 3 shows this case.

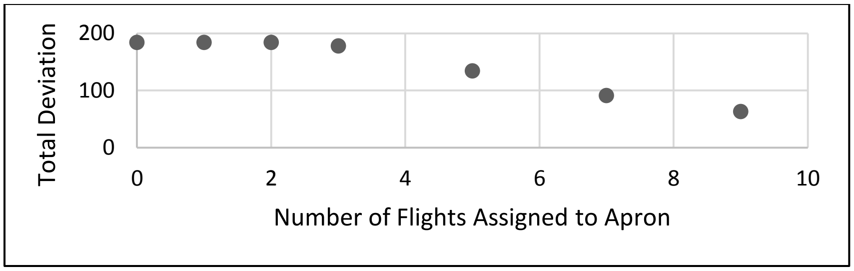

Figure 3. Total Delay vs. Number of Flights Assigned to The apron

3.3. CONCLUSIONS AND FUTURE RESEARCH

In this chapter, we considered gate assignment and scheduling problem as a bi-objective optimization problem and presented new mathematical formulations, *Model-I* and *Model-II* that are used in a two-phase approach to minimize the number of flights assigned to the apron and to minimize the total deviation of the gate schedules from flight schedules. We compared *Model-I* and *Model-II* with respect to solution time and solution quality. The results show that *Model-II* is more capable of handling frequent flight arrivals and is more efficient than *Model-I*. It is also shown that considered objectives are conflicting with each other. Future research may be directed to relaxing the assumption that the arrival and departure activity of a flight has to be in the same gate and developing metaheuristics that takes into account multiple objectives for the problem. Another extension would be in a setting where stochastic arrival and departure times are considered with the objective of generating robust gate schedules.

CHAPTER 4

TAXIWAY SCHEDULING MODEL

This chapter discusses a new formulation of taxiway traffic scheduling problem of airports with the objective of minimizing the total taxiing time and the deviations from the runway departures for arriving aircrafts and deviations from the gate departure times for departing aircrafts. A mixed integer linear programming (MIP) model that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* has been developed without adapting a state-time network in which the decision variables are defined with time indices. Instead, the non-time segmented model proposed in this thesis, determines a taxi plan for each aircraft by identifying the sequence of taxiway intersections represented as nodes to be visited and determines the aircrafts' exact arrival and departure times to these nodes, average speed used on the taxiway represented as links between two consecutive nodes while ensuring the safety conditions that avoid aircraft collisions. The cost incurred from arrival and departure delays with total taxiing time is minimized.

4.1. PROBLEM FORMULATION

In this section, the details of the mathematical model are provided. In the modeling of the airport ground traffic scheduling problem, it is assumed that all aircrafts in the set F enter a 2D network in which the nodes ($v \epsilon V$) are used to represent the gates, taxiway intersections, runway enter and exit points and dummy nodes that represent the runways and links ($l \epsilon L$) are used to represent the taxiways and that connects between two consecutive nodes. While arriving aircrafts ($f \epsilon F_A$) enter the network from the nodes that represent the gates that they are assigned to, departing aircrafts ($f \epsilon F_D$) enter the network from one of the possible entry points of the runway which they assigned to. All arriving aircrafts leave the system when they reach to their assigned gates through the taxiways and all departing aircrafts leave the system from one of the available exit points of the runway that is assigned. The objective of the model is to minimize the weighted sum of total taxiing time and total deviations of arrivals and departures from their scheduled times by determining a taxi plan for each aircraft without violating any safety rules. The aircraft taxi plan (TP^f) includes a set of links (x_l^f =1), arrival (a_l^f) and departure (d_l^f) times to these links, time (t_l^f) spent on the link while the aircraft is moving, and waiting time (w_l^f) and average speed (s_l^f) on these links. It is assumed that waiting can only be done when arrived to the nodes. Hence the taxi plan is defined as $TP^f = (x_l^f, a_l^f, d_l^f, t_l^f, w_l^f, s_l^f : f \epsilon F, l \epsilon L)$. The unique characteristic of the model is the use of a non-segmented (non-time-indexed) approach by introducing the exact arrival and departure times as decision variables. Moreover, instead of assuming the speed constant which is a traditional approach in literature, the model has the flexibility to change the flight speed based on the necessity at every link in the network which results in an enhancement in the control options by the addition of speed control to the use of waiting the aircrafts at the end of links. Knowledge of exact arrival and departure times to and from nodes, the speed used on the links and the exact waiting time on nodes is crucial for ensuring safety in real life applications. The model is also capable of dealing with restricted taxiways which might be due to technical or weather conditions.

The details of the model are discussed in the following subsections. First, the assumptions made are discussed then the list of parameters and decision variables are presented along with their definitions and required explanations. Finally the formulation of the problem is provided.

4.1.1. Assumptions

The assumptions made in the modeling of airport ground traffic scheduling problem along with discussions are provided above.

- The taxi system in the airport is composed of runway passageways, taxiways, and parking apron. For a departure flight, after finishing the work in an assigned gate, such as cleaning, on-off passengers, catering, and fueling, the aircraft will wait for controller's command. The air traffic control (ATC) in the tower will give commands about taxi path as well as take-off runway and entrance. The aircraft will be pushed out and begin taxiing. In general, more than two aircrafts taxi on the taxiway at the same time; a basic safety separation between aircrafts is required. According to the aircraft operation management manual, a minimum safety separation is regulated between different types of aircraft (including heavy, medium-size, and light aircraft).
- We assume that a flight in a taxiway system has only two states, moving and holding. Any flight can only be held at holding areas or parking aprons, which are modeled as nodes with infinite capacity.
- During taxiing, the pilot can keep safety separation with the following aircraft by adjusting aircraft speed. Only one aircraft is allowed to pass the same node at one time and other aircrafts are required to wait to ensure safety. When two aircrafts need to taxi on the same segment of taxiway from different nodes, one aircraft must hold and wait at the entrance node if the minimum safety separation is not satisfied. If an aircraft arrives at the assigned runway entrance, it can enter runway and take off when ATC allows.
- For the arrival flight, the aircraft enters taxiway from assigned runway and exits according to ATC instructions. The taxi path and stand are assigned before the aircraft enters taxi system. Taxiing is over when the aircraft arrives at the gate.
- An aircraft can visit a node only once.
- Minimum and maximum speed that an aircraft can taxi is aircraft dependent.

4.1.2. Parameters and Decision Variables

While the sets and the parameters of the formulation are shown in Table 5, Table 6 shows the decision variables.

Table 5. Sets and Parameters of the Problem Formulation

F	Set of all flights indexed by f
F_A	Set of arriving flights: $F_A \subset F$
F_D	Set of arriving flights: $F_D \subset F, F_A \cup F_D = F$
V	Set of nodes of the network indexed by v
V_G	Set of nodes used to represent gates: $V_G \subset V$
V_R	Set of nodes used to represent the runways: $V_R \subset V$
V_T	Set of nodes used to taxiway intersections: $V_T \subset V$
$V_{R'}$	Set of nodes used to represent runway entrance and exit points: $V_R \subset V$
L	Set of links of the network indexed by l
$OPP(l)$	The link corresponding the opposite of link l: $l \epsilon L$
v_{IN}^f	Entry point of flight f which represent the gate for arrivals and dummy runway node for departures: $v_{IN}^f \subset V$
v_{OUT}^f	Exit point of flight f which represent the dummy runway nodes for departures and gates for arrivals: $v_{OUT}^f \subset V$
$\omega^-(v)$	Set of incoming nodes that can route aircrafts to node v: $v \epsilon V$
$\omega^+(v)$	Set of outgoing nodes that node v can route aircrafts to: $v \epsilon V$
$LENGTH_l$	Length of link l : $l \epsilon L$
T_{IN}	Scheduled entry time to the taxiway system for flight f: $f \epsilon F$
T_{OUT}	Scheduled exit time from the taxiway system for flight f: $f \epsilon F$
$LATE_{IN}^f$	Latest entry time to the system for flight f: $f \epsilon F$
$EARLY_{OUT}^f$	Earliest exit time from the taxiway system for flight f: $f \epsilon F$
$LATE_{OUT}^f$	Latest exit time from the taxiway system for flight f: $f \epsilon F$
$st^{ff'}$	Aircraft dependent separation distance expressed in time units for flight f' following departure of f within the same nodes: $f, f' \epsilon F$

Table 6. Decision Variables of the Problem Formulation

$a_l^f \epsilon R^+$	Arrival time of flight f at the end of link l: $f \epsilon F, l \epsilon L$
$d_l^f \epsilon R^+$	Departure time of flight f from link l: $f \epsilon F, l \epsilon L$
x_l^f	$= \begin{cases} 1 \text{ if flight } f \text{ travels on link } l \\ 0 \; otherwise \end{cases} : f \epsilon F, l \epsilon L$
$\beta_l^{ff'}$	$= \begin{cases} 1 \text{ if flight } f' \text{follows flight } f \text{ on link } l \\ 0 \; otherwise \end{cases} : f, f' \epsilon F, l \epsilon L$
$\theta_v^{ff'}$	$= \begin{cases} 1 \text{ if flight } f \text{ leaves node } v \text{ before flight } f' \\ \quad 0 \; otherwise \end{cases} : f, f' \epsilon F, v \epsilon V$
$\alpha_v^{ff'}$	$= \begin{cases} 1 \text{ if flight } f' \text{follows flight } f \text{ on link } l \\ 0 \; otherwise \end{cases} : f, f' \epsilon F, v \epsilon V$

The proposed formulation avoids non-linearity under all circumstances, yet achieves all of its objectives. Precise control of average speed on each link enables determination of exact travel times so the taxiway collision is avoided. The control options used in the model are average speed control on each link, waiting the aircrafts at the end of links, and path generation for each flight. The proposed mathematical model considers the minimization of total taxiing time and waiting times of flights at their initial nodes. Constraints of the model are categorized into 4 groups: routing constraints, timing constraints, speed related constraints, and safety and conflict avoidance constraints.

4.1.3. Objective Function

The objective of the model considers the minimization of the cost of total taxiing time including waiting times and it is given below:

$$minimize\ \sum_f \left(t_{OUT}^f - T_{IN}\right)) \qquad (1)$$

4.1.4. Aircraft Routing Constraints

Aircraft routing constraints determine a taxi plan as a set of visited links.

$$\sum_{l \epsilon \omega^+(v_{IN}^f)} x_l^f = 1 \qquad f \epsilon F \qquad (2)$$

$$\sum_{l \epsilon \omega^-(v_{IN}^f)} x_l^f = 0 \qquad f \epsilon F \qquad (3)$$

$$\sum_{l \epsilon \omega^-(v_{OUT}^f)} x_l^f = 1 \qquad f \epsilon F \qquad (4)$$

$$\sum_{l \epsilon \omega^+(v_{OUT}^f)} x_l^f = 0 \qquad f \epsilon F \qquad (5)$$

$$\sum_{l \epsilon \omega^-(v)} x_l^f = \sum_{l \epsilon \omega^+(v)} x_l^f \qquad v \epsilon V, f \epsilon F \qquad (6)$$

$$x_l^f + x_{l'}^f \leq 1 \qquad l, l' \epsilon L : l_{OPP} = l', f \epsilon F \qquad (7)$$

$$\sum_{l \epsilon \omega^+(v) : v \in V \setminus \{V^T\}} x_l^f \leq 1 \qquad f \epsilon F^D \qquad (8)$$

$$\sum_{l\epsilon\omega^-(v):v\in V\setminus\{V^T\}} x_l^f \leq 1 \qquad f\epsilon F^A \tag{9}$$

$$\sum_{l\epsilon\omega^-(v)} x_l^f \leq 1 \qquad v\epsilon V \setminus \{v_{IN}^f\}\ ,f\epsilon F \tag{10}$$

$$\sum_{l\epsilon\omega^+(v)} x_l^f \leq 1 \qquad v\epsilon V \setminus \{v_{OUT}^f\}, f\epsilon F \tag{11}$$

Constraint (2) and (3) ensure all aircraft to enter the taxiway network from the proper entry node using a single link and aircraft do not go back to their origins throughout their taxiing process. Similarly, Constraint (4) and (5) ensures all aircraft to reach their destinations through a single link. Conservation constraint (6) forces all aircraft entering an interior node to leave the node. Constraint (7) enforces aircraft not to make use of opposite links consecutively to ensure avoidance of loops. Inequalities (8) and (9) ensure that no aircraft can travel through the same node and link more than once. The reason constraints (8) and (9) are imbedded in to the models is to reduce the computational complexity. In order to allow a flight to travel through the same node or link multiple times, either additional indices (visiting index) to differentiate each visit, or multiple links between node pairs (i.e., use of a multi-graph) to allow alternatives should be introduced to the model. Note that constraints (2) and (3) are easy to extend for systems with several entrance/exit points:

$$\sum_{v\epsilon V_{IN}^f} \sum_{l\epsilon\omega^+(v)} x_l^f = 1 \qquad f\epsilon F \tag{2'}$$

$$\sum_{v\epsilon V_{OUT}^f} \sum_{l\epsilon\omega^+(v)} x_l^f = 1 \qquad f\epsilon F \tag{4'}$$

where V_{IN}^f and V_{OUT}^f are the sets of possible entry and exit points for each flight. For the arriving aircrafts while V_{IN}^f includes the nodes that represent the possible runways that the aircraft can land in, V_{OUT}^f includes the nodes that represent the possible gates that the aircraft can be assigned to. The situation is exactly the opposite for the departing aircrafts. Notice that with this new definition, an integrated problem of gate assignment, taxiway scheduling and runway assignment could be solved.

4.1.5. Timing Constraints

In this subsection, we describe the constraints setting the relationship between arrival and departure times on nodes and links.

$$x_l^f(EARLY_{IN}^f) \leq d_l^f \leq x_l^f(LATE_{IN}^f) \qquad l\epsilon\omega^+(v_{IN}^f), f\epsilon F \qquad (12)$$

$$x_l^f(EARLY_{OUT}^f) \leq a_l^f \leq x_l^f(LATE_{OUT}^f) \qquad l\epsilon\omega^-(v_{OUT}^f), f\epsilon F \qquad (13)$$

$$d_l^f \leq Mx_l^f \qquad l\epsilon\omega^+(v), v\epsilon V\backslash\{v_{OUT}^f\}, f\epsilon F \qquad (14)$$

$$a_l^f \leq Mx_l^f \qquad l\epsilon\omega^-(v), v\epsilon V\backslash\{v_{IN}^f\}, f\epsilon F \qquad (15)$$

$$\sum_{l\epsilon\omega^+(v_{IN}^f)} d_l^f = t_{IN}^f \qquad f\epsilon F \qquad (16)$$

$$\sum_{l\epsilon\omega^-(v_{OUT}^f)} a_l^f = t_{OUT}^f \qquad f\epsilon F \qquad (17)$$

$$\frac{Length_l}{maxSpeed^f} \leq a_l^f - d_l^f \leq \frac{Length_l}{minSpeed^f} \qquad l\epsilon L, \; f\epsilon F \qquad (18)$$

$$\sum_{l\epsilon\omega^-(V)} a_l^f \leq \sum_{l\epsilon\omega^+(V)} d_l^f \qquad v\epsilon V\backslash\{v_{IN}^f, v_{OUT}^f\} f\epsilon F \qquad (19)$$

While constraint set (12) and (13) ensure the departure and arrival of the aircraft to be within the allowed time range, Constraints (14) and (15) ensure that when an aircraft is not assigned to a link, then the arrival or departure time to that link is forced to be zero in order to sustain the accurate network flow without creating non-linearity. In the following constraints (16) and (17) specify the entry (t_{IN}^f) and exit times (t_{OUT}^f) to and from the taxiway system for each aircraft respectively. Finally, while Constraint set (18) gives the speed based relation on the time required to traverse a link, Constraint set (19) specifies the relation between arrival and departure times on the nodes.

4.1.6. Safety and Conflict Avoidance Constraints

In the following constraints we ensure aircraft minimum separation distances between consequent aircraft and we ensure avoidance of conflicts for aircraft that use the same taxiway in the opposite directions. Since the time needed to guarantee minimum separation distances depends on the leading aircraft type, we model this issue with the help of aircraft order dependent minimum separation time parameter $st^{ff'}$ where $st^{ff'} \neq st^{f'f}$. While inequalities (23) – (26) guarantee the minimum separation distances for the aircraft that use the same taxiway in the same direction, inequalities (27) - (28) and inequalities (29) – (30) ensures conflict avoidance for the aircraft taxiing on the same link and approaching the same node through different links; respectively.

$$d_l^{f'} - d_l^f \geq st^{ff'} - M\left(1 - \beta_l^{ff'}\right) - M\left(2 - x_l^f - x_l^{f'}\right) \qquad v\epsilon V\backslash\{v_{OUT}^f\},\ l\epsilon\omega^+(v), f, f'\epsilon F \tag{23}$$

$$d_l^f - d_l^{f'} \geq st^{f'f} - M\beta_l^{ff'} - M\left(2 - x_l^f - x_l^{f'}\right) \qquad v\epsilon V\backslash\{v_{OUT}^f\},\ l\epsilon\omega^+(v), f, f'\epsilon F \tag{24}$$

$$a_l^{f'} - a_l^f \geq (st^{ff'}) - M\left(1 - \beta_l^{ff'}\right) - M\left(2 - x_l^f - x_l^{f'}\right) \qquad v\epsilon V\backslash\{v_{IN}^f\},\ l\epsilon\omega^-(v), f, f'\epsilon F \tag{25}$$

$$a_l^f - a_l^{f'} \geq (st^{ff'}) - M\beta_l^{ff'} - M\left(2 - x_l^f - x_l^{f'}\right) \qquad v\epsilon V\backslash\{v_{IN}^f\},\ l\epsilon\omega^-(v), f, f'\epsilon F \tag{26}$$

Inequalities (23) and (24) ensure that when two aircraft are traveling on the same direction using the same link, a minimum separation distance of $st^{ff'}$is guaranteed at the point when they enter the link from node v. Through inequalities (25) and (26), when such two aircrafts arrive to the next node, the minimum separation distance is sustained in order to avoid for aircrafts to pass each other while they are traveling on l. Binary decision variable $\beta^{ff'} = 1$ implies that flight f is the leader on link l.

The purpose of the next set of inequalities is to ensure that no two aircrafts fly on the same link from opposite directions at the same time. The binary decision variable $\alpha^{ff'} = 1$ if flight f occupies the link earlier than f'. Consequently, the model enforces flight f to keep least $st^{ff'}$distance from flight f on node v.

$$d_{l'}^{f'} - a_l^f \geq (st^{ff'}) - M\left(1 - \alpha_l^{ff'}\right) - M\left(2 - x_l^f - x_{l'}^{f'}\right)$$

$$v\epsilon V\backslash\{v_{IN}^f\},\ l\epsilon\omega^-(v): l' = OPP(l),\ f, f'\epsilon F \qquad (27)$$

$$d_l^f - a_{l'}^{f'} \geq (st^{ff'}) - M\alpha_l^{ff'} - M\left(2 - x_l^f - x_{l'}^{f'}\right)$$

$$v\epsilon V\backslash\{v_{IN}^f\},\ l\epsilon\omega^-(v): l' = OPP(l),\ f, f'\epsilon F \qquad (28)$$

Finally, the next set of inequalities ensures the separation of aircrafts by a given time $st^{ff'}$ at any node. The binary decision variable $\theta_v^{ff'} = 1$ if aircraft f passes through node v before aircraft f'. Consequently, a safe separation distance (time) between aircraft pairs is imposed.

$$\sum_{l\epsilon\omega^-(v)} a_l^{f'} - \sum_{\epsilon\omega^-(v)} (a_l^f) \geq st^{ff'} - M\left(1 - \theta_v^{ff'}\right) - M(2 - \sum_{l\epsilon\omega^-(v)} x_l^{f'} - \sum_{\epsilon\omega^-(v)} x_l^f \ )$$

$$v\epsilon V\backslash\{v_{IN}^f, v_{IN}^{f'}\},\ f, f'\epsilon F \qquad (29)$$

$$\sum_{l\epsilon\omega^-(v)} (a_l^f - \sum_{\epsilon\omega^-(v)} a_l^{f'} \geq st^{ff'} - M\theta_v^{ff'} - M(2 - \sum_{l\epsilon\omega^-(v)} x_l^{f'} - \sum_{\epsilon\omega^-(v)} x_l^f \ )$$

$$v\epsilon V\backslash\{v_{IN}^f, v_{IN}^{f'}\},\ f, f'\epsilon F \qquad (30)$$

4.2. IMPLEMENTATION

In this section we provide two sets of results for two different airport layout configuration: One for small airport, one for medium size airport. In the following subsections, first we present the data for each airport network and then we present the optimization results.

4.2.1. Small Airport Network

Considered airport consists of 17 nodes: 7 gates, 8 taxiway intersections, 1 runway and one apron. Figure 4 shows the airport network configuration for the small airport.

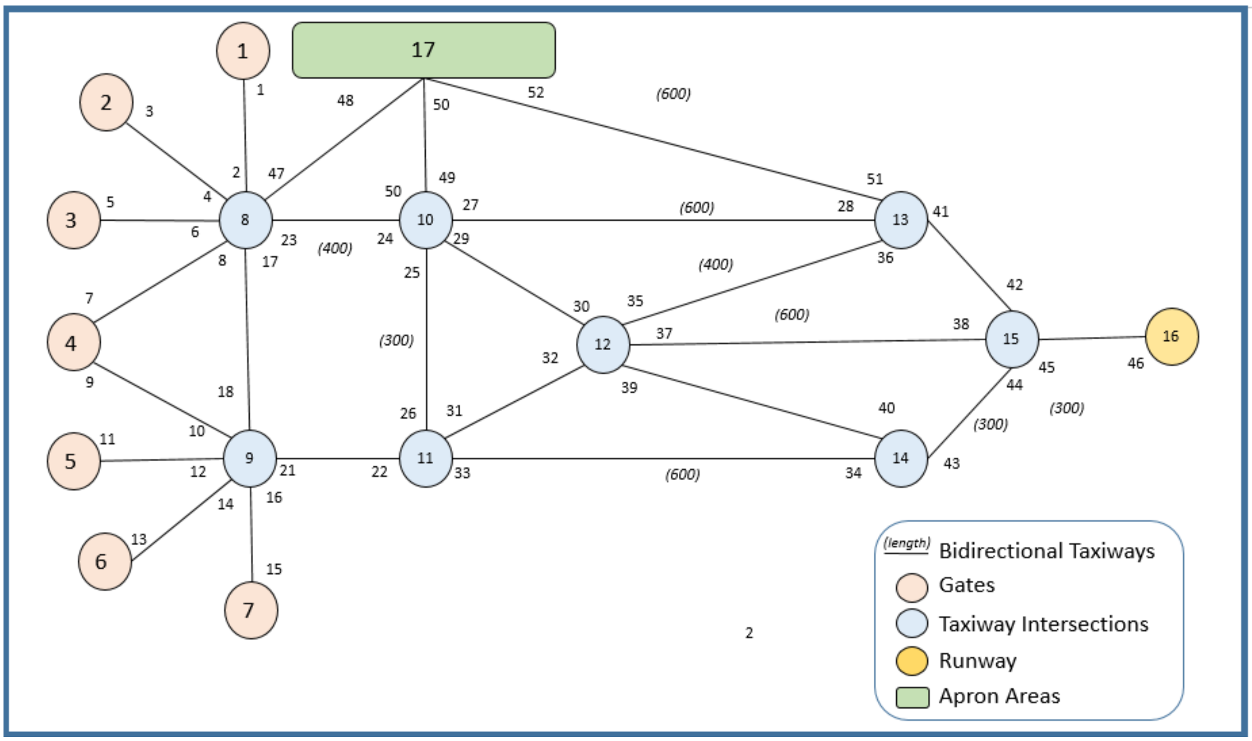

Figure 4. Small Airport Network

4.2.2. Small Airport Flight Data

It is assumed that 7 flights are ready to depart at their assigned gates, and there is one arrival on average in every 5 minutes. Speed is assumed to be constant 600m/minute. Earliest in and out times are calculated assuming each flight can be delayed at most 30 minutes and minimum taxiing time on the ground is 3 minutes with an average delay ranging from 0 to 5 minutes. The following table shows the hypothetical flight information for the TSM considered for the small airport. Separation distances are assumed to be 0.5 minutes for all flights.

Table 7. Flight Data for the small Airport

id	typ e	pair ID	siz e	V in	V out	T IN	T OUT	early IN	late IN	early OUT	late OU T	max Speed	min Speed	apron
3	1	0	2	5	16	0	6	0	30	3	43	600	600	0
5	1	0	3	3	16	0	8	0	30	3	43	600	600	0
1	1	0	1	6	16	1	6	1	31	4	44	600	600	0
2	1	0	3	7	16	1	9	1	31	4	44	600	600	0
4	1	0	3	4	16	1	6	1	31	4	44	600	600	0
8	2	34	3	16	2	1	9	1	31	4	39	600	600	1
7	1	0	2	1	16	2	10	2	32	5	45	600	600	0
6	1	0	3	2	16	5	9	5	35	8	48	600	600	0
9	2	35	2	16	6	7	13	7	37	10	45	600	600	1
1	2	36	2	16	5	14	22	14	44	17	52	600	600	1
1	2	37	3	16	4	21	29	21	51	24	59	600	600	1
1	2	38	1	16	3	26	29	26	56	29	64	600	600	1
1	2	39	1	16	7	33	37	33	63	36	71	600	600	1
1	2	40	3	16	1	41	48	41	71	44	79	600	600	1
1	2	41	1	16	17	49	57	49	79	52	87	600	600	1
3	1	8	3	2	16	54	62	54	84	57	92	600	600	1
1	2	42	3	16	6	55	59	55	85	58	93	600	600	1
3	1	9	2	6	16	58	65	58	88	61	96	600	600	1
1	2	43	3	16	5	62	69	62	92	65	100	600	600	1
1	2	44	1	16	2	64	71	64	94	67	102	600	600	1
3	1	10	2	5	16	67	75	67	97	70	105	600	600	1
1	2	45	1	16	4	72	76	72	102	75	110	600	600	1
2	2	46	2	16	3	74	81	74	104	77	112	600	600	1
3	1	11	3	4	16	74	78	74	104	77	112	600	600	1
3	1	12	1	3	16	74	77	74	104	77	112	600	600	1

4.2.3. Conflict Free Taxiway Scheduling Results

In this section we present results obtained from the TSM for the considered 25 flights. Table 8 shows the detailed taxiway schedules while Figure 5 and Figure 6 show the detailed taxiway schedules for the first 7 minutes and the last 6 minutes.

Table 8. Taxiway Schedules for 25 Flights

Flight ID	arc	from	to	d	a
3	11	5	9	0.00	0.50
3	21	9	11	0.50	1.17
3	33	11	14	1.17	2.17
3	43	14	15	2.17	2.67
3	45	15	16	2.67	3.17
5	5	3	8	0.00	0.50
5	19	8	10	0.50	1.17
5	27	10	13	1.67	2.67
5	41	13	15	2.67	3.17
5	45	15	16	3.17	3.67
1	13	6	9	1.00	**1.50**
1	21	9	11	**1.67**	**2.33**
1	33	11	14	**2.67**	3.67
1	43	14	15	3.67	4.17
1	45	15	16	4.17	4.67
2	23	7	11	1.00	1.83
2	33	11	14	1.83	**2.83**
2	43	14	15	**3.17**	3.67
2	45	15	16	3.67	4.17
4	9	4	9	2.00	2.50
4	21	9	11	2.50	3.17
4	31	11	12	3.17	3.67
4	37	12	15	3.67	4.67
4	45	15	16	4.67	5.17
8	4	8	2	3.67	4.17
8	20	10	8	3.00	3.67
8	30	12	10	2.50	3.00
8	38	15	12	1.50	2.50
8	46	16	15	1.00	1.50
7	1	1	8	2.00	2.50
7	17	8	9	2.50	3.00
7	21	9	11	3.00	3.67
7	33	11	14	3.67	4.67
7	43	14	15	4.67	5.17
7	45	15	16	5.17	5.67
6	3	2	8	5.00	5.50
6	19	8	10	5.50	6.17
6	27	10	13	6.17	**7.17**
6	41	13	15	**7.50**	8.00
6	45	15	16	8.00	8.50
9	14	9	6	9.67	10.17
9	22	11	9	9.00	9.67
9	34	14	11	8.00	9.00
9	44	15	14	7.50	8.00
9	46	16	15	7.00	7.50
10	12	9	5	16.67	17.17
10	22	11	9	16.00	16.67
10	32	12	11	15.50	16.00
10	38	15	12	14.50	15.50
10	46	16	15	14.00	14.50
11	8	8	4	23.67	24.17
11	20	10	8	23.00	23.67
11	30	12	10	22.50	23.00
11	38	15	12	21.50	22.50
11	46	16	15	21.00	21.50

Flight ID	arc	from	to	d	a
13	24	11	7	35.17	36.00
13	34	14	11	**34.17**	35.17
13	44	15	14	33.50	**34.00**
13	46	16	15	33.00	33.50
14	2	8	1	43.67	44.17
14	20	10	8	43.00	43.67
14	30	12	10	42.50	43.00
14	38	15	12	41.50	42.50
14	46	16	15	41.00	41.50
15	42	15	13	**50.50**	51.00
15	46	16	15	49.00	**49.50**
15	51	13	17	51.00	52.00
34	3	2	8	54.00	54.50
34	19	8	10	54.50	55.17
34	29	10	12	55.17	55.67
34	37	12	15	55.67	56.67
34	45	15	16	56.67	57.17
16	14	9	6	57.67	58.17
16	22	11	9	57.00	57.67
16	34	14	11	56.00	57.00
16	44	15	14	55.50	56.00
16	46	16	15	55.00	55.50
35	13	6	9	58.67	59.17
35	21	9	11	59.17	59.83
35	33	11	14	59.83	60.83
35	43	14	15	60.83	61.33
35	45	15	16	61.33	61.83
17	12	9	5	65.00	65.50
17	22	11	9	64.33	65.00
17	32	12	11	63.83	64.33
17	38	15	12	62.83	63.83
17	46	16	15	62.33	62.83
18	4	8	2	66.67	67.17
18	20	10	8	66.00	66.67
18	30	12	10	65.50	66.00
18	38	15	12	64.50	65.50
18	46	16	15	64.00	64.50
36	11	5	9	67.00	67.50
36	21	9	11	67.50	68.17
36	33	11	14	68.17	69.17
36	43	14	15	69.17	69.67
36	45	15	16	69.67	70.17
19	10	9	4	74.67	75.17
19	22	11	9	74.00	74.67
19	34	14	11	73.00	74.00
19	44	15	14	72.50	73.00
19	46	16	15	72.00	72.50
20	6	8	3	76.83	77.33
20	20	10	8	76.17	76.83
20	30	12	10	**75.67**	76.17
20	38	15	12	74.50	**75.50**
20	46	16	15	74.00	74.50
37	7	4	8	74.00	74.50
37	19	8	10	74.50	75.17
37	27	10	13	75.17	76.17

12	6	8	3	28.67	29.17
12	20	10	8	28.00	28.67
12	30	12	10	27.50	28.00
12	38	15	12	26.50	27.50
12	46	16	15	26.00	26.50

37	41	13	15	76.17	76.67
37	45	15	16	76.67	77.17
38	5	3	8	74.50	75.00
38	19	8	10	75.00	75.67
38	27	10	13	75.67	76.67
38	41	13	15	76.67	77.17
38	45	15	16	77.17	77.67

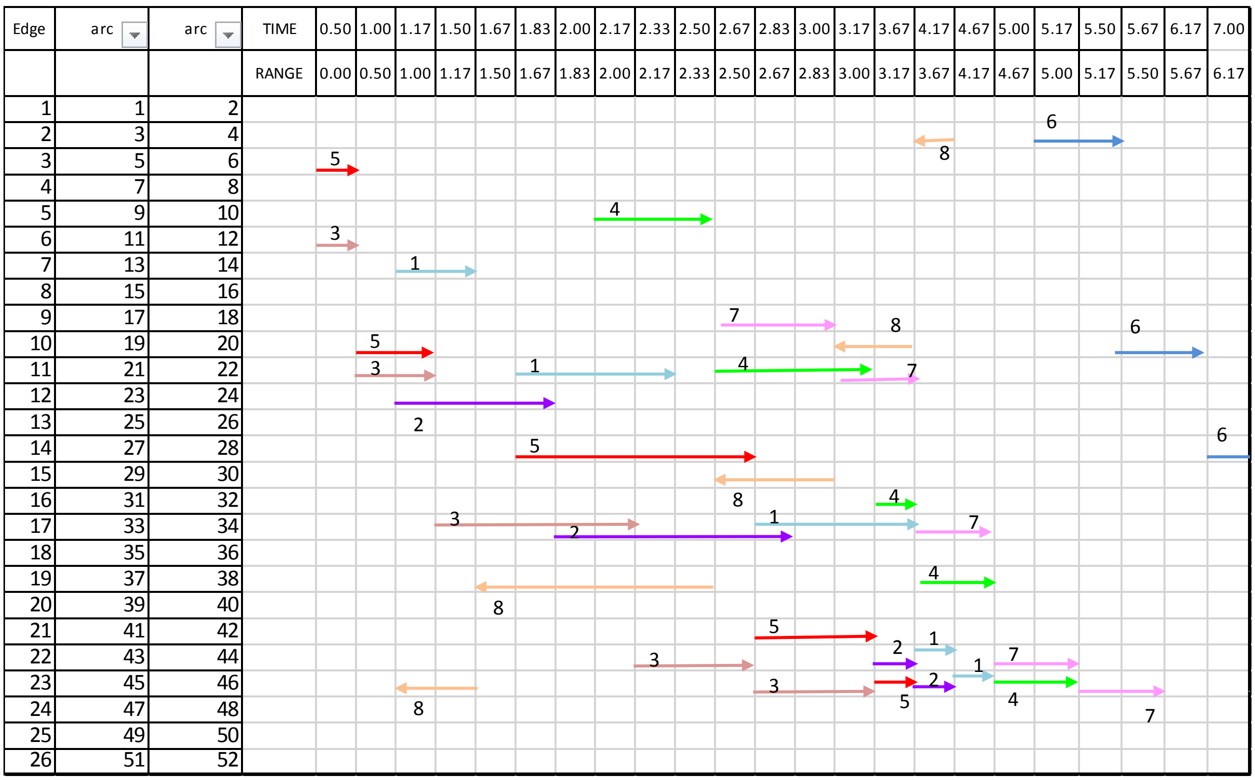

Figure 5. Conflict free Taxiway Schedules: First 7 minutes

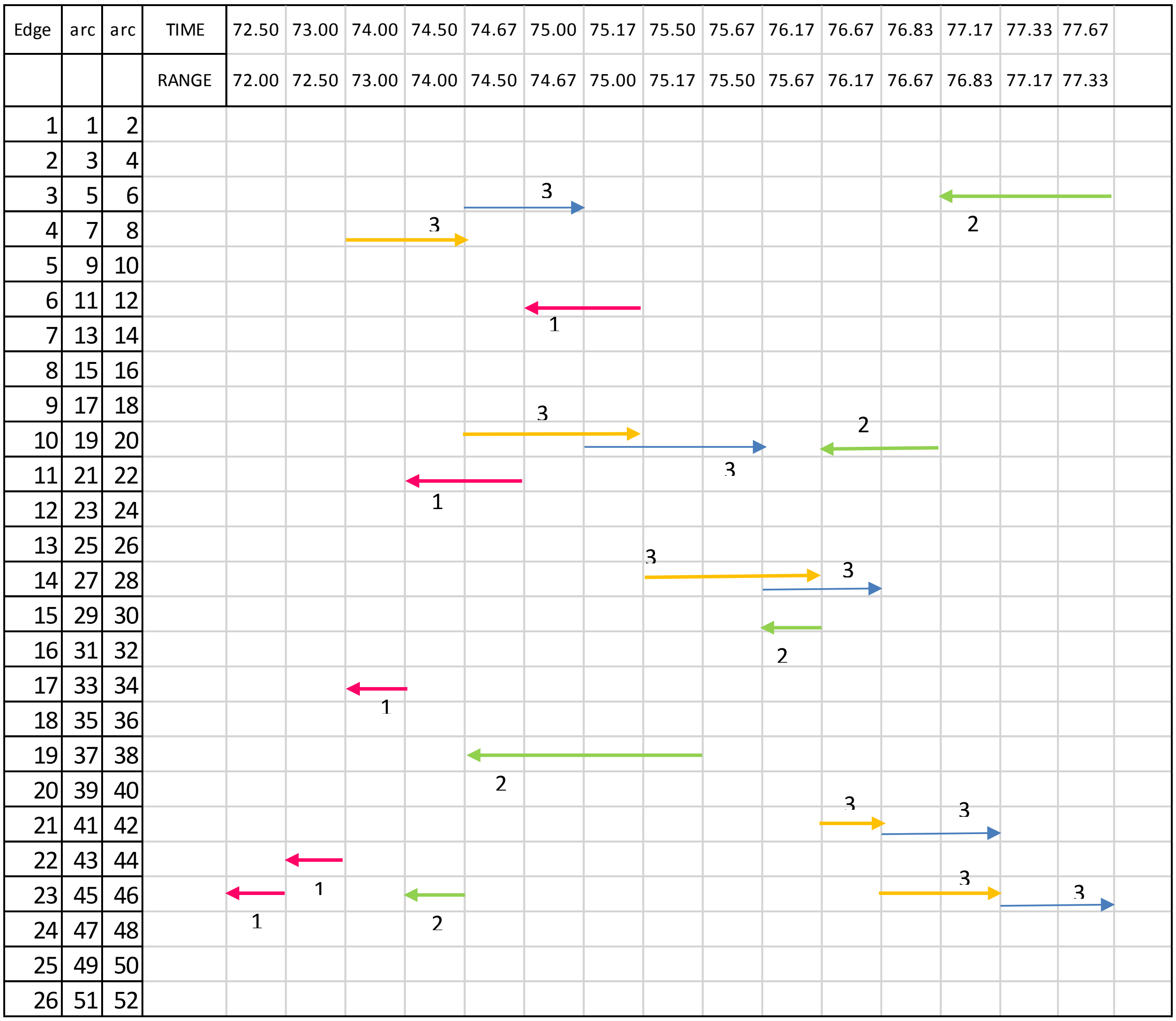

Figure 6. Conflict free Taxiway Schedules: Last 6 minutes

4.2.4. Airport Network for Medium Size Airport

Considered medium size airport consists of 10 gates, two apron areas where flights can load and unload passengers instead of gates when there is a congestion, a shared runway for departures and arrivals and 17 taxiway intersections. The layout of the airport is given in the following figure.

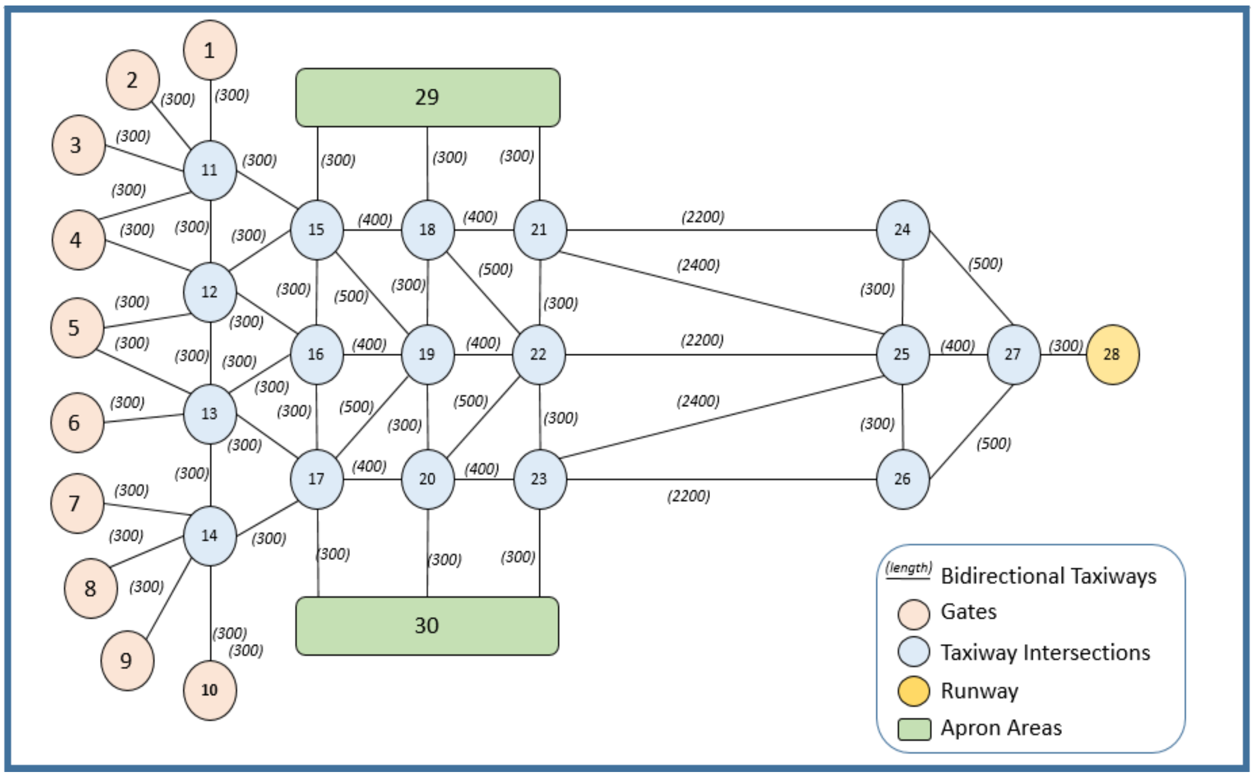

Figure 7. Medium Size Airport Layout for Taxiway Scheduling

4.2.5. Flight Information for Medium Size Airport

We consider a set of flight data assuming that average time between arrivals is 3 minutes. Since there are 10 gates, it is assumed that 10 flights are ready to depart within the next 10 minutes and there are 5 more flights ready to take passengers from the gates between time 10 and 30. Flight information is generated in two steps. In the first step, we create departures and arrivals and get their gate schedules using the model presented in Chapter 3. In the second step, we generate a departure flight from each arrival using the resulting gate in and out times.

Step I: Generating Flight Information for the Gate Scheduling System

In the first step first we generate 10 departure flights ready to depart from the gates and 5 departure flights ready to take the passengers from the gates and take off. It is assumed that for the first 10 flights scheduled arrival times (sa^f) to gates vary between [0,10]. Since the first 10 flights are ready to depart, their gate dwelling times ($dwel^f$) are taken as 0. On the other hand, for the next 5 departure flights, sa^f is assumed to be between [10,30] and their $dwel^f$ is assumed to be constant 25 minutes. Then we randomly create arrivals so as there is one arrival on average in every 3 minutes. That is to say, landing (T_{IN}^f) times are generated using ($T_{IN}^{f-1} + Random[1,5]$) function. It is also assumed that taxiing time delays vary in between [0, 10] minutes from the minimum taxiing time which is 7 minutes for the considered airport network so sa^f are generated using ($T_{IN}^f + 7 + Random[0,10]$) Once flights arrive to their gates, it is assumed that they stay there for constant 45 minutes ($dwel^f$) before starting their departure legs. Gate departure times (sd^f) are then taken as $sa^f + dwel^f$ and turnaround times (t^f) are taken as 1 minute for all flights. Table 9 shows all the flights that are expected to be in the gate scheduling system in the next 120 minutes with their resulting gate schedules (sorted with respect to sa^f).

Table 9. Flight Schedules for Gate Scheduling

Flight No	T_{IN}^{f}	sa^{f}	$dwel^{f}$	sd^{f}	t	Gate No
1	9	0	0	9	1	10
2	0	0	0	0	1	6
3	2	0	0	2	1	10
4	3	0	0	3	1	3
5	4	0	0	4	1	4
6	2	0	0	2	1	7
7	7	0	0	7	1	5
8	2	0	0	2	1	2
9	5	0	0	5	1	8
10	8	0	0	8	1	1
15	11	11	25	36	1	4
16	0	11	45	56	1	8
13	12	12	25	37	1	10
17	3	12	45	57	1	2
12	15	15	25	40	1	7
11	20	20	25	45	1	1
18	6	23	45	68	1	29
21	17	25	45	70	1	5
19	11	28	45	73	1	9
20	15	28	45	73	1	30
14	30	30	25	55	1	6
22	20	31	45	76	1	29
23	24	33	45	78	1	3
24	29	40	45	85	1	4
25	32	43	45	88	1	10
26	34	48	45	93	1	29
27	38	53	45	98	1	1
28	40	55	45	100	1	7
29	43	59	45	104	1	6
32	51	62	45	107	1	2
31	49	63	45	108	1	29
30	48	65	45	110	1	30
33	55	65	45	110	1	8
34	60	70	45	115	1	29
36	65	77	45	122	1	5
39	71	78	45	123	1	9
38	70	79	45	124	1	30
35	64	81	45	126	1	29
37	69	84	45	129	1	30
40	76	90	45	135	1	29
41	80	94	45	139	1	3
42	85	95	45	140	1	30
43	89	99	45	144	1	29
44	90	103	45	148	1	30
45	91	103	45	148	1	10
46	92	105	45	150	1	6
47	95	105	45	150	1	4
48	98	107	45	152	1	29
50	105	114	45	159	1	1
51	107	114	45	159	1	7
49	101	116	45	161	1	2
52	108	119	45	164	1	8

Step II: Generating Flight Information for Taxiway Scheduling System

Once we obtain the gate schedules for the departure flights that are already in the airport and for the arriving flights, next step is to generate one departure flight from each arrival flight and updating the T_{OUT}^{f} and T_{IN}^{f} times for arriving and departing flights, respectively. For each arrival flight, T_{OUT}^{f} is taken as their sa^{f} and for each departing flight T_{IN}^{f} s taken as sd^{f}. Following table shows the flight information for a total of 54 flights that are going to be in the taxiway scheduling system within the next 90 minutes ordered with respect to their T_{IN}^{f}. The second column in the table specifies if a flight is a departure (type=1), or an arrival (type=2), while the third column shows the id of the pairing flight. Since we don't allow flight pairs (an arrival and its departure) to use different gates, this information is used to force them to arrive and depart from the same gates. While V_{IN}^{f} specifies departure gates and runway nodes for departing and arriving flights, respectively, V_{OUT}^{f} specifies runway node and arrival gates for departures and arrivals, respectively. Earliest time to enter the taxiway scheduling system ($Early_{IN}^{f}$) is taken as T_{IN}^{f} and earliest time to leave the system ($Early_{OUT}^{f}$) is taken as $Early_{IN}^{f} + 7$. Latest entrance and exit times are assumed to be large enough in order to prevent any infeasibilities. The last column in Table 10 specifies if a flight is allowed to land in or depart from the apron. Speed is assumed to be constant 600 meters per minute.

Table 10. Flight Schedules for Taxiway Scheduling

ID	Type	Pair ID	V_{IN}^{f}	V_{OUT}^{f}	T_{IN}^{f}	T_{OUT}^{f}	$(Early_{IN}^{f})$	$(Early_{OUT}^{f})$	Apron
2	1	0	6	28	0	9	0	7	0
16	2	53	28	8	0	11	0	7	1
3	1	0	10	28	2	10	2	9	0
6	1	0	7	28	2	17	2	9	0
8	1	0	2	28	2	10	2	9	0
4	1	0	3	28	3	11	3	10	0
17	2	54	28	2	3	12	3	10	1
5	1	0	4	28	4	17	4	11	0
9	1	0	8	28	5	20	5	12	0
18	2	55	28	29	6	23	6	13	1
7	1	0	5	28	7	16	7	14	0
10	1	0	1	28	8	16	8	15	0
1	1	0	10	28	9	23	9	16	0
15	1	0	4	28	11	52	11	18	0
19	2	56	28	9	11	28	11	18	1
13	1	0	10	28	12	46	12	19	0
12	1	0	7	28	15	49	15	22	0
20	2	57	28	30	15	28	15	22	1
21	2	58	28	5	17	25	17	24	1
11	1	0	1	28	20	59	20	27	0
22	2	59	28	29	20	31	20	27	1
23	2	60	28	3	24	33	24	31	1
24	2	61	28	4	29	40	29	36	1
14	1	0	6	28	30	72	30	37	0
25	2	62	28	10	32	43	32	39	1
26	2	63	28	29	34	48	34	41	1
27	2	64	28	1	38	53	38	45	1
28	2	65	28	7	40	55	40	47	1
29	2	66	28	6	43	59	43	50	1
30	2	67	28	30	48	65	48	55	1
31	2	68	28	29	49	63	49	56	1
32	2	69	28	2	51	62	51	58	1
33	2	70	28	8	55	65	55	62	1
53	1	16	8	28	56	68	56	63	1
54	1	17	2	28	57	64	57	64	1
34	2	71	28	29	60	70	60	67	1
35	2	72	28	29	64	81	64	71	1
36	2	73	28	5	65	77	65	72	1
55	1	18	29	28	68	78	68	75	1
37	2	74	28	30	69	84	69	76	1
38	2	75	28	30	70	79	70	77	1
58	1	21	5	28	70	85	70	77	1
39	2	76	28	9	71	78	71	78	1
56	1	19	9	28	73	84	73	80	1
57	1	20	30	28	73	86	73	80	1
40	2	77	28	29	76	90	76	83	1
59	1	22	29	28	76	90	76	83	1
60	1	23	3	28	78	91	78	85	1
41	2	78	28	3	80	94	80	87	1
42	2	79	28	30	85	95	85	92	1
61	1	24	4	28	85	95	85	92	1
62	1	25	10	28	88	96	88	95	1
43	2	80	28	29	89	99	89	96	1
44	2	81	28	30	90	103	90	97	1

4.2.6. Analysis and Results

In this section, first we present the performance of the mathematical formulation with respect to varying flight sizes. We also propose a batch by batch solution procedure since the solution time of the problem increases exponentially with the increase in the flight size considered. Finally we present the results. The tests are performed on a computer with an Intel i5 1.80 GHz CPU and 12 GB RAM and Cplex 12.6 is used as the solver.

Table 11 shows the performance of the mathematical model solved with varying flight sizes.

Table 11. Performance Comparison of TSM

Flight Number	Objective function Value (minutes)	Solution Time	Flight Number	Objective function Value (minutes)	Solution Time
5	36.33	2.15 seconds	18	130.33	04.50.12 minutes
6	43.67	7.10 seconds	19	137.50	4.00.08 minutes
7	51.00	9.56 seconds	20	144.83	3.26.50 minutes
8	58.17	10.97 seconds	21	151.83	16.58.46 minutes
9	65.50	8.84 seconds	22	159.17	05.28.35 minutes
10	72.50	32.32 seconds	23	166.33	12.52.59 minutes
11	79.67	43.60 seconds	24	173.50	11.41.22 minutes
12	87.00	38.12 seconds	25	180.83	10.18.42 minutes
13	94.33	59.55 seconds	26	187.83	11.37.08 minutes
14	101.50	56.69 seconds	27	195.17	10.19.03 minutes
15	108.83	01.08.09 minutes	28	202.33	22.25.80 minutes
16	116.16	01.42.49 minutes	29	209.50	19.06.13 minutes
17	123.33	02.28.26 minutes	30	>1 HR	

The results show that solution time increases significantly with an increase in the number of flights considered in the model. Unfortunately, we could not get any feasible solution within an hour when the flight size is more than 29. Therefore, we adopted a batch by batch policy where we solve the model for a specific batch of flights and fix the route and timing variables of the flights in the batch while solving the next batch of flights. Table 12 shows the results obtained for different sizes of batches.

Table 12. Performance Comparison of TSM by batching

Batch Size	Number of Iterations	Total Algorithm Time (minutes)	Total Solution Time (minutes)	Objective Value (minutes)
10	6	21.07	17.63	394.33
15	4	18.05	15.37	453.17
20	3	9.23	7.23	388
25	3	13.52	11.10	392.33

The results obtained by batch by batch policy doesn't show a linear correlation between the batch size and the solution time and between the batch size and the objective function value. In all cases, total number of flights assigned to apron was zero. Moreover, we obtained the best results with a batch of 20 with three iterations both in terms of solution time and objective function value. Therefore in the following in Table 13 we present the results obtained when the problem is solved with a batch of 20.

Table 13. Results of TSM

	Scheduled before		Solution of Taxiway Model				
Flight ID	T_{IN}^{f}	T_{OUT}^{f}	t_{IN}^{f}	t_{OUT}^{f}	Total Arcs Used	Gate Holding Time	$t_{OUT}^{f} - T_{IN}^{f}$
2	0	9	0.00	7.17	7	0.00	7.17
16	0	11	0.00	7.33	7	0.00	7.33
3	2	10	2.00	9.33	7	0.00	7.33
6	2	17	2.00	9.17	7	0.00	7.17
8	2	10	2.00	9.33	7	0.00	7.33
4	3	11	3.00	10.33	7	0.00	7.33
17	3	12	3.00	10.33	7	0.00	7.33
5	4	17	4.00	11.17	7	0.00	7.17
9	5	20	5.00	12.33	7	0.00	7.33
18	6	23	6.00	13.00	4	0.00	7.00
7	7	16	7.00	14.17	7	0.00	7.17
10	8	16	8.00	15.33	7	0.00	7.33

1	9	23	9.00	16.33	7	0.00	7.33
15	11	52	11.00	18.17	7	0.00	7.17
19	11	28	11.00	18.33	7	0.00	7.33
13	12	46	12.00	19.33	7	0.00	7.33
12	15	49	15.00	22.17	7	0.00	7.17
20	15	28	15.00	22.00	5	0.00	7.00
21	17	25	17.00	24.17	7	0.00	7.17
11	20	59	20.00	27.33	7	0.00	7.33
22	20	31	20.00	27.00	6	0.00	7.00
23	24	33	24.00	31.33	7	0.00	7.33
24	29	40	29.00	36.17	7	0.00	7.17
14	30	72	30.00	37.17	7	0.00	7.17
25	32	43	32.00	39.33	7	0.00	7.33
26	34	48	34.00	41.00	4	0.00	7.00
27	38	53	38.00	45.33	7	0.00	7.33
28	40	55	40.00	47.17	7	0.00	7.17
29	43	59	43.00	50.17	7	0.00	7.17
30	48	65	48.00	55.00	5	0.00	7.00
31	49	63	49.00	56.00	5	0.00	7.00
32	51	62	51.00	58.33	7	0.00	7.33
33	55	65	55.00	62.33	7	0.00	7.33
53	56	68	56.00	63.33	7	0.00	7.33
54	57	64	57.00	64.33	7	0.00	7.33
34	60	70	60.00	67.00	5	0.00	7.00
35	64	81	64.00	71.00	5	0.00	7.00
36	65	77	65.00	72.17	7	0.00	7.17
55	68	78	68.00	75.00	6	0.00	7.00
37	69	84	69.00	76.00	4	0.00	7.00
38	70	79	70.00	77.00	5	0.00	7.00
58	70	85	70.00	77.17	7	0.00	7.17
39	71	78	71.00	78.33	7	0.00	7.33
56	73	84	73.00	80.33	7	0.00	7.33
57	73	86	74.50	80.00	4	1.50	7.00
40	76	90	76.00	83.00	4	0.00	7.00
59	76	90	76.83	83.00	5	0.83	7.00
60	78	91	78.00	85.33	7	0.00	7.33
41	80	94	80.00	87.33	7	0.00	7.33
42	85	95	85.00	92.00	4	0.00	7.00
61	85	95	85.00	92.17	7	0.00	7.17
62	88	96	88.00	95.33	7	0.00	7.33
43	89	99	89.00	96.00	5	0.00	7.00
44	90	103	90.00	97.00	5	0.00	7.00

4.3. CONCLUSION AND DISCUSSION

A MILP that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, all safety constraints are modeled with Big-Ms. This enables us to know the exact arrival and departure times for each flight on each link on the ground. Collision free taxiway scheduling is achieved. Since the models in the existing literature either assumes arbitrary capacities on the nodes of the network or discretizes time, they do not guarantee collision avoidance. Speed changes, rerouting, and holding at gates and taxiway intersections are used as control options. Both airlines and airport authorities' objectives are considered. Proposed models have the capability to be adopted as a decision support tool for the ground controllers and they allow airport traffic authorities to do what-if analysis in case of a change in the flight or airport network information. Proposed TSM also minimizes to total taxiing time which results in less costly taxiway schedules for airlines in terms of fuel costs and CO2 emissions.

Two solution strategies are proposed for the TSM: *iterative TSM* and *GA-TSM.* While *iterative TSM* decomposes the problem into batches of flights, solves each batch by fixing the schedules of the previous batch in each batch, GA-TSM decomposes the problem into routing and timing. While *GA* searches for the best set of routes for the flights, *fixed TSM* solves the timing problem for a given set of routes.

As far as our concern, this is the first study focuses the problem from both aspects: safety and efficiency.

CHAPTER 5

TAXIWAY SCHEDULING OF AIRCRAFTS WITH A GENETIC ALGORITHM

This chapter considers the airport taxiway scheduling problem respecting all type of safety (minimum separation) restrictions for all arriving and departing aircraft in a dynamic environment of airports. Speed arrangement, holding at gates and at the intersection of taxiways, and routing are used as control options in order to achieve conflict-free, efficient, and environment-friendly taxiway schedules. Due to the complexity of the problem, a genetic algorithm (GA) employing a taxiway schedule generation scheme is proposed. Evaluation of the chromosome is based on the results of a mathematical formulation which aims to minimize total taxiing and waiting times at their initial positions for all flights. This chapter is motivated by the taxiway scheduling problem of aircraft in a dynamic environment of airports. A mathematical programming model (*Taxiway Scheduling Model, TSM*) that makes routing and timing decisions at the same time is developed and presented in Chapter 4. The model uses routing, holding and speed arrangement as control options in order to obtain conflict-free, taxiway schedules for all arriving and departing aircraft. Due to the complexity of this model, a new scheduling methodology that decomposes the problem into two as *routing* and *timing* is proposed. In this methodology, while the best routes are searched by a genetic algorithm (GA), timing decisions are made by employing a taxiway schedule generation scheme which makes use of a fixed-path taxiway scheduling mathematical model (*F-TSM*). In the next section proposed GA methodology is detailed. Finally, in Section 3, this chapter is concluded with a discussion on the preliminary results.

5.1. FRAMEWORK OF THE PROPOSED GENETIC ALGORITHM

Proposed GA starts with randomly creating the initial population consisting N number of chromosomes. Each gene in a chromosome represents the randomly selected route number assigned to the corresponding flight among the set of K shortest paths. Then fitness of each chromosome in the initial population is evaluated by solving the F-TSM. To form the offspring population, we apply reproduction steps by the use of parent selection, crossover and mutation operators. First we choose two chromosomes from the current population as parents, then we apply crossover with a predefined crossover probability to obtain two offsprings. Then, mutation operator is applied with a mutation probability. We continue this reproduction process until we obtain N number of chromosomes in the offspring population. Before merging the current population with the offspring population, the fitness of each offspring is evaluated. After merging the populations, we sort the combined population with respect to fitness of each chromosome and we move the best N chromsomomosomes to the next population. We continue forming next population until a predefined number of generations are created. The best chromosome in the last generation is used as the best solution of the algorithm. Algorithm 1 gives the pseudocode of the algorithm.

1. **[Start]** Generate random population of *N* chromosomes
2. **[Fitness]** Evaluate the fitness *f(x)* of each chromosome *x* in the population
3. **[New population]** Create a new population by repeating following steps until the new population is complete
    1. **[Selection]** Select two parent chromosomes from a population according to their fitness
    2. **[Crossover]** With a crossover probability cross over the parents to form new offspring (children). If no crossover was performed, offspring is the exact copy of parents.
    3. **[Mutation]** With a mutation probability mutate new offspring at each position
4. **[Replace]** Use new generated population for a further run of the algorithm
5. **[Test]** If the end condition is satisfied, **stop**, and return the best solution in current population
6. **[Loop]** Go to step **2**

Algorithm 1: Framework of the proposed methodology

5.2. CHROMOSOME REPRESENTATION

Chromosome structure in the proposed GA is composed of a set of real numbers, from 1 to R_k where R_k is the total number of routes considered for a flight. Each number in the chromosome stands for the route assigned to the corresponding flight from the set of possible routes. Once a chromosome is created, it is decoded as a schedule through the optimization of the *fixed-path taxiway schedule model* (*F-TSM*) where routing variables of the model presented in Chapter 4 are fixed.

5.3. CHROMOSOME EVALUATION

Evaluation of a chromosome is based on mathematical programming formulation, *fixed-path taxiway scheduling model* (*F-TSM*). For a chromosome with its preassigned taxiway routes for each flight, total taxiing time and waiting times at initial positions is assessed by optimizing *F-TSM* by CPLEX solver.

5.4. INITIAL POPULATION

The initial population is comprised of *N* randomly selected feasible taxiway route lists. A feasible taxiway route for a flight is a set of positions on the airport to be followed that starts from the origin of the flight and ends at the destination during taxiing.

5.5. CONSTRUCTION OF THE NEXT GENERATION

Construction of the next generation starts with sorting of the current population with respect to its fitness function and then parent pairs are selected from the current population and the offspring population of size *N* is generated. Before the combination of the current population with the offspring population, *F-TSM* is solved for all chromosomes in the offspring population and the fitness scores are calculated for each offspring. After the combined population of size 2*N* is obtained, this population is reduced to the population size of *N* with a reduction procedure. The steps in constructing the next generation are given in the following subsections.

5.6. SELECTION OF PARENT PAIRS

The construction of the next generation continues with the selection of parent pairs. There are many selection schemes for GAs, each with different characteristics. Tournament selection (see, e.g., [3] for details) has increasingly been used as a GA selection scheme. To obtain the parent pairs from the population at hand, the mother (*M*) population and father (*F*) population are generated using a binary tournament selection procedure. Between two randomly selected chromosomes for being an *M* with different fitness scores, the procedure prefers the one with the higher fitness score. When both chromosomes have the same fitness score, then makes the selection randomly. The same selection procedure is applied for the selection of F, but this time it is repeated until a distinct *M-F* pair is formed.

5.7. CROSSOVER OPERATOR

We make use of a one-point crossover operator for which one point (*p*) is randomly selected. Let us assume that parent pairs are selected for crossover, i.e., we have a mother chromosome *M* and a father chromosome *F*, and two child chromosomes, a daughter d and a son s, are to be constructed. To create the d, the genes are first chosen from *M* until the randomly selected point is reached, and the rest are then chosen from *F*. This crossover operator is applied to all *M-F* pairs until an offspring population of the required size is generated.

5.8. MUTATION OPERATOR

Modification of the newly produced chromosomes plays an important role in increasing a population's diversity. The *random mutation operator* generates a new route for each flight with a mutation probability.

5.9. REDUCING THE POPULATION SIZE

Given the current generation h, binary tournament selection, crossover, and mutation operators are used to create an offspring population Q_h of size *N* then a combined population $R_h = P_h U Q_h$ of size 2*N* is formed, where P_h is the current population. Then, the combined population R_h is sorted according to fitness scores of the chromosomes. Since all the previous and current population members are included, elitism is ensured.

5.10. DISCUSSION

For the implementation of the proposed approach, the hypothetical data presented in Chapter 4 is used. All code is written in Microsoft Visual C#, and CPLEX 12.6 is used as the MIP solver. All tests are performed on a computer with a 3.20 GHz Intel(R) Core(TM) i7 960 processor and 8 GB of RAM.

K-shortest paths for each flight is generated using Yen's algorithm (1971). The algorithm makes use of the well-known Dijkstra's shortest path algorithm. The steps of the algorithm is given in Algorithm 2.

1. Determine the shortest path $\boldsymbol{P^1}$ from source $\boldsymbol{s}$ to destination $\boldsymbol{t}$ in a graph $\boldsymbol{G}$ by using the *Dijkstra's shortest path algorithm*.
2. Assume that $\boldsymbol{k-1}$ (where $k = 2, 3 \ldots K$) shortest paths are already determined and stored in $\boldsymbol{list\ A}$ and candidate paths for next shortest path are stored in $\boldsymbol{list\ B}$.
3. In order to determine the shortest path $\boldsymbol{P^k}$, get the shortest path $\boldsymbol{P^{k-1}}$ and let the path be and the set of vertices to be analysed is $\boldsymbol{DS} = \{\boldsymbol{s}, \boldsymbol{v_1^{k-1}}, \boldsymbol{v_2^{k-1}}, \ldots \boldsymbol{v_l^{k-1}}\}$.
4. For each vertex $\boldsymbol{v}$ in $\boldsymbol{DS}$ do
    1. If there exists a path $\boldsymbol{P^j}$ in $\boldsymbol{list\ A}$ that has the path as the sub path. Then set the weight of the edge from $\boldsymbol{v}$ to its immediate neighbour to infinity for $\boldsymbol{P^j}$.
    2. Set the sub path $< \boldsymbol{s}, \boldsymbol{v_1^{k-1}}, \boldsymbol{v_2^{k-1}}, \ldots, \boldsymbol{v} >$ in $\boldsymbol{P^{k-1}}$ as the root path $\boldsymbol{R^k}$. Set the path to be determined from $\boldsymbol{v}$ to $\boldsymbol{t}$ is as the spur path $\boldsymbol{S^k}$. Remove the vertices in the $\boldsymbol{R^k}$ from the graph so that they are not repeated in spur path.
    3. Compute the shortest path from $\boldsymbol{v}$ to $\boldsymbol{t}$ by using the *Dijkstra's algorithm*.
    4. If a path is found and returned by *Dijkstra's algorithm*, then add both $\boldsymbol{R^k}$ and $\boldsymbol{S^k}$ to form a candidate path, for next shortest path. Add this path into $\boldsymbol{list\ B}$ and continue.
    5. Choose the path from $\boldsymbol{list\ B}$ with shortest distance as P^k and move it to $\boldsymbol{list\ A}$.
    6. Go to step 3 and continue until $\boldsymbol{K}$ shortest paths have been determined

Algorithm 2: Yen's Algorithm [1971]

Proposed method motivates from the idea of decomposition the model into two as routing and timing problem and incorporates a genetic algorithms with TSM. Main reason that this genetic algorithm is developed is that routing is more difficult compared to timing decisions. For the considered 54 flights, assuming 20 generations of GA each with 20 chromosomes, it requires optimization of timing variables 400 times. To get the results in a reasonable time (<10 minutes), each timing problem should be solved in 1.5 seconds. However, our *F-TSM* is not capable of making timing decisions for a given route within 1.5 seconds. More research should be done on decomposing the problem in a more efficient way.

CHAPTER 6

CONCLUSION AND FUTURE WORK

Airport administration involves difficult decisions concerning the trade-offs among the quality and cost of service. This challenge is exacerbated by the congestion and competition across the air transportation industry, the increasing costs of service and the growing desire for more comfort in the air transportation customers. Although significant strides have been made concerning the strategic and tactical decision-making process in airports, there is a gap in the academic literature on the optimization of day-to-day operational decisions. An example of such a decision in airport ground surfaces is "how can we optimize the aircraft routes so as to increase taxiway utilization by avoiding conflicts?" It is not possible to efficiently tackle the question above without detailed ground-level process data. Indeed, without a solid understanding of the dynamic and complex nature of ground surface operations, the question of "what is the total cost of lateness and earliness resulting from the deviations from scheduled plans?" constitutes a major challenge.

The overarching goal of this thesis is to make contributions to the methodology and current practice of operational level decision-making in airports. The immediate benefits of this project would be the proposed ground traffic management improvements. These improvements would be aimed at increasing the overall quality of surface operations i.e., increased on-time performance, and better utilization of taxiways. The findings of this research is expected to not only have a significant impact on the efficiency of ground surface operations, but also to enable the airport authorities to have insights on the possible improvements that can be achieved.

This thesis proposes conflict-free mathematical models and solution strategies for both gate scheduling and taxiway scheduling problems by taking account all meaningful airport and flight characteristics into consideration that are not yet extensively studied in current academic literature. Since gate schedule performance has a great impact on the performance of the taxiway, we consider gate scheduling as a bi-objective optimization problem, present mathematical models and propose a two-phase solution approach.

We also propose a mixed integer programming (MIP) model that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, the non-time segmented model proposed in this thesis, determines a taxi plan for each aircraft by identifying the sequence of taxiway intersections represented as nodes to be visited and determines the aircrafts' exact arrival and departure times to these nodes, average speed used on the taxiway represented as links between two consecutive nodes while ensuring the safety conditions that avoid aircraft collisions. The cost incurred from arrival and departure delays with total taxiing time is minimized. The model enables collision free airport operations considering both airlines and airport controller's objectives in continuous time where we know the *exact arrival and departure* times which is more accurate in tackling collision issues. However, accuracy comes with a cost of solution time. To overcome the difficulty to solve, two solution methods: an iterative heuristic and a genetic algorithm are proposed. The first strategy proposed, called the *iterative-TSM,* adopts a batch by batch policy and optimizes the TSM by solving it in an iterative way where in each iteration, schedules of the previous iteration are fixed. The second strategy proposed motivates from the idea of decomposition the model into two as routing and timing problem and incorporates a genetic algorithms with TSM. All the models proposed are tested on a hypothetical data and the results are presented. More research is required in order to understand the characteristics of the problem in more detail and decrease the solution time.

Main contributions of this thesis can be listed as follows:

- A MILP model is presented for flight gate scheduling problem. The model is compared to modified version of one of the existing MILP model in literature and efficiency of the proposed model is evaluated. A two phase solution approach making use of the proposed MILP is also presented and the characteristics of the problem are analysed. While utilization of gates is maximized, on time performance is also considered.
- A MILP that considers *collision avoidance on the taxiways*, *separation distances between aircrafts*, *speed changes* and *exact travelling times* without adapting a state-time network in which the decision variables are defined with time indices. Instead, all safety constraints are modeled with Big-Ms. This enables us to know the exact arrival and departure times for each flight on each link on the ground.
- Collision free taxiway scheduling is achieved. Since the models in the existing literature either assumes arbitrary capacities on the nodes of the network or discretizes time, they do not guarantee collision avoidance.
- Speed changes, rerouting, and holding at gates and taxiway intersections are used as control options.
- Both airlines and airport authorities' objectives are considered. Proposed models have the capability to be adopted as a decision support tool for the ground controllers and they allow airport traffic authorities to do what-if analysis in case of a change in the flight or airport network information. Proposed TSM also minimizes to total taxiing time which results in less costly taxiway schedules for airlines in terms of fuel costs and CO2 emissions.
- Two solution strategies are proposed for the TSM: *iterative TSM* and *GA-TSM.* While *iterative TSM* decomposes the problem into batches of flights, solves each batch by fixing the schedules of the previous batch in each batch, GA-TSM decomposes the problem into routing and timing. While *GA* searches for the best set of routes for the flights, *fixed TSM* solves the timing problem for a given set of routes.

As far as our concern, this is the first study focuses the problem from both aspects: safety and efficiency.

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