Multimodal substitution in airline recovery operations. ASIANA crash case study.

Master Thesis

Pablo A. Colomar Roig
Matricel number: 03650710

Advisors:

Univ.-Prof. Dr.-Ing. Mirko Hornung
Technische Universität München

Univ.-Prof. Dr.-Ing. Eric Feron
Georgia Institute of Technology

Supervisor:

Dipl.-Ing., MBA Christoph Schinwald
Technische Universität München

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Abstract

The Master Thesis "Multi-modal substitution in airline recovery operations. ASIANA crash case study" offers a detailed view of the consequences of ASIANA crash in the network, and proposes the implementation of an inter-modal rerouting of the diverted passengers in order to enhance a faster and cost-effective recovery from the disruption.

The thesis is introduced by a description of the research project in which this study is circumscribed, as well as the data sources. Then, Chapter 2 presents the ASIANA crash factual summary, along with the impact of the crash in the schedules during the following days. Chapter 3 shows an estimated cost evaluation of the crash impact on schedules, followed by the argumentation in Chapter 4 of the research motivations.

Once the research focus is narrowed, Chapter 5 discusses in detail all the issues related to the implementation of inter-modal operations in the airline industry. The chapter starts explaining the state-of-the-art of inter-modal operations in the airline industry, then assesses the two possibilities of implementation of an inter-modal rerouting to SFO, and finally discusses secondary aspects of inter-modal operations, such as safety issues, motor-coaches service handling or how passengers may respond to an inter-modal rerouting.

After discussing how an inter-modal rerouting should be operated for ASIANA crash case, Chapter 6 offers a mathematical model to optimise the rerouting costs by applying inter-modal substitution of diverted flights, and Chapter 7 shows the model implementation over the busiest airports involved in the diversions triggered by Asiana Crash, computing the results and comparing them to non-inter-modal reroutings.

The thesis is closed extracting the conclusions of the implementations, and offering possibilities for further research in this field.
Chapter 1

Introduction

1.1 Disaster Project background

On the morning of 6th of July 2013, the Boeing 777-200ER aircraft operating the Asiana Airlines flight 214 crashed on final approach into SFO, with 307 people aboard. Two passengers died at the crash scene, and a third died in a hospital several days later. Additionally, 181 passengers were injured, 12 of them critically. The crash had direct consequences in the air traffic network, as two of the San Francisco International Airport (SFO) runways were temporary closed. Incoming flights had to be diverted to other airports, and outgoing flights could not take-off. Such impact triggered severe costs of delays, diversions and cancellations, that perhaps could have been more efficiently handled.

As a result of similar situations as the one ASIANA crash triggered, 'disruptions management' is a recurrent topic in aviation operations. Due to the great expense of purchasing and maintaining aircraft, airlines are pressured to maximize their fleet utilization by creating aircraft routings with as little embedded idle time as possible. Therefore, when schedule disruptions occur, either as a result of bad weather, mechanical problems or flight accidents, the consequences are extremely costly for airlines.

The difficulties in handling efficiently such disruptive situations have raised the willingness of the authorities to investigate the indirect consequences that they concatenate. The Asiana Crash Disaster Project, in which this Master Thesis research was circumscribed, is a joint research project between the Daniel Guggenheim School of Aerospace Engineering, at Georgia Institute of Technology, and the Civil and Environmental Engineering School at University of California Berkeley,
that aims to cover this need of explaining the crash anatomy, quantify how the coupling between the air and ground traffic network impacts, and finally try to propose measures that enhance an efficient disruption recovery.

Particularly, the research performed in this Master Thesis has focused on defining the optimal cost-efficient inter-modal rerouting of diverted passengers. A thorough analysis of the crash impact in the network and its cost consequences for the actors involved has been performed. Furthermore, this thesis proposes a more cost-efficient handling of the rerouting of diverted passengers by implementing inter-modal operations. The main subjects that will be covered along the thesis are:

- Analysis of the network impact of the crash; in terms of delays, cancellations and diversions.
- Cost evaluation of the crash impact in the air network. Focus on rerouting costs.
- Is there a more cost-effective way of rerouting passengers by implementing inter-modal operations?
- Development of mathematical optimization model of the diverted passengers’ reaccommodation costs.
- Implementation of the linear programming developed in Asiana crash case study.

1.2 Data sources available for analysis

This section will first discuss the two data sources available, secondly will explain the data that each database provide, as well as the differences between them. Finally, the section will expose the decision on which database would be used as input for the preliminary analysis and mathematical modeling.

Two databases are available, the first one provided by the Bureau of Transportation Statistics (BTS), and the second one is provided by the Federal Aviation Administration (FAA).
1.2.1 BTS Airline On-Time Performance Database

This first database is maintained by the Bureau of Transportation Statistics, part of the Research and Innovative Technology Administration (RITA), from the United States Department of Transportation (DOT). The database is called TranStats, and provides statistics on all transportation modes supplying the United States. Particularly, the data concerning this research is displayed in the Airline On-Time Performance Data [1].

The Airline On-Time Performance Database provides detailed information about air carrier on-time performance key indicators. Specifically, the database contains on-time arrival data for non-stop domestic flights, sorted by major air carriers. It is actualized with monthly frequency, with records starting on 1987. The data covers the following information:

- Scheduled and actual departure times.
- Scheduled and actual arrival times.
- Departure and arrival delay times.
- Taxi-out and taxi-in times.
- Wheels-on time and wheels-off times.
- Origin and destination airports per flight.
- Flight number and tail number assigned.
- Carrier code.
- Cancellation or diversion confirmations, with updated destination and arrival times in case of diverted flights.
- Airbone times.
- Non-stop flight distances.

1.2.2 Avation System Performance Metrics Database

The Aviation System Performance Metrics (ASPM) database is maintained by the Federal Aviation Administration (FAA). This online access system provides data on flights to and from the ASPM airports (currently 77); and all flights
by the ASPM carriers, including flights by those carriers to international and
domestic non-ASPM airports. All IFR traffic, and some VFR traffic for these
carriers and airports is included. The table can be accessed in the FAA Operations & Performance Data website [2].

ASPM flight records are divided into two groupings: Efficiency and Metrics
counts. The Efficiency Counts are intended to capture all traffic handled by con-
trollers. They include the full set of ASPM records, including some that are missing
one or more pieces of key data. In contrast, ASPM Metrics counts, the basis of
delay calculations displayed in the Analysis and Individual Flights modules, only
include complete records, and records for which accurate estimates are possible for
the few pieces of missing data. Metrics counts also exclude records from General
Aviation, Military flights and International flights missing data on the non-U.S.
portion of the flight.

The data relevant for the study proposed in this thesis is included in two mod-
ules of the ASPM database, the Taxi Times module and the Individual Flight mod-
ule. The first module, Taxi Times Module, contains data on actual and unimpeded
taxi times by airport. The second module, Individual Flight Module, provides in-
formation on aircraft departure and arrival times, as well as on flight delays for
individual flights compared to the schedule and flight plan times. The content of
both modules relevant for this study can be summarized in the following list:

- Scheduled and actual departure times.
- Scheduled and actual arrival times.
- Departure and arrival delay times.
- Origin and destination airports per flight.
- Flight number and tail number assigned.
- Diversion confirmations, avoids cancelled flights.
- Taxi-out and taxi-in times, and the unimpeded taxi times.
- Wheels-on time and wheels-off times.
- Gate-in and gate-out times.
- Season of the flight departure.

May one remark that the unimpeded times report of taxi times provides in-
formation on unimpeded Taxi Out and Taxi In times compared to the average,
median, and 10th percentile times for a selected airport or group of airports. These
Taxi In and Out Times are estimated times by airport and by carrier under optimal operating conditions (when congestion, weather, or other delay factors are not significant), and may serve as a theoretic reference for analysis.

### 1.2.3 Comparison between ASPM and BTS database

After analysing the content provided by both databases, one can conclude that the information provides is similar. The differences distinguished between the previously mentioned databases are summarized in the following table:

<table>
<thead>
<tr>
<th>BTS database</th>
<th>ASPM database</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Includes data for air carriers with ≥ 1% of total domestic service passenger revenues (20 carriers).</td>
<td>- Includes data for 30 air carriers.</td>
</tr>
<tr>
<td>- Includes data for operations of airports that account for ≥ 1% of total domestic service passenger enplanements (total of 32 airports).</td>
<td>- Includes data for 77 airports.</td>
</tr>
<tr>
<td>- Does not include international flights information.</td>
<td>- Does not include cancelled flights information.</td>
</tr>
<tr>
<td>- Does not include information of aircraft type.</td>
<td>- Includes international flights information.</td>
</tr>
<tr>
<td>- Contains tail and flight number of all flights.</td>
<td>- Includes information regarding aircraft type.</td>
</tr>
<tr>
<td></td>
<td>- Only provides the tail number for the flights that are also in BTS.</td>
</tr>
</tbody>
</table>

Figure 1.1: Comparison of BTS and ASPM databases content.

The database that has been selected as input for the crash schedule consequences analysis and the mathematical programming is the *Airline On-Time Performance Database* from the Bureau of Transportation Statistics (BTS), described in table 1.1 in the column 'BTS database'.

The information provided by this database is narrowed to the 20 major air carriers, as well as to the major national airports in terms of domestic operating service. Furthermore, it provides detailed information about diverted and cancelled flights, which was crucial for the research performed in this master thesis.
1.3 Master Thesis workflow

The following workflow scheme aims to clarify the structure and consistency of this research. The scheme displays the consecutive tasks that have been performed in order to ensure a coherent research flow:

![Figure 1.2: Master Thesis workflow scheme.](image)

1. ASIANA crash case study – Disaster Project (UC Berkeley – Georgia Tech)
2. Situation analysis in the Bay Area airports. Analysis time period: 6th July – 9th July
3. Disruption Costs - Major cost component for airlines
4. Rerouting costs - Critical in highly disruptive situations
5. QUESTION: Could the inter-modal substitution be a cost-effective solution in highly disruptive situations?
6. Analysis of current inter-modal operations in airline industry
   - Focus in passenger rerouting
   - Case-based model development: Asiana Crash case study
7. Develop mathematical programming to solve the most cost-effective rerouting given ASIANA crash disruption
8. 1st Model: Airport pairs optimization model
   - Linear-programming
   - Passenger-centric model
   - Rerouting on pairs: Diverted Airport – SFO
   - Matlab & Gurobi optimizer implementation
   - Sensitivity analysis
   - Results evaluation
9. 1st Approach: Whole network optimization model
   - Linear-programming
   - Flight-centric model
   - Rerouting of all flights at the same time

Figure 1.2: Master Thesis workflow scheme.
Chapter 2

Asiana Crash Consequences

2.1 Asiana Crash description

2.1.1 Crash factual Summary

On January 17th 2014, the City and County of San Francisco submitted the report on the Asiana accident investigation [3]. The accident investigation provides detailed information of the crash incidents as well as on the protocols of emergency response performed by the San Francisco Fire Department - Airport Bureau (SFFD-AB) and the San Francisco Police Department (SFPD), that were the parties involved in the handling of the accident.

The accident was registered to happen on Saturday July 6th 2013, at 11:27:48 Pacific daylight time, when the Boeing 777 registration HL7742, operated by Asiana Airlines as Flight 214, struck the seawall short of Runway 28L at SFO. The airplane was destroyed by impact forces and fire. The flight was a regularly scheduled passenger flight that originated in Shanghai Pudong International Airport, Shanghai (China), with a stop in Inchon International Airport, Seoul (Republic of Korea).

The aircraft impacted the approach end of Runway 28L and progressed into the level dry dirt infield between Runway 28L and Taxiway Foxtrot. The impact sequence severely damaged the tail assembly, or empennage, shearing it off the aircraft. The aircraft rotated counterclockwise approximately 330 degrees, creating a heavy cloud of dust and debris before crashing onto the infield or safety area approximately 2300 feet from the seawall. Aboard the aircraft were 307 individuals: 4 flight crew members, 12 cabin crewmembers and 291 passengers. The evacuation
started 90 seconds after the final impact, primarily out the back of the plane and by slides deployed at the forward two left doors. Three of the 291 passengers were fatally injured.

As it can be seen in the figure 2.1, both engines, reprinted from [4], the main landing gear and the tail section separated from the aircraft. The vertical and both horizontal stabilizers fell on the runway before the threshold. The remainder of the fuselage and wings rotated counter-clockwise and slid westward, stopping at the left side of the runway, 2,400 feet (730 m) from the initial point of impact at the seawall.

Due to emergency vehicles and cleaning tasks, runway 28L remained unavailable on the 6th of July, and stayed also closed for some hours on the 7th of July. Furthermore Runway 28R remained also closed for some hours during the 6th of July to ensure the correct removal of the accidented aircraft.

2.1.2 San Francisco International Airport

San Francisco International Airport (SFO) is an airport owned by the county of San Francisco. The airport is a department of the City and County but is located outside of San Francisco’s geographic boundaries. The airport is located in an unincorporated area of San Mateo County, approximately 13 miles south of downtown San Francisco. A five-member Airport Commission, appointed by the Mayor, oversees the operation and management of the Airport.

SFO is the largest airport in northern California. It has been the 7th busiest
airport by total passenger boardings in 2013, with 21,706,567 boardings and an average of 1,163 daily flight operations to and from locations all over the world (last recorded 2012). The distribution within air carrier operations is 89% domestic and 11% international.

As one can observe in the Federal Aviation Administration airport diagram of SFO, displayed in figure 2.2, San Francisco intl. airport is bounded by the San Francisco Bay to the north and east and by land to the west and south. It has two sets of parallel and intersecting runways: 1/19 parallel Left and Right and 10/28 parallel Left and Right. The approaches to runways 28 Left and Right are over water.

### 2.1.3 Alternative airports in the San Francisco Bay Area

A part from San Francisco International Airport, there are two additional international airports in the Bay Area: San Jose International Airport (SJC) and
Oakland International Airport (OAK). These two airports are recurrently used to absorb arrival diverted flights when a disruption occurs in SFO. The following section will introduce an overview of the main characteristics of the two airports.

As it can be observed in figure 2.3, OAK is located within 30 miles from SFO, and SJC is located within less than 50 miles from SFO. The short distances between the three major airports in the Bay Area make very feasible the inter-modal substitution at least within the Bay Area.

### 2.1.3.1 Oakland International Airport

Oakland International Airport is a public airport five miles south of downtown Oakland, in Alameda County, California. The airport has passenger service to destinations in the United States, as well as Mexico and Europe. Cargo flights fly to destinations in the United States, Canada and Japan. Furthermore, OAK is the closest airport to the San Francisco financial district.
Passengers at the airport peaked in 2007 at 14.6 million and declined to 9.3 million in 2011, from when it remains approximately steady. An advantage of OAK over SFO is OAK’s history of a high, on-time arrival percentage, despite many days of rainy and foggy weather in each city. In 2009 OAK had the highest on-time arrival percentage among the 40 busiest North American airports.

2.1.3.2 Mineta San Jose International Airport

Norman Y. Mineta San Jose International Airport is a city-owned public airport in San Jose, Santa Clara County, California. It is located two miles northwest of Downtown San Jose near the intersections of U.S. Route 101, Interstate 880, and State Route 87. Despite San Jose being the second largest city in the Bay Area, SJC is the smallest of the three Bay Area commercial airports in terms of passenger boarding. SJC served 8,783,319 passengers in 2013.

Regarding customer profile, SJC is a "downtown airport", unlike SFO and OAK which are on opposite shores of San Francisco Bay. SJC’s convenient location near downtown San Jose has also drawbacks; it is surrounded by the city and had little room for expansion. Like Oakland airport, SJC attracts Bay Area residents who find SFO flight times too unreliable.

2.2 Asiana crash impact on flight schedules

The historical time-series recorded for San Francisco International Airport was analysed in order to determine the "normal" conditions in SFO. In order to determine when the abnormality triggered by the Asiana crash could be considered finished, the historical time-series was analysed, in order to compare it to the schedule disruption of the week of the crash. After the analysis, it was concluded that the four day period starting on the 6th of July to the 9th of July 2013, was the disrupted period of study. After this time period, the disruption was considered to be mitigated.

2.2.1 Schedule impact overview

The aircraft crash triggered a severe capacity reduction at SFO and consequent delays and cancellations. The first step conducted was to analyse the distribution
of the flights that were scheduled to arrive to SFO or departure from SFO during the four-day period of study. The following figure shows the evolution of scheduled arrival flights to SFO on the 4-day period of study.

![Figure 2.4: Evolution of arrivals scheduled to SFO](image)

As previously mentioned, the Asiana crash disrupted the flight schedule at SFO, generating abnormal cancellations and diversions. One can observe how the day of the crash supposed a peak of abnormality in the operations at SFO, with a 41% of arrival flights cancelled and 16.9% of arrivals diverted. At the end of the period of study, the 9th of July, more stable indicator supported the idea of the disruption mitigation, with a 13.6% of arrival flights cancelled and a 2.6% of arrivals diverted. Nevertheless, it can also be seen how the trend is an increasing recovery from the 6th to 8th of July, and then another slight downfall on the 9th, with an increase of 47 flights cancelled. In order to analyse if this variation enters the normality margins, figures 2.5 and 2.6, reprinted from the article [5], presents the cancellations along the month of July 2013, in order to understand if any pattern exists.
One can observe how this additional variation has not been found to be directly attributable to one single factor. For the information analysed, there is no apparent variation attributable to the increase in cancellations the 9th of July, and furthermore, after this date the recovery continued smoothly to more normal
conditions. Therefore, apparently no direct conclusions can be extracted from the re-peak of cancellations in the 9th of July.

Moreover, the same analysis has been performed for departure flights, the results of which are presented in figure 2.7.

![Figure 2.7: Evolution of departures scheduled from SFO](image)

As for departures, the same situation occurs, starting from $52.5\%$ of departures cancelled finishing in a more reasonable $14.4\%$. The diversion of departure flights has a more constant trend, as a great part of the flights were cancelled. Having an overview of the distribution of cancelled and diverted flights during the four day period of study, the focus will now be the analysis of the passengers that perceived diversions, and how this diversions translated into delay times.

### 2.2.2 Diverted flights analysis

#### 2.2.2.1 Evolution of number of diversions

The following section will focus on analysing the disruption that diverted passengers perceived, in order to be able to determine later how a more efficient rerouting could positively impact the passengers. With that objective, an analysis of the diverted passengers from the 6th to 9th of July was conducted. Using the Federal Aviation Administration (FAA) registry, all the tail number of the diverted flights were tracked to determine the type of the aircraft assigned to each flight.
Then, using the Bureau of Transportation Statistics estimations for flight load factors, the number of passengers reaching the diverted airports was estimated.

Figure 2.8 shows the average load factors that have been used for estimating the flight loads, according to the FAA registry of flights arriving to San Francisco Intl. Airport in July 2013:

<table>
<thead>
<tr>
<th>Airline</th>
<th>Carrier code</th>
<th>Load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Airlines</td>
<td>AA</td>
<td>93.78%</td>
</tr>
<tr>
<td>Alaska Airlines</td>
<td>AS</td>
<td>87.71%</td>
</tr>
<tr>
<td>Jet Blue Airways</td>
<td>B6</td>
<td>89.15%</td>
</tr>
<tr>
<td>Delta Airlines</td>
<td>DL</td>
<td>89.98%</td>
</tr>
<tr>
<td>Frontier Airlines</td>
<td>F9</td>
<td>96.94%</td>
</tr>
<tr>
<td>Airtran Airways</td>
<td>FL</td>
<td>89.53%</td>
</tr>
<tr>
<td>SkyWest Airlines</td>
<td>OO</td>
<td>80.76%</td>
</tr>
<tr>
<td>United Airlines</td>
<td>UA</td>
<td>89.87%</td>
</tr>
<tr>
<td>US Airways</td>
<td>US</td>
<td>91.73%</td>
</tr>
<tr>
<td>Southwest Airlines</td>
<td>WN</td>
<td>82.12%</td>
</tr>
<tr>
<td>Virgin America</td>
<td>VX</td>
<td>81.73%</td>
</tr>
</tbody>
</table>

Figure 2.8: Load factors used for estimations

Once the load of all the diverted flights was estimated, the number of passengers diverted can be computed. Figure 2.9 shows the number of diverted passengers during the 4 day period of study separated by airports.
As one would expect the greatest part of the diversions was absorbed by Mineta San Jose International Airport (SJC) and Oakland International Airport (OAK), as both airports are the closest airports to SFO, located within less than 50 miles. After analysing the figures though, it can now be observed how Salt Lake City Intl. Airport (SLC), Sacramento Intl. Airport (SMF), Phoenix Sky Harbor International Airport (PHX) and Los Angeles Intl. Airport (LAX) also absorbed part of the diverted flights.

This figure thus support the idea of enlarging the Regional Airport System to include major alternative airports in the case of severe capacity restrictions in an Airport. The ferrying of Aircraft back to SFO is a costly operation, and an intermodal substitution in the rerouting may suppose a more cost-effective solution that airlines should take into account in such disruptive situations. Having now a look at the disrupted airlines in figure 2.10.
The previous analysis has permitted to compute the number of flights and passengers that were diverted due to the ASIANA crash. Nevertheless, in order to compute the delays that these passengers incurred, the flights should be classified in two groups:

- Flights that could reach their final destination (SFO).
- Flights that could not reach SFO.

Using the data provided by the FAA, the distinction can be made in order to analyse the flights separately. The logic behind the separation is that the flights that finally reached SFO will have substantially lower delay times than the flights that did not reach their original destination (SFO), and had to remain in the diverted airports. The few flights that were able to reach SFO can be considered a non highly disruptive situation flights, and therefore for these flights an intermodal substitution will be less cost-effective. Figures 2.11 and 2.12 show the number of diverted flights and diverted passengers separated in the two groups previously mentioned.

It can be observed in figure 2.11 how the number of flights that were not able to reach the final destination diminishes with the days, which denotes the process
of recovery till normal operations of SFO. On the day of the crash, only the 29% of the flights that were diverted were able to flight back to SFO.

Although on the Sunday 7th and Monday 8th of July SFO was not closed, the runway 28L where the crash occurred remained unavailable for a long time. One can observe how no diverted flights reached SFO during the 7th and 8th., so the decision was not to ferry back the diverted flights, but use the remaining capacity to accept some of the scheduled arrivals on the days. Finally, on the 9th of July, reaching fairly a stable situation, a 79% reached SFO. Now can be computed the delay that suffered this passengers that could reach SFO.

2.2.2 Delay times of diverted flights that reached SFO

As it can be seen in figure 2.11, there were only diverted flights that could finally reach SFO the 6th and the 9th of July. Consequently, it has been computed first the delay times of these diverted flights that could reach SFO.

Then, performing a quantitative analysis of the delays incurred during the 6th of July, the table 2.13 summarizes the computed delays. The average block delay
of these flights was 405 minutes in the 6th of July, while the weighted average computed is 426 minutes, meaning the flights with greater passenger load suffered more delays than the less loaded flights.

<table>
<thead>
<tr>
<th>Tail number</th>
<th>Sched. Dep.</th>
<th>Actual Dep.</th>
<th>Sched. Arrival</th>
<th>Actual Arrival</th>
<th>Total block delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>N33292</td>
<td>8:54</td>
<td>8:54</td>
<td>12:32</td>
<td>19:55</td>
<td>403</td>
</tr>
<tr>
<td>N846VA</td>
<td>9:35</td>
<td>9:21</td>
<td>12:35</td>
<td>18:01</td>
<td>380</td>
</tr>
<tr>
<td>N9215W</td>
<td>9:39</td>
<td>9:49</td>
<td>12:00</td>
<td>17:40</td>
<td>330</td>
</tr>
<tr>
<td>N528VA</td>
<td>10:00</td>
<td>9:57</td>
<td>12:45</td>
<td>18:33</td>
<td>391</td>
</tr>
<tr>
<td>N851VA</td>
<td>10:05</td>
<td>10:03</td>
<td>11:50</td>
<td>18:46</td>
<td>418</td>
</tr>
<tr>
<td>N7437</td>
<td>10:01</td>
<td>10:02</td>
<td>13:44</td>
<td>19:33</td>
<td>345</td>
</tr>
<tr>
<td>N2298W</td>
<td>10:19</td>
<td>10:20</td>
<td>11:55</td>
<td>19:45</td>
<td>469</td>
</tr>
<tr>
<td>N73806K</td>
<td>10:23</td>
<td>10:29</td>
<td>12:00</td>
<td>18:32</td>
<td>346</td>
</tr>
<tr>
<td>N962SW</td>
<td>9:51</td>
<td>10:40</td>
<td>12:00</td>
<td>18:41</td>
<td>312</td>
</tr>
<tr>
<td>N522VA</td>
<td>10:30</td>
<td>10:45</td>
<td>13:45</td>
<td>18:30</td>
<td>320</td>
</tr>
<tr>
<td>N130DL</td>
<td>10:55</td>
<td>10:52</td>
<td>13:05</td>
<td>9:21</td>
<td>1,178</td>
</tr>
<tr>
<td>N7395K</td>
<td>11:12</td>
<td>11:11</td>
<td>12:30</td>
<td>17:34</td>
<td>325</td>
</tr>
<tr>
<td>N4311UA</td>
<td>11:21</td>
<td>11:21</td>
<td>14:00</td>
<td>21:04</td>
<td>424</td>
</tr>
<tr>
<td>N701BR</td>
<td>11:30</td>
<td>11:27</td>
<td>12:22</td>
<td>19:34</td>
<td>405</td>
</tr>
<tr>
<td>N532NW</td>
<td>11:45</td>
<td>11:37</td>
<td>13:44</td>
<td>20:32</td>
<td>416</td>
</tr>
<tr>
<td>N37422</td>
<td>12:55</td>
<td>12:52</td>
<td>16:05</td>
<td>22:08</td>
<td>366</td>
</tr>
</tbody>
</table>

Figure 2.13: Analysis of delays the 6th of July

The same analysis was performed for the 9th of July. A detail of the quantitative analysis performed can be seen in table 2.14 where it can be observed how on the 9th of July the average block delay of these flights was 143 minutes, whilst the weighted average computed is 139 minutes, meaning smaller flights suffered a greater impact on their schedules.
Figure 2.14: Analysis of delays the 9th of July

After this quantitative delay analysis, the delay time values can be summarized in figure 2.15 for every day of the period of study, in order to be able to understand the evolution of the impact of the crash in the diverted passengers.

<table>
<thead>
<tr>
<th>Tail number</th>
<th>Sched. Dep.</th>
<th>Actual Dep.</th>
<th>Sched. Arrival</th>
<th>Actual Arrival</th>
<th>Total block delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>N851VA</td>
<td>0:50</td>
<td>1:06</td>
<td>6:25</td>
<td>9:05</td>
<td>144</td>
</tr>
<tr>
<td>N410SW</td>
<td>5:30</td>
<td>5:26</td>
<td>6:34</td>
<td>9:19</td>
<td>190</td>
</tr>
<tr>
<td>N7105K</td>
<td>5:35</td>
<td>5:31</td>
<td>6:36</td>
<td>9:14</td>
<td>199</td>
</tr>
<tr>
<td>N853UA</td>
<td>5:35</td>
<td>5:30</td>
<td>7:15</td>
<td>8:44</td>
<td>94</td>
</tr>
<tr>
<td>N5605W</td>
<td>6:00</td>
<td>5:56</td>
<td>7:19</td>
<td>9:13</td>
<td>160</td>
</tr>
<tr>
<td>N902WN</td>
<td>6:00</td>
<td>5:59</td>
<td>7:20</td>
<td>9:41</td>
<td>182</td>
</tr>
<tr>
<td>N7255K</td>
<td>6:00</td>
<td>6:00</td>
<td>7:27</td>
<td>9:38</td>
<td>131</td>
</tr>
<tr>
<td>N2928W</td>
<td>6:06</td>
<td>6:03</td>
<td>7:40</td>
<td>9:09</td>
<td>92</td>
</tr>
<tr>
<td>N4364A</td>
<td>6:06</td>
<td>6:08</td>
<td>7:51</td>
<td>10:05</td>
<td>172</td>
</tr>
<tr>
<td>N6377A</td>
<td>7:10</td>
<td>7:38</td>
<td>9:55</td>
<td>11:29</td>
<td>106</td>
</tr>
<tr>
<td>N5233B</td>
<td>16:30</td>
<td>18:03</td>
<td>19:59</td>
<td>23:15</td>
<td>103</td>
</tr>
</tbody>
</table>

Average [min] 143
Weighted Average [min] 139
Standard deviation 40

Figure 2.15: Delay minutes of the diverted flights that could reach SFO

The "Average" block delay has been calculated per flight, whilst the "Weighted average" block delay has been calculated per passenger, taking into account the different aircraft capacities and average load factors of the diverted flights.

Please note how there are no values for the 8th and 9th of July, as due to the disruption no diverted flights were able to arrive at SFO, therefore the delays on the 7th and 8th of July were even greater. Then, it can be observed how the impact grows until the 9th of July. The difference between the block delays is considerably high, as the block delay was reduced a 65%, confirming also the attenuation of the disruption. Finally, it can be concluded that, even though this diverted passengers represent the best scenario in terms of delay perception, the delays incurred were extremely high.
Chapter 3

Cost Evaluation

3.1 Introduction

Airlines invest a large amount of resources in order to develop efficient flight schedules for their fleets. A flight schedule consists of the originating city, departure time, destination, and arrival time for flights that the airline intends to serve. Due to the seasonality of passenger travel, these schedules are created every 2 to 3 months. The ordered sequence of flights to which an aircraft is assigned is called an aircraft route. A collection of aircraft routes that can be used to service scheduled flights is defined as an aircraft routing.

The great expense of purchasing and maintaining aircraft, pressures airlines to maximize their utilization by creating aircraft routings with as little embedded idle time as possible. Therefore, when schedule disruptions occur, the consequences are extremely costly for airlines.

Nevertheless, unplanned aircraft shortages and resulting flight schedule disruptions are an unavoidable occurrence in the daily operations of an airline. Aircraft are grounded or temporarily delayed when equipment failures make flying unsafe, when severe weather closes an airport, or when the required flight crews are unavailable. Real-time decisions must be made to minimize lost revenues, passenger inconvenience, and operational costs by reassigning available aircraft and canceling or delaying flights.

Furthermore, in extreme cases where severe weather closes airports in a region, or when airports are closed due to accidents and safety issue such as in
Asiana crash situation, aircraft are prohibited from taking off or landing at the affected airports. This results in massive flight cancellations whose effects propagate through the system causing missed connections and other disruptions at upstream and downstream airports.

For a typical airline, approximately 10% of its scheduled revenue flights are affected by irregularities, with a large percentage being caused by severe weather conditions and the associated loss of airport capacity. The New York Times published a study the 21th of January 1997, noting that the financial impact of irregularities on the daily operations of a single major US domestic carrier can exceed $ per annum in lost revenue, crew overtime pay, and passenger hospitality costs. Furthermore, in an article published in the Handbook of Airline Economics, it was stated that on average 0.1 - 0.2 % of a typical airline’s flights were interrupted due to maintenance problems. In addition, an equal average 0.1 - 0.2 % of that same airline’s flights will experience irregularities due to weather problems. In January 1996, it was estimated that a single snowstorm, the 'Blizzard of '96' costs the US airline industry between $50 - $100 million (Aviation Week, 1/15/1995).

It is a fact that airlines have to cope with reduced fleet size on a daily basis, as a result of aircraft breakdown, as well as other many external factors. Nevertheless, very little research has been done on the problem of addressing the impact of irregular operations, and developing potential decision support systems which could assist short term aircraft rescheduling. The impact of irregular airline operations on the daily activities of a carrier can lead to significant loss in profitability.

In this thesis, inter-modal substitution in the rerouting of diverted passengers is proposed as a measure of airline recovery operations after highly disruptive situations, with the objective to lower the impact of irregular operations in airlines’ image and profitability.

Thus, the following section will first assess which was the economic impact of Asiana crash during the crash weekend, in order to get a sense of the disruption’s dimension of the Asiana crash, and then it will introduce the previous research done in addressing the impact of irregular operations.
3.2 Methodology

If one may recall from the crash consequences section, the crash had direct consequences in the air traffic network, as the SFO runways were temporary closed. Incoming flights had to be diverted to other airports, and outgoing flights could not take-off. Such impact triggered severe costs of delays, diversions and cancellations, that perhaps could have been more efficiently handled.

In order to have a sense of how severe, in economic terms, the Asiana crash was, not only for Asiana Airlines but for San Francisco International Airport, a cost evaluation has been performed. The objective is to determine the dimension of the disruption costs, and to distinguish which are the major cost variables that take part in disruptions.

The first thing that must be addressed when starting a cost evaluation of the consequences of Asiana Crash at San Francisco International Airport, is to define which costs components will be taken into account. For the data available, it was decided to compute three main costs:

- Cost of delays
  - Arrival delay costs
  - Departure delay costs
- Cost of cancellations
  - Cancellation of arrivals to SFO
  - Cancellation of departures from SFO
- Cost of diversions
  - Diversion of arrivals to SFO
  - Diversion of departures from SFO

One must notice that the cost evaluation will be an underestimation, as the delay costs will be computed only from passengers point of view. Although there are no reference estimations of aircraft operating expenses, published by the Bureau of Transportation Statistics (BTS), it is difficult to assess to which extent a delayed departured flight is using an aircraft, therefore it has been substracted from the analysis.
3.3 Cost evaluation

3.3.1 Delay costs estimates

The cost of delay to airline operations comprises several components. These include the costs of passenger delay to the airline, plus crew and other additional expenses that airlines may absorb in order to ensure that their passengers perceive the least unpleasant delay. Also, primarily in the airborne phase, fuel costs need to be considered, and in the future, emissions charges. The total cost is often dominated by the passenger component.

This passenger delay cost component is described by Cook et al. [6] to be split into "hard" costs, such as those due to passenger rebooking compensation and care, and "soft" costs. Hard costs are typically difficult to define for a given flight due to accounting complexities, but are in theory, at least identifiable deficits in the airline’s bottom line. Soft costs manifest themselves in several ways. Even with no experience of an airline, a passenger may perceive it to be unpunctual and choose another, instead. Soft costs, exemplified by these types of revenue-loss, are rather more difficult to quantify, but may even dominate the hard costs.

As described previously, the "hard" cost component of passenger delay cost, is subjected to aviation passenger rights in cases of flight disruption, average travelling distances, or rerouting transportation alternatives, as well as other factors that influence the disruption cost impacts. These factors can considerably differ between the United States and Europe. For instance, US aviation passengers are less covered in case of disruptions, nevertheless average travel distances between US and EU main destinations also substantially differ. Furthermore, surface transportation alternatives in US are far less efficient, and airline policies have much aggressive client loyalty initiatives. As a result, airlines’ cost perceived as a result passenger delays notably vary in case of disruptions between US and EU.

Cook et al. (2009) in [6] propose an estimation for hard and soft aggregate costs in the European context. As a result of the European Union’s air passenger compensation and assistance scheme (Regulation (EC) NO. 261/2004) introduced on 17 February 2005, passengers in Europe are now afforded with additional rights in flight disruptive situation, such as denied boarding, cancellation or delays. This new regulation applies to any flight departing from the EU and to all flights operated by EU carriers from or to an EU airport. The resulting aggregate cost estimations are summarised in table 3.1.
3 – Cost Evaluation

Assuming a 'Base' cost estimate, it can now be concluded for the European context a total aggregated passenger delay cost of 0.36 € per minute.

Nevertheless, as it has been stated previously, passenger delay costs may considerably differ between EU and US. Having in mind that in the current Bureau of Transportation Statistics (BTS) database used to perform the optimization there are no international flights to which the European Union’s air passenger compensation and assistance scheme (Regulation (EC) NO. 261/2004) would apply, a US focused estimator of passenger delay costs will be assumed.

The United States Department of Transportation (DOT), that is the US government agency in North America devoted to transportation, proposes in [7] an approach to measure the hourly values of travel time for aviation passengers. These values are used by the Federal Aviation Administration (FAA), and are not to be updated for changes in price levels. Table 3.2 shows the recommended hourly values of travel time savings, proposed by the Department of Transportation (DOT) upon guidance furnished by the Office of the Secretary of Transportation of the United States of America (OST).

<table>
<thead>
<tr>
<th>Category</th>
<th>Recommendation</th>
<th>Sensitivity Range</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Carrier:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal</td>
<td>$23.30</td>
<td>$20.00</td>
<td>$30.00</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>$40.10</td>
<td>$32.10</td>
<td>$48.10</td>
<td></td>
</tr>
<tr>
<td>All Purposes</td>
<td>$28.60</td>
<td>$23.80</td>
<td>$35.60</td>
<td></td>
</tr>
<tr>
<td><strong>General Aviation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal</td>
<td>$31.50</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>$45.00</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>All Purposes</td>
<td>$37.20</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
</tbody>
</table>

As there is no specific data on the travel purpose of the diverted passengers,
3 – Cost Evaluation

it will be assumed that all the passengers in our study can be embraced by the category 'air carrier, all purposes'. Therefore, it can be concluded that the cost coefficient $CostP$ that will be used in the mathematical model, to represent the diverted passengers value of time, will be equal to US$ 28.60, or equivalently 0.48 US$ per minute.

### 3.3.2 Delay costs evaluation

#### 3.3.2.1 Delay costs of arrival flights to SFO

In order to compute the delay costs triggered by the Asiana Crash during the 4-day period of study, all the planes having delays during the crash weekend have been selected. Then, tracking the flight tale numbers in the FAA registry, the flights’ passenger capacity has been computed. Using the average load factors provided by the BTS, it has been estimated passenger load of all the flights. Finally, analysing their scheduled and actual arrival times in the BTS database mentioned in ref to introduction data, it has been computed the delay hours perceived by all the flights arriving at SFO.

The following table shows the average load factors that have been used to estimate the actual loads of the delayed flights:

<table>
<thead>
<tr>
<th>Average load factor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic flights</td>
<td>88.68%</td>
</tr>
<tr>
<td>International flights</td>
<td>91.66%</td>
</tr>
</tbody>
</table>

Figure 3.3: SFO arrival flights’ load factors in July 2013.

The load factors displayed in table 3.3 correspond only to US Carriers, as no international Carriers are recorded in the flight schedules’ database that has been analysed. Once the average load factors are defined, the total estimated delay hours can be computed. The results are displayed in the following table:

In order to compute the accurate economic impact of this delays, the 'Total Passenger delay hours' have been computed multiplying independently each flight delay per its passenger load. Table 3.4 shows the aggregated value of these
passenger delay hours for every day of study.

As it has been concluded in 3.3.1 the economic value of time decided to represent the passenger cost of delay is $28.60, as displayed in table 3.2. Finally, the arrival flight delay's cost can be computed by multiplying the passenger cost of delay per total passenger delay hours. As it has been previously stated, the flight delay hours will not be taken into account to compute the extra operational cost triggered by delaying the flights, as there are no accurate estimates regarding this matter currently. Thus, the total delay costs of arrival flights for the 4 day period of study are summarized in the following table 3.3.

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of flights</th>
<th>Capacity</th>
<th>Passenger load</th>
<th>Total flight delay hours</th>
<th>Total passenger delay hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>149</td>
<td>23.917</td>
<td>21.647</td>
<td>306</td>
<td>40.887</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>322</td>
<td>50.967</td>
<td>46.130</td>
<td>588</td>
<td>80.681</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>441</td>
<td>63.252</td>
<td>57.249</td>
<td>648</td>
<td>79.481</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>445</td>
<td>62.847</td>
<td>56.883</td>
<td>691</td>
<td>78.213</td>
</tr>
</tbody>
</table>

Figure 3.4: Arrival flight delay hours in the 4 day period of study.

<table>
<thead>
<tr>
<th>Day</th>
<th>Total passenger delay hours</th>
<th>Total delay costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>40.887</td>
<td>$1,169,368.20</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>80.681</td>
<td>$2,307,476.60</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>79.481</td>
<td>$2,273,156.60</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>78.213</td>
<td>$2,236,891.80</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$7,986,893.20</td>
</tr>
</tbody>
</table>

Figure 3.5: Arrival flight delay costs in the 4 day period of study.

One can observe from table 3.3 how the costs diminish during the 7th to 9th of July, the days after the Asiana Crash. This is due to the fact that during the crash day there were more cancellations than delays, and therefore there were greater cancellation costs. The overall cost of delays that can be allocated to the Asiana crash disruptions is close to the US$ 8 million.
3.3.2.2 Delay costs of departure flights to SFO

The same procedure has been performed to compute the delay cost of departure flights to SFO during the 4 day period of study. In the case of departure flights, the average load factor estimates that BTS provides are summarized in Table 3.6.

<table>
<thead>
<tr>
<th></th>
<th>Average load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic flights</td>
<td>86.66%</td>
</tr>
<tr>
<td>International flights</td>
<td>83.72%</td>
</tr>
</tbody>
</table>

Figure 3.6: SFO departure flights load factor estimates in July 2013.

Once the average load factors are defined, the total estimated delay hours can be computed. The results are displayed in Table 3.7.

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of flights</th>
<th>Capacity</th>
<th>Passenger load</th>
<th>Total flight delay hours</th>
<th>Total passenger delay hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>116</td>
<td>17.612</td>
<td>14.900</td>
<td>195</td>
<td>33.302</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>326</td>
<td>52.604</td>
<td>44.503</td>
<td>468</td>
<td>72.762</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>389</td>
<td>56.218</td>
<td>47.560</td>
<td>401</td>
<td>46.682</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>374</td>
<td>55.961</td>
<td>47.343</td>
<td>384</td>
<td>44.957</td>
</tr>
</tbody>
</table>

Figure 3.7: Departure flight delay hours in the 4 day period of study.

Analogously to section 3.3.2.1, it can be computed the departure flights’ delay costs by multiplying the passenger cost of delay per total passenger delay hours. Thus, the total delay costs of departure flights for the 4 day period of study are:

<table>
<thead>
<tr>
<th>Day</th>
<th>Total passenger delay hours</th>
<th>Total delay costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>33.302</td>
<td>$952,437,20</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>72.762</td>
<td>$2,080,993,20</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>46.682</td>
<td>$1,335,105,20</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>44.957</td>
<td>$1,285,770,20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$5,654,305,80</td>
</tr>
</tbody>
</table>

Figure 3.8: Departure flight delay costs in the 4 day period of study.
3.3.2.3 Summary of delay costs

After computing separately the cost of arrival flights’ delays and departure flights’ delays, one can now conclude that the total costs of delays triggered by Asiana crash disruption are:

\[
\text{Total cost of delays} = $13.64 \text{ Million}
\]  \hspace{1cm} (3.1)

3.3.3 Cancellation costs evaluation

3.3.3.1 Cancellation costs estimates

Flight cancellations are costly to both airlines and air passengers, and although many attempts have been made to try to empirically value the cost of a flight cancellation, there is still few published literature that quantifies this value. This study will assess the cost of cancellation from Airlines and Passengers point of view. Both cost components will be then aggregated to compute a total cost of cancellations.

Regarding the Airlines point of view, Banavar Sridar, stated in his presentation at the National Center of Excellence for Aviation Operations Research Conference in 2007 [8], that one cancellation is equivalent to between 200 and 300 minutes of delay in terms of cost. Furthermore, Hansen et al. stated in [9] how Metron Aviation in 2006 (Metron Project Report, unpublished) assigned $6,000 per flight as the cost of flight cancellation in an unpublished report. Finally, Hansen et al. compute in [9] a cost of cancellation to be worth $4,977, assuming the cost of ground delays to be $30 dollars.

As there is no empirical basis of which approach is more correct, this study will assume that the value reported by Merton serves as an upper bound for the cancellation cost value, whilst the value proposed by Hansen et al. will serve as a lower bound. Therefore, the cancellation cost value from airlines point of view will be considered to be of $5488.50 per flight.

In the case of passengers point of view, and according to Sridar estimation, it will be assumed that each flight cancellation impacts in between 200 to 300 minutes of delay. For the following calculations, it will be assumed that every cancelled flight is comparable to 250 delay minutes, and the passenger value of time will be used to compute the total passenger cancellation costs.
3.3.3.2 Cancellation costs of arrival flights to SFO

**Airline cancellation costs:** In section 3.3.3.1 it has been concluded how the cancellation cost value from airlines point of view will be considered to be of $5488.50 per flight. According to this estimation, the following figure shows the calculation of the airline cancellation costs, taking into account all the cancelled flights during the 4 day period of study.

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of Cancelled arrivals</th>
<th>Cost of Cancelled arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>180</td>
<td>$987,950.00</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>155</td>
<td>$850,717.50</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>43</td>
<td>$236,005.50</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>70</td>
<td>$384,195.00</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$2,458,848.00</td>
</tr>
</tbody>
</table>

Figure 3.9: Arrival flight cancellation costs in the 4 day period of study.

**Passenger cancellation costs:** In the case of the passenger cancellation cost component, in section 3.3.3.1 it has been concluded how the cancellation cost value from passengers point of view will be considered to be equivalent to 250 delay minutes. Having in mind that the passenger value of time has been estimated to be $28.6, the total passenger cancellation costs can be computed. The following figure shows the calculation of the passenger cancellation costs, taking into account all the cancelled flights during the 4 day period of study:

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of Cancelled arrivals</th>
<th>Passenger load</th>
<th>Equivalent delay hours</th>
<th>Mean number of passengers per flight</th>
<th>Passengers' point cost of cancellations</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>180</td>
<td>15.459</td>
<td>750</td>
<td>86</td>
<td>$1,844,700.00</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>155</td>
<td>12.642</td>
<td>646</td>
<td>82</td>
<td>$1,514,999.20</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>43</td>
<td>3.677</td>
<td>179</td>
<td>86</td>
<td>$440,268.40</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>70</td>
<td>4.584</td>
<td>292</td>
<td>65</td>
<td>$542,828.00</td>
</tr>
<tr>
<td>Total</td>
<td>448</td>
<td>36.362</td>
<td>1,867</td>
<td>319</td>
<td>$4,342,795.60</td>
</tr>
</tbody>
</table>

Figure 3.10: Arrival flight passenger cancellation costs in the 4 day period of study.

Once both cancellation cost components have been computed for the arrival cancelled flights, the total arrival cancellation costs can be computed by aggregating both cost components:
Total cost of arrival cancellations = $ 6,80 Million (3.2)

3.3.3.3 Cancellation costs of departure flights from SFO

Airline cancellation costs: Analogously to the calculation for arrival flights, in this section the cancellation cost value from airlines point of view will be considered to be of $ 5488.50 per flight. According to this estimation, the following figure shows the calculation of the airline cancellation costs, taking into account all the cancelled departure flights during the 4 day period of study.

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of Cancelled departures</th>
<th>Cost of Cancelled departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>231</td>
<td>$1,267,843.50</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>174</td>
<td>$954,999.00</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>62</td>
<td>$340,287.00</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>74</td>
<td>$406,149.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>$2,969,278.50</td>
</tr>
</tbody>
</table>

Figure 3.11: Departure flight cancellation costs in the 4 day period of study.

Passenger cancellation costs: In the case of the passenger cancellation cost component, in section 3.3.3.1 it has been concluded how the cancellation cost value from passengers point of view will be considered to be equivalent to 250 delay minutes. Having in mind that the passenger value of time has been estimated to be $ 28.6, the total passenger cancellation costs can be computed. Figure 3.12 shows the calculation of the passenger cancellation costs:

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of Cancelled arrivals</th>
<th>Passenger load</th>
<th>Equivalent delay hours</th>
<th>Mean number of passengers per flight</th>
<th>Passengers’ point cost of cancellations</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>231</td>
<td>20.194</td>
<td>963</td>
<td>87</td>
<td>$2,396,136.60</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>174</td>
<td>14.632</td>
<td>725</td>
<td>84</td>
<td>$1,741,740.00</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>62</td>
<td>4.715</td>
<td>258</td>
<td>76</td>
<td>$560,788.80</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>74</td>
<td>4.712</td>
<td>308</td>
<td>64</td>
<td>$563,763.20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>541</td>
<td>44.253</td>
<td>2,254</td>
<td>311</td>
<td>$5,262,428.60</td>
</tr>
</tbody>
</table>

Figure 3.12: Departure flight passenger cancellation costs in the 4 day period of study.
Once both cancellation cost components have been computed for the arrival cancelled flights, the total arrival cancellation costs can be computed by aggregating both cost components:

\[
\text{Total cost of departure cancellations} = \$8.23 \text{ Million} \quad (3.3)
\]

### 3.3.3.4 Summary of cancellation costs

After computing separately the cost of arrival flight and departure flight cancellations, it can now be concluded that the total costs of cancellations triggered by Asiana crash disruption are:

\[
\text{Total cost of cancellations} = \$15.03 \text{ Million} \quad (3.4)
\]

### 3.3.4 Diversion costs evaluation

Flight diversions are a common and expensive disruptive element of flight operations, costing at least 300 Million $ of dollars annually for US carriers for domestic flights alone. The cost of diversions though can considerably differs depending on the point in which the flight is in his journey. Jenkins & Cotton state in [10] how diversion costs can range from $15,000 for a narrow-body domestic flight, to over $100,000 for a wide-body international flight.

Depending on the position in the scheduled route of the flight, the aircraft might be severely overweighted for landing, due to a too high fuel load, or it may have been flying for too long and at the point of the diverted landing must be replaced or inspected, or what’s more the crew extra-hours force them to be replaced or to overnight in a hotel, due to FAA crew schedule legislations. For instance, a single passenger unstable behaviour forced a Qantas flight to be diverted in 2012, costing the airline $120,000, as the aircraft had to dump 60,000 litres of fuel before being able to land filled up with 350 passengers, as informed by the the Australian Federal Police.

Furthermore, high-end airlines may want to make this unpleasant situation for their passengers the least disruptive, by issuing free meal vouchers and overnights at closer hotels, so that passengers can wait to be rebooked comfortably. For instance, after the Asiana crash some airlines like Delta or United Airlines offered such amenities. For instance, the News10 from ABC featured the 6th of July [11]
an article stating how Delta and United Airlines Delta Airlines arranged taxi and shuttle services for passengers to get to San Francisco after their planes were forced to land in Sacramento. Quoting from the article, "They’re paying for everything - Delta is. For everybody on our flight, so they’re taking care of us," said Delta passenger Shawn Scott, who was flying from Atlanta to SFO on a family vacation."

An unpleasant diversion journey may trigger severe irritations within the airline customers, damaging their punctuality and customer relationship image. Therefore, airlines may implement measures to reduce this perceived insatisfaction, and thus increasing considerably the amount allocated to reroute their passengers.

### 3.3.4.1 Diversion costs of arrival flights

If one recalls from chapter 2, there were a total of 119 diverted flights from the 6th to 9th of July 2013, from which a 38% could not reach their final destination SFO. Figure 3.13 summarizes the diverted flights distribution during the 4-day period of study:

<table>
<thead>
<tr>
<th>Reached final destination SFO</th>
<th>Could not reach final destination SFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>All airports</td>
<td>SJC or OAK</td>
</tr>
<tr>
<td>06/07/2013</td>
<td>21</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>0</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>0</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>0</td>
</tr>
<tr>
<td>Total flights</td>
<td>21</td>
</tr>
</tbody>
</table>

Figure 3.13: Number of diverted flights during the 4 day period of study.

In order to do a more accurate estimation of the cost evaluation of the ASIANA crash, two cost components should be distinguished: Airline cost component and the Passengers cost component.

**Airline cost component:**

Concerning the ASIANA crash cost evaluation, within this study it was decided to assume an average of $25,000 per diverted flight that could not reach their final destination (SFO). Furthermore, diverted flights reaching the alternatively the Bay Area (SJC or OAK), will be assumed to have an operational cost negligible. The same cost value has been given to the flights that were diverted to alternative
airports, but could reach SFO, as the delays triggered have been already taken into account in the delays cost evaluation.

One can now compute the total costs of these diverted flights according to the diverted flight distribution shown in 3.13. Table 3.14 shows the computed results:

<table>
<thead>
<tr>
<th>Reached final destination SFO</th>
<th>Could not reach final destination SFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>All airports</td>
<td>SJC or OAK</td>
</tr>
<tr>
<td>Total flights</td>
<td>21</td>
</tr>
<tr>
<td>Total cost</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3.14: Cost of the diverted flights during the 4 day period of study.

Therefore, one can conclude how the total cost of arrival flights from the Aircraft point of view is $600,000 dollars.

**Passengers cost component:**

Following the distinction made in figure 3.14 separating the diverted flights that finally reached SFO from those who couldn’t, it will be assessed first the diversion cost of the passengers that could finally reach SFO. These passengers, although they were diverted, they could reach SFO with the same flight, therefore they only perceived delays. The diversion cost for these first type of passengers has been computed tracking their flight delays and multiplying per the estimated load of the flight.

\[
Cost \ of \ diversions = \sum_f Flight_{Delay_f} \times Estimated\_Flight\_Load_f =
\]
\[
= 32.146 \text{ (hours)} \cdot 28.6 \text{ ($/\text{hour})} = $ 919.376
\]

(3.5)

In the case of the cost of passengers who could not reach SFO within the same flight, it was decided within the research project to draw three hypothesis, in order to be able to estimate the total cost of diversions:

- The 100% of the diverted passengers are assumed to have SFO as final destination, even if OAK or SJC are closer airports to their end-of-journey destination.
The passengers are rerouted back to SFO with surface means of transport. It was assumed within the research project an average speed of 1 mile per minute for surface means of transport.

The passengers diverted to airports within more than 400 miles of driving distance to SFO will not be rerouted by surface means of transport, thus these diverted flights will be estimated as cancelled flights in terms of cost.

The flight distances between SFO and the airports that absorbed diversions on the 4 day period of study have been computed, in order to distinguish which assumption apply to every diversion case. First, table 3.15 shows the diverted airports within less than 400 miles driving distance to SFO.

<table>
<thead>
<tr>
<th>Diverted airport</th>
<th>OAK</th>
<th>SJC</th>
<th>SMF</th>
<th>FAT</th>
<th>LAX</th>
<th>RNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diverted flights</td>
<td>32</td>
<td>24</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total div. passengers</td>
<td>4,815</td>
<td>3,976</td>
<td>1,132</td>
<td>167</td>
<td>760</td>
<td>455</td>
</tr>
<tr>
<td>Flight distance* (miles)</td>
<td>11</td>
<td>30</td>
<td>86</td>
<td>158</td>
<td>338</td>
<td>192</td>
</tr>
<tr>
<td>Driving distance* (miles)</td>
<td>31</td>
<td>34</td>
<td>103</td>
<td>198</td>
<td>391</td>
<td>235</td>
</tr>
</tbody>
</table>

*Travel distances extracted from www.travelmath.com

Figure 3.15: Diverted airports within less than 400 miles from SFO.

All the diverted airports in table 3.15 are located within less than 400 miles driving distance from SFO, thus a rerouting through surface means of transport would be feasible. In this case, the total cost of diversion has been computed as the total travel time of the diverted passengers multiplied per the passenger value of time. The results are as summarized in table 3.16.

<table>
<thead>
<tr>
<th>Diverted airport</th>
<th>OAK</th>
<th>SJC</th>
<th>SMF</th>
<th>FAT</th>
<th>LAX</th>
<th>RNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total div. passengers</td>
<td>4,815</td>
<td>3,976</td>
<td>1,132</td>
<td>167</td>
<td>760</td>
<td>455</td>
</tr>
<tr>
<td>Total rerouting hours</td>
<td>0.52</td>
<td>0.57</td>
<td>1.72</td>
<td>3.30</td>
<td>6.52</td>
<td>3.92</td>
</tr>
<tr>
<td>Total diversion cost</td>
<td>$71,150</td>
<td>$64,438</td>
<td>$55,577</td>
<td>$15,761</td>
<td>$141,646</td>
<td>$50,968</td>
</tr>
</tbody>
</table>

Figure 3.16: Cost of diversion for airports located within less than 400 miles from SFO.

The second grouping of airports includes the diverted airports located within more than 400 miles from SFO. In this case, the diversion costs, as explained
previously in the assumptions, will be considered to be equiparable to a cancelled flight. Therefore, as seen in section 3.3.3.3, these flights will have the cost of $5.489 per flight. Table 3.17 shows the total costs of this second group of diverted flights:

<table>
<thead>
<tr>
<th>Diverted airport</th>
<th>LAS</th>
<th>PHX</th>
<th>DEN</th>
<th>MSP</th>
<th>HNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diverted flights</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total div. passengers</td>
<td>926</td>
<td>55</td>
<td>340</td>
<td>182</td>
<td>151</td>
</tr>
<tr>
<td>Flight distance* (miles)</td>
<td>414</td>
<td>651</td>
<td>967</td>
<td>1.598</td>
<td>2.398</td>
</tr>
<tr>
<td>Driving distance* (miles)</td>
<td>568</td>
<td>759</td>
<td>1.286</td>
<td>2.051</td>
<td>n/a</td>
</tr>
<tr>
<td>Total diversion cost</td>
<td>$21,956</td>
<td>$5,489</td>
<td>$10,978</td>
<td>$5,489</td>
<td>$5,489</td>
</tr>
</tbody>
</table>

*Travel distances extracted from www.travelmath.com

Figure 3.17: Diverted airports within more than 400 miles from SFO.

Now, the total diversion costs can be computed as the sum of the passenger and aircraft cost components:

\[
\text{Total cost of arrival diverted flights} = \$1,368,317
\]

(3.6)

3.3.4.2 Diversion costs of departure flights

During the 4 day period of study, 44 flights that departed from SFO were diverted to other airports. In this case, as the destination of the diverted flights is not the truly disrupted airport, it is difficult to assess to which extent the flights were diverted due to Asiana crash impact on their operational performance, or if otherwise was result of another external factors. Thus, as it is not accurate to allocate this cost to Asiana crash, they will not be computed as part of the cost impact of the crash. Furthermore, all the 44 flights were able to reach their final destination within the same day, and thus their cost has been included only as delay costs.

3.4 Cost evaluation summary

The total cost of Asiana Crash disruption in the network can be now computed as the sum of the total Cost of Delays, the total Cost of Cancellations and finally
the total Cost of Diversions. The following figure summarizes these three values, in order to have a sense of the dimension of each cost component in relation to the others.

![Figure 3.18: Summary of cost evaluation.](image)

The computation performed in 3.3 has shown how the cost of delays accounted for a 45% of the total cost, the cost of cancellations accounted for a 50%, and the diverted flights accounted for a 5% of the disruption costs. This is due to the fact that most of the flights were cancelled instead of diverted or delayed on the ground. The accident happened on a Saturday, and as the airline officers expressed, the flights were highly booked, making the reaccommodation of passengers difficult.

Furthermore, the evaluation performed is an underestimation of the real costs that airlines and passengers perceived, as it is based on BTS data base schedules, where no international flights are included. Additionally, the diversions costs have been computed without taking into account the reaccommodation costs that the airlines had to unexpectedly face, and that are very difficult to track. Nevertheless, the figures already gives us a reasonable estimate of how the closing of the SFO runways for long hours triggered costly consequences for the airlines operating in SFO.
Chapter 4

Research motivation: Inter-modal rerouting of diverted passengers

There is many research performed in flight delay management, or optimisation of aircraft and crew schedulings, but few research has been on passenger-centric recovery from highly disruptive situations. Until great disruption events as the Eyjafjallajökull volcanic eruption in 2010, the low frequency of highly disruptive situations supported the fact that few researchers focused in the efficient handling of these situations. Nevertheless, as the airlines’ trend is to optimise the flight schedules to leave the minimum idle time possible, when such huge disruptions occur, airlines are surpassed, resources are inefficiently allocated, and the impact of the disruption snowballs becoming very costly for airlines.

This master thesis research started with the analysis of Asiana Crash impact on schedules, as well as an economic estimation of the costs triggered by the crash. As explained in Chapter 2, 9,770 passengers were diverted the 6th of July, 4,260 on the 7th and approximately 1,470 on the 8th and 9th of July. Only a 21% of these passengers could reach their final destination SFO with the same flight. These are large numbers, but could have been greater if airlines hadn’t cancelled the major part of scheduled departure flights. After digging how the crisis was handled, the news showed how the disruption left most of the diverted passengers unattended and uninformed, waiting for the airline representatives to figure out how to reaccommodate them urgently. Twitter quickly started to be the most updated channel of information for passengers:

As seen previously, most of the flights were diverted to either SJC, OAK, or to the closest hubs to SFO (SEA, LAX, PHX). The problem arised when flights
started to be forced to land in airports in which they don’t operate. That was the case of a United Airlines flight from Seattle, that ended being diverted in Oakland. Willit News [12] interviewed the 6th of July 2013 some of these passengers: "We were dumped here," the man said. "United has no support here. They sent a dislocation team, but basically what they keep saying is: "You’re dislocated." The officials said they had to bring extra staff to accommodate all those passengers that were landing at the same time.

Additionally, some passengers were diverted to airports where their airline operates at low frequency. For instance, at the Virgin America counter of Seattle Tacoma International Airport on the 6th of July, Seattle Times [13] describes how customer-service representative Jody Devereaux collected traveler names and phone numbers so the airline could rebook or cancel flights without the people standing line. "Just to cause them less stress," Devereaux said. She advised travelers that the quickest option to get home would be to rebook through another carrier and obtain a refund, as "the soonest flights on Virgin America will be Monday or Tuesday". Although being notified that waiting times could reach the two days, passengers argued they had no extra money to purchase new flights and be refunded later, causing them a lot of stress. Seattle Times reported the 6th of July [3], "We don’t really have $500 to buy another ticket and wait for a refund" the couple said, as they were flying to Dulles International Airport on their way home.
CBS news [14] published how in Sacramento, although being less than 100 miles from SFO, the people waited for hours uninformed, queueing around help desks waiting for airline representatives to inform about the rerouting options. CBS News reported the witness of a couple, "We were not even aware of what had happened until someone on the flight was able to turn on the cell phone.", and how they also said "Our carrier had no information whatsoever. Basically we were booted off the plane and with no direction whatsoever." Such witnesses support the fact that airlines had no systematic rerouting scheme for such disruptive situation.

Furthermore, ABC Eyewitness News [15] informed about the situation in LAX, explaining that, as Asiana Crash happened on a Saturday, the Airlines were fully booked, and thus the rerouting of passengers was impossible. "Sunday’s flights between LAX and SFO are heavily booked due to the combination of holiday weekend and peak summer travel. It is expected the airlines will need one or two days to catch up on the backlog of canceled flights.", adding also that "The route between LAX and SFO is very busy, served by seven airlines including American, Delta, United, United Express, Virgin, US Airways and Southwest. But Saturday night’s cancellations are making a big disruption for travelers on this holiday weekend. Some travelers will spend the night in L.A."

The few information that airlines delivered, added to the highly booked situation at the diverted airports, made the passengers perceive a very stressful and irritating situation. The chaotic situation that the shutdown of the two main SFO runways triggered, made the schedules collapse around SFO, and the cancellations were increasing. At that point, some airlines decided to implement first inter-modal operational measures, placing buses and taxis to reroute their passengers, but they did so in an ineffective and non-collaborative way between ground and air networks.

For instance, ABC Eyewitness News reported some inter-modal rerouting measures that some airlines took for LAX diverted passengers. Quoting from [15], 'Airlines that canceled flights between LAX and SFO are making arrangements for passengers, including rebooking flights, adding special flights if aircraft are available, bussing passengers to SFO, putting up passengers in airport-area hotels and asking passengers to return to LAX on Sunday.' Additionally, they explained
how although the inter-modal rerouting saved passengers from spending the night in the diverted airports, many of them were disappointed for the disorganized and discentralized way in which they were assigned to the modes.

Therefore, after analysing how airlines started to implement first insights of inter-modalism in the rerouting of diverted passengers, the scope of the research was narrowed to try to develop a cost-effective model that may serve as first start for a decision-making support tool to determine the inter-modal rerouting passengers. The work presented in this master thesis explains the state of the art in inter-modal operations in the airline industry, analyses the operational issues of inter-modal rerouting, and offers two mathematical models to optimise the cost of reroutings in a passenger-centric way. The first model is an airport-pairs optimisation model, and has been implemented on a real set of data corresonding to the Asiana Crash period of study. The second optimisation model, attached in the Annex, expands the first model to a whole network level. Its implementation has not been performed, reason why it has been proposed as a possible path for further research in this topic.
Chapter 5

Operational issues in airlines inter-modal operations

5.1 Introduction

In order to correctly implement inter-modal strategies for the rerouting of passengers as proposed in this study, several fundamental issues need to be considered. The goals of this chapter are to identify these issues, assess their importance, determine the difficulties that might arise, and suggest solutions based on preliminary investigation.

In the current Asiana Crash case study, two possible inter-modal implementations have been taken into account for the rerouting of diverted passengers.

- **Approach I: Partial inter-modal substitution.** The substitution of modes is applied when the diverted passengers land in the alternative airports in the Bay Area, where they do a short commute to travel to SFO by surface means of transport.

- **Approach II: Complete inter-modal substitution.** The substitution is executed straight from the diverted airport. The diverted passengers are transported back to SFO by surface means of transport.

The chapter will first analyse the state of the art in inter-modal transportation in the airline industry, then explain the results obtained in a survey to SFO customers about their modes of transportation, followed by an analysis of the Approach I and Approach II implementations at SFO, and finally the assessment of further operational issues in inter-modal substitution.
5.2 Previous literature in integration of multi-modal operations in the airline industry

The Eyjafjallajokull volcanic eruption in 2010 had such an impact on aviation that it also had a series of knock-on effects on other modes of transportation. These can be explained by the rigidity and complex nature of transport networks, as well as by the lack of appropriate preparation. Since then, academia has started to realize the importance of the integration within transportation modes, in order to be able to absorb the permanently increasing demand in the airline industry. For instance, the partial substitution of some short-haul flights with High Speed Rail transport, either through modal competition or complementarity, is already in place in four European hubs (Frankfurt Main, Paris CDG, Madrid Barajas, Amsterdam Schipol).

Intermodality must be understood in the work proposed here, as the use of several transport modes in one trip when the transport modes are coordinated thanks to an adequate intermodal infrastructure, and intermodal agreements concluded by transport operators. Marzuoli et al. [16] particularizes how at an airport level, it can be distinguished two different types of intermodality:

- **Airport Access Intermodality**: when the use of the land transport (bus, tramway, train, etc.) aims at linking the airport to the city center, usually a short commute.

- **Network Integration Intermodality**: when the use of the land transport is in the scope of the airport integration in the regional or national network of the landside transport modes (High-Speed train, etc.). Related to including the airport in a multimodal network linking to centers.

Airport Access Intermodality is widely implemented nowadays, as most of the airports have put efforts to integrate rail transportation and shuttle bus services to efficiently connect airports with the city centers. These measures have helped to reduce congestion in roads close to the airports, as a result of the permanently increasing air transportation demand, and have enabled to smoothly link airports to the real final destination of the passengers. Nevertheless, the problem of Network Integration Intermodality has started to be tackled recently, as it is difficult for the airline industry to clearly understand the benefits of integrating competitor modes of transport to its network.
In order to try to understand how airlines may react to a change in demand towards surface means of transport, Janic [17] shows that High Speed Rail substitutive capacity does not act as a barrier to developing air/rail substitutions at the airport. Furthermore, he states how a modest substitution may produce substantial savings in airline costs and passenger delays. Furthermore, Steel et al. [18] pose the problem of predicting the changes in passenger demand between different modes of transports during a disturbance of one or more of its systems. Their research develops a simplified dual-mode UK transport model using system dynamics and recent data, to test responses to disturbances.

Few research has been performed to try determine a feasible and efficient integration of ground and air transportation. For instance, Zhang et al. [19] build a supernetwork, where the networks for different modalities are integrated. They distinguish road, rail, air, water transportation as well as private (e.g. foot, bike, car) or public modes (e.g. bus, train, tram, metro). The authors tested their tool for the Eindhoven region with success. Furthermore, Hsu [20] develops a simple model to represent the transfer waiting time for a connecting service at multimodal stations, where waiting time takes into account the characteristics of both the connecting service and its feeder service. The Results show that transfer waiting times is mostly affected by the capacities and headways of the connecting and feeder services.

Finally, Zhang [21] performed a thorough research to assess the effectiveness of integrating surface modes of transport to connect spokes to hubs in a Hub-and-Spoke network. Zhang interviewed with representatives at United Airlines and American Airlines, to analyse when did these airlines find optimal to apply inter-modal strategies. She found for instance, how in Chicago O’Hare (ORD), if flights with destinations close to ORD were cancelled, passengers would be re-accommodated on buses to avoid staying at the terminal overnight, or even longer when snowstorms are sever at ORD. The direct cost of hiring buses, as estimated by the customer relation division, is equivalent to the cost of providing discount vouchers for hotel accommodations and reassigning passengers on later flights, and additionally saves passengers from an unpleasant enlargement of their trip. Furthermore, at UA’s LAX hub, when thunderstorms lead to cancellations of flights out of the airport, the station occasionally hires buses to transport passengers to San Diego (SAN), two hours from LAX. As in the case of ORD, buses are used so that passengers do not have to stay at the terminal overnight.

Additonally, Zhang reports how American Airlines (AA) implemented in March 2007 inter-modal reroutings, due to a sever thunderstorm passing through Dallas
Fort Worth International Airport (DFW). Because of the cancellation, there would be no protected space for several days and buses became the best option. AA set up pseudo flight numbers for the buses and the passengers were booked according to first-landing-in-first-out. As a result of the experience, they intend to make it a more formal part of the off-schedule operations (OSO) planning package with detailed procedures on how to handle similar situations.

It is reasonable to decide to use buses in highly disruptive situations, nevertheless, airlines are performing reactively in these cases, without a systematic way to integrate airfield and ground operations. The mathematical programming proposed here aims to offer an optimization modal that may serve as a future tool to ensure a cost-efficient network integration of inter-modal operations in the rerouting of diverted passengers, after highly disruptive situations.

5.3 Customer survey on transportation modes at SFO

5.3.1 Modes of transportation to SFO

To assess the mode of transport that best fits the travelers expectatives, and thus that would impact the least in their delay perception, two surveys that were done to SFO passengers in the year 2009 and 2011 have been analysed. The surveys asked for the mode of transport with which they had arrived to SFO. It will be assumed that the passengers who arrived at SFO use the same modes of transport as those who fly from SFO. Therefore, the survey results will help to disentangle which surface modes of transports are more commonly used within SFO customers.

In the following table, reprinted from one of the reports of A. Ucko at the Institute of Transportation Studies of UC Berkeley, it is summarized the modes of transport used by the passengers interviewed.

Please have in mind that there were differences in the survey response options between 2009 and 2011, and although in some cases the responses do not match the same modes, the survey it is still a useful indicator of how the SFO customers are used to arrive or leave the airport.

As one can observe, the highest percentage (26%) corresponds to passengers
that were dropped off at SFO. Only around a 8.5% of the passengers, both in 2009 and 2011, used Bay Area Rapid Transport (BART) as mode of transport to reach SFO. Very few passengers, only a 0.08% of the passengers use another public transit other than Bay Area Rapid Transport (BART). Finally, a total of approximately 16% use either door-to-door van services, private scheduled bus or free hotel shuttle. That means, a 16% of the SFO customers are used to involve a motor coach transport as part of their journeys when they fly from or to SFO. Additionally, it is also interesting to see how only an average of 20% of the interviewed passengers were connecting passengers.

From these two surveys one can infer three main conclusions:

- The most used mode of transport are private cars.
- The preferred public surface mode of transport is Bay Area Rapid Transport (BART) service.
- Private motor coaches or shuttle bus are also highly used by SFO passengers to reach the airport.

Therefore, it can be concluded how the use of private motor-coaches or train vouchures will impact in a low extent the customers travel routines, and therefore are suitable modes of transport to be assessed in the inter-modal rerouting proposed in this study.
5.3.2 Final destination of SFO arrival passengers

One of the important things that one has to assess when diverting flights to the Bay Area, is how many of the diverted passengers must actually go to SFO. SFO is the greatest hub in the Bay Area, and consequently with wider range of flight options. Reason why some of the passengers might be forced to take flights from SFO although they may live closer to the other 2 alternative airports in the Bay Area.

The following figure shows the county distribution in the Bay Area, in order to have a better reference of possible passenger final destinations:

![Bay Area counties’ distribution](image)

Figure 5.2: Bay Area counties’ distribution.

For instance, passengers that started their journeys from Santa Clara or Alameda would rather prefer to stay in OAK or SJC than having to go back to SFO. The same situation would happen to passengers from Contra Costa, Solano, Napa or Sonoma, as if being diverted to OAK that would leave them closer to their final destinations.
The SFO customer survey of 2011 also reported the county from which passengers departed to go to SFO. Again, it will be assumed that the origin county of the passengers is also their trip’s final destination. The following table, borrowed from [22], shows the results from the 2011 SFO survey regarding passengers’ trips’ origin.

<table>
<thead>
<tr>
<th>Q: What county did you depart from to get to the airport today?</th>
<th># observations</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco</td>
<td>1401</td>
<td>36.19%</td>
</tr>
<tr>
<td>Not applicable (connecting passengers)</td>
<td>688</td>
<td>17.77%</td>
</tr>
<tr>
<td>San Mateo</td>
<td>363</td>
<td>9.38%</td>
</tr>
<tr>
<td>Santa Clara</td>
<td>267</td>
<td>7.41%</td>
</tr>
<tr>
<td>Alameda</td>
<td>276</td>
<td>7.13%</td>
</tr>
<tr>
<td>Blank</td>
<td>212</td>
<td>5.48%</td>
</tr>
<tr>
<td>Contra Costa</td>
<td>139</td>
<td>4.11%</td>
</tr>
<tr>
<td>Marin</td>
<td>122</td>
<td>3.15%</td>
</tr>
<tr>
<td>Sonoma</td>
<td>106</td>
<td>2.74%</td>
</tr>
<tr>
<td>Solano</td>
<td>48</td>
<td>1.24%</td>
</tr>
<tr>
<td>Napa</td>
<td>43</td>
<td>1.11%</td>
</tr>
<tr>
<td>Sacramento</td>
<td>32</td>
<td>0.83%</td>
</tr>
<tr>
<td>Monterey</td>
<td>21</td>
<td>0.54%</td>
</tr>
<tr>
<td>San Joaquin</td>
<td>18</td>
<td>0.46%</td>
</tr>
<tr>
<td>Stanislans</td>
<td>18</td>
<td>0.46%</td>
</tr>
<tr>
<td>Santa Cruz</td>
<td>15</td>
<td>0.39%</td>
</tr>
<tr>
<td>Placer</td>
<td>11</td>
<td>0.28%</td>
</tr>
<tr>
<td>Mendoceino</td>
<td>9</td>
<td>0.23%</td>
</tr>
<tr>
<td>Yolo</td>
<td>8</td>
<td>0.21%</td>
</tr>
<tr>
<td>Mendocino</td>
<td>6</td>
<td>0.15%</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>0.13%</td>
</tr>
<tr>
<td>Humboldt</td>
<td>5</td>
<td>0.13%</td>
</tr>
<tr>
<td>Lake</td>
<td>4</td>
<td>0.10%</td>
</tr>
<tr>
<td>El Dorado</td>
<td>4</td>
<td>0.10%</td>
</tr>
<tr>
<td>San Luis Obispe</td>
<td>3</td>
<td>0.08%</td>
</tr>
<tr>
<td>Fresno</td>
<td>3</td>
<td>0.08%</td>
</tr>
<tr>
<td>Amador</td>
<td>2</td>
<td>0.05%</td>
</tr>
<tr>
<td>Shasta</td>
<td>1</td>
<td>0.03%</td>
</tr>
<tr>
<td>Butte</td>
<td>1</td>
<td>0.03%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3871</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Figure 5.3: Results of the survey to SFO customers asking for their departure county.

The first thing one can notice is that most of the people had to go to San Francisco once they arrived in SFO, a 36% of the interviewed passengers. Another additional 10% had to go to San Mateo, which is the county where SFO is located in, thus having to go back to SFO would not disturb their journey. One can also observe how 20% of the passengers were connecting passengers, which will have to go to SFO to catch their connecting flight. Finally, there is about a 20% of passengers which have Alameda, Santa Clara or Contra Costa as final destinations. These counties are the counties where the two alternative airports (SJC and OAK) are located in, reason why is very likely that these passengers would not want to be rerouted back to SFO. Only a 7% of the passengers will travel to Napa, Marin
and Sonoma, which are counties from similar distance to SFO than to OAK.

In order to ensure mathematical simplicity, it will be assumed in the model that all the passengers that have been squeezed into flights to SJC and OAK will be transported back to SFO. Nevertheless, further implementations should take into account that only an average 80% of the squeezed passengers should be transported back to SFO. The estimation has been computed based on the fact that a 20% would prefer to stay in either SJC or OAK and go back to their destination counties by their own means of transport.

5.4 Approach I: Partial inter-modal substitution

As it has been explained previously, the first approach consists in implementing the inter-modal substitution when the diverted passengers reach the Bay Area. This approach involves the passengers being ferried to OAK or SJC, and then transported to SFO by surface means of transport. For this first approach, as mentioned in the assumption made in 5.3.1 two possibilities of modes of transport exist: Public and Private transportation. According to this distinction, each type of transportation in the Bay Area will be assessed.

5.4.1 Public transportation within the Bay Area

One of the most critical aspects when considering the rerouting of diverted passengers through the Bay Area which is the best way of transporting passengers from one airport to another. An inefficient handling of the transition between airports would increase the irritation of the customers, and therefore increase the disruption perceivenss, negatively affecting airlines to a greater extent.

In the case that, for instance, a high percentage of the passengers are rerouted back to SFO through the Bay Area, and once at either SJC or OAK are given all taxi vouchers, close to 5.000 passengers would enter the road network, creating large traffic jams and long taxi waiting times. Therefore, the focus will be to look at the public transportation options that passengers may want to consider once in the Bay Area, in order to reduce the road network disruption impact.

As one can see in the figure 5.4 displayed above, there are two main rail public
transits connecting SFO and the alternative airports in the Bay Area, SJC and OAK.

Caltrain is serving the west and south part of the Bay, thus efficiently connecting SFO with SJC. On the other hand, one can see BART serving the north and east part of the Bay, therefore most efficiently connecting SFO with OAK. Now can be assessed which would be the passengers journeys from each airport individually.
5.4.1.1 Public transport connection between SFO and OAK

As previously stated, the public trail service best connecting SFO and OAK is the Bay Area Rapid Transit (BART). This heavy-rail public transit and subway system connects San Francisco with cities in the East Bay and suburbs in northern San Mateo County. Bay Area Rapid Transport (BART) operates five routes on 104 miles (167 km) of line, with 44 stations in four counties.

As one can observe in figure 5.4, there is no possibility of going from SFO Intl. Airport to OAK Intl. Airport without transferring between Bay Area Rapid Transport (BART) lines and Airport shuttle bus services. Therefore, starting from Oakland International Airport terminal, the trip that passengers would have to follow if using Bay Area Rapid Transport (BART) network is presented below:

<table>
<thead>
<tr>
<th>Journey description</th>
<th>Estimated minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk from Oakland airport terminal to AirBART Terminal</td>
<td>4 min</td>
</tr>
<tr>
<td>Shuttle bus to Coliseum/Oakland Airport BART station</td>
<td>13 min</td>
</tr>
<tr>
<td>Take BART line blue, orange or green.</td>
<td>33 min*</td>
</tr>
<tr>
<td>Transfer to yellow line and get down at SFO Airport station</td>
<td>20 min*</td>
</tr>
<tr>
<td>Walk into SFO Intl. Airport Terminal</td>
<td>1 min</td>
</tr>
<tr>
<td>Total travel time</td>
<td>1 hour 11 min</td>
</tr>
<tr>
<td>Total estimated average waiting time in transfers</td>
<td>15 min</td>
</tr>
<tr>
<td>Total journey time</td>
<td>1 hour 26 min</td>
</tr>
</tbody>
</table>

* Travel time estimated if taking green line and transferring at BART Park to yellow line.

Figure 5.5: BART journey to connect OAK with SFO.

As stated in figure 5.5, the trip would take an estimated time of 1 hour and 26 min (conditional upon real waiting times), could be done with 15 min frequency, and has a total fare of 12,40$ per passenger. Now, the capacity of the lines and estimated load factors will be computed, and thus it will be assessed the impact that the use of this mode of transport by diverted passengers could have in the Bay Area Rapid Transport (BART) operational performance.

The average number of passengers is 373,945 passengers during week days, an average of 176,616 passengers on Saturdays, and 119,247 passengers on Sundays, according to data recorded in January 2013. The maximum number of stuck diverted passengers per day was 7,371 passengers on the 6th of July, as shown in Chapter 2. The 6th of July of 2013 was a Saturday, meaning that on the 6th of July, Bay Area Rapid Transport (BART) was serving an estimate number of
Assuming that passengers are aproximetly evenly distributed through the 5 BART lines, that would mean that 35,300 passengers would be using the Pittsburg-SFO line (Yellow in figure 5.4) and the Richmond-Millbrae line (Green in figure 5.4) during that day. Finally, one should have in mind that during week days the same lines would serve more than the double of passengers (74,800 passengers each line). Therefore, even if all the 7,371 passengers were diverted through OAK during the whole day, and then sent to SFO through Bay Area Rapid Transport (BART) lines, that would not disturb the operational performance due to remaining capacity.

5.4.1.2 Public transport connection between SFO and SJC

As previously stated, the public rail service that offers the best connection between SFO and SJC is Caltrain. Caltrain is a California commuter rail line serving the San Francisco Peninsula and in the Santa Clara Valley (Silicon Valley). The north end of the line is San Francisco, at 4th and King streets; whilst its south end is Gilroy.

The Caltrain departures’ frequency in the area of interest, San Francisco and San Jose, are about hourly on weekdays, and more frequently during commute hours or sporting events.

One can see in figure 5.6 how the connection between SFO and SJC is done through the same Caltrain line, with the only transfers to the Airport shuttle buses. Therefore, starting from Mineta San Jose International Airport terminal, the trip that passengers would have to follow if they are rerouted using public transportation vouchers is presented below:

As stated in figure 5.7 the trip would take a total time of 1 hour and 53 min (conditional upon real waiting times), could be started with 30 minutes frequency, and has a tota estimated fare of 11.25$ per passenger. The total travel time in the case of the connection between SJC and SFO could fluctuate more, as Caltrain service varies depending on the hour of the day and the day of the week, and thus it may force the passengers to take another similar route. In any case, travel time may raise up to 2h and 10 or 20 min, which would not make much of a difference.
Now, finding the capacity of the Caltrain line described, as well as its estimated load factors, and thus assess the impact that the use of this mode of transport by diverted passengers could have in the Bay Area Rapid Transport (BART) operational performance.
According to the findings on *Caltrain passenger counts* issued in February 2013 [23], the weekday ridership averaged 47,060 passengers, with ridership at Bullet stations making up 83.5% of total boardings. The maximum number of stuck diverted passengers per day was 7,371 passengers on the 6th of July, as shown in Chapter 2. The 6th of July of 2013 was a Saturday, meaning on that day Caltrain was serving approximately 40% less passengers than during business days, making up an estimate number of 28,236 passengers using the Caltrain line on the 6th of July.

The maximum number of stuck diverted passengers per day was 7,371 passengers on the 6th of July, as shown previously in Chapter 2. Even if all the 7,371 passengers were diverted through OAK during the whole day, and they would be send to SFO through Caltrain *Limited* or *Baby Bullet* lines, that would mean an increase in demand of 26%, not even reaching the number of passengers using the line during weekdays. Therefore, one can conclude that it is not likely that the rerouting of the passengers through the Caltrain would disturb the operational performance of the train.

### 5.4.2 Private transportation within the Bay Area

In the case of private transportation, as shown figure [5.3] the survey made to SFO passengers showed that the most used modes of transport were; shuttle buses or hotel private motor coaches (16% of the interviewed passengers) and private car drop-offs (26% of the passengers).

Translating these results into possibilities of airlines’ operational measures, the most convenient mode of handling the private surface mode of transport rerouting would be by offering a motor-coach service. Passengers are used to involve this mode of transport as part of their flight trips, and thus the perceived delay would be probably lower.

#### 5.4.2.1 Analysis of charter companies in the Bay Area.

As discussed in [5.6.1], the alternative that seems more feasible for airlines to implement is alternative 3. Then, if airlines outsource the operation to local companies, contracting them for the inter-modal services in an on-call basis, the ability of such companies to respond in a timely manner to requests for service, which will be evidently urgent and unpredictable, is critical.
The first thing one must assess is how many charter companies offer such service in the Bay Area, understand the type of buses that can best substitute airlines’ arrivals, and finally determine which will be the time impact of the substitution in passengers trips. In the following table 5.8 it is summarized the number of charter companies offering 3 different types of buses, as well as the quantity of buses available and rental fees.

The table 5.8 lists 3 categories of motor-coaches, and their existing offer for each type of motor-coach, (last accessed in June 2014). The charter companies have been grouped in the following 3 areas:

- Area 1: San Jose, Santa Clara and South Bay area.
- Area 2: San Francisco and San Mateo.
- Area 3: Oakland, Concord and Stockton.

Please notice how the charter companies located in counties within less than 50 miles of any of the 3 airports of the Bay Area have been allocated to serve their closest airport. Furthermore, the charter companies located in Area 2 (San
Francisco and San Mateo), in case of inter-modal substitution, could attend both Oakland and San Jose airports demands.

The 3 types of bus that have been considered are: Minibuses, Charter Buses and Limobuses or Executive Buses.

The sitting capacity of Minibuses ranges from 21 to 37 people, depending on the charter company. Charter buses have higher capacity, ranging from 36 to 58 passengers. Finally, Limobuses or Executive buses range from 21 to 45 passengers capacity. All motor-coaches types have shelf and belly space to accommodate luggage. Restrooms, air conditioning, Public adress systems and TV/DVD are current standard equipement also. Some of them dispose of Satellite TV on board and WiFi service, although not so widely spread. The difference between minibuses and Charter buses does not reside in the service quality, as the ammenities offered in both are considerably similar, but in the passengers capacity. Limobuses and Executive buses though are customized to enhance the passengers experience. Plush perimeter seating, tables shared by 2 to 4 passengers, individual TV monitors, and on-board concierge to serve drinks are some of the special features of this high-end type of buses offered.

In order to have an overview of the number of motor-coaches offered of each type in the Bay Area as a whole, the following table summarizes the results sorted by type of bus. Furthermore, an estimation has been made of the number of passengers that could be rerouted, assuming all the motor-coaches are used (none was already booked), and using an estimated average passenger capacity per motor-coach type.

<table>
<thead>
<tr>
<th>Type of Bus</th>
<th># of available charter companies</th>
<th># of available motor-coaches</th>
<th>Estimated number of reroutable passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minibus</td>
<td>14</td>
<td>111</td>
<td>2.775</td>
</tr>
<tr>
<td>Charter Bus</td>
<td>22</td>
<td>271</td>
<td>13.550</td>
</tr>
<tr>
<td>Executive \ Limobus</td>
<td>6</td>
<td>19</td>
<td>570</td>
</tr>
</tbody>
</table>

Figure 5.9: Summary of the motor-coach charter service in the Bay Area.

As one can observe, assuming alternative 3 implies that local charter companies would be contracted under the condition that they should supply service whenever
the inter-modal operations are needed, and thus, that all of them would be available, the maximum number of reroutable passengers would be 16,895 passenger, which is more than sufficient. If one recalls from Chapter 2, the maximum number of stuck diverted passengers were 7,371 passengers. Additionally, one must have in mind that the the diversions occurred along the whole afternoon of the 6th of July, and that the flights that were able to reach SFO didn’t arrive at the same time. Therefore, it can be inferred how all the diverted passengers rerouted through the Bay Area would not reach the Bay at the same time period, and thus can be concluded that the current charter service offer in the Bay would be more than sufficient to reroute all the diverted passengers.

5.4.2.2 Cost evaluation of private transportation

After analysing the private transportation in the Bay Area, and concluding that there is enough offer to meet airlines’ unpredicted inter-modal service requests, one can now set the cost evaluation. The following table shows the costs of charter buses contracting for the 3 areas distinguished in the Bay Area:

<table>
<thead>
<tr>
<th></th>
<th>Minibus (~ 30 pax)</th>
<th>Charter Bus (~ 45 pax)</th>
<th>Executive Limobus (~ 30 pax)</th>
</tr>
</thead>
<tbody>
<tr>
<td># available</td>
<td>cost per day</td>
<td># available</td>
<td>cost per day</td>
</tr>
<tr>
<td>Area 1</td>
<td>21</td>
<td>$750</td>
<td>74</td>
</tr>
<tr>
<td>Area 2</td>
<td>11</td>
<td>$575</td>
<td>18</td>
</tr>
<tr>
<td>Area 3</td>
<td>79</td>
<td>n/a</td>
<td>179</td>
</tr>
<tr>
<td>Total</td>
<td>111</td>
<td>$670</td>
<td>271</td>
</tr>
</tbody>
</table>

Figure 5.10: Summary of the motor coach charter service costs.

One can observe how the renting prices vary within the Area. The row 'Total' of table 5.10 computes a weighted average cost per day for each type of motor coach offered. Therefore, and in order to simplify the mathematical modeling, the motor coaches offers will be aggregated, without taking into account to which charter company they belong, nor their exact renting fee. Thus, the cost of renting motor coaches per passenger and day are as follow:

Cost per passenger and day

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minibus</td>
<td>$11 (~ 30 pax)</td>
</tr>
<tr>
<td>Charter Bus</td>
<td>$10 (~ 45 pax)</td>
</tr>
<tr>
<td>Executive Limobus</td>
<td>$23 (~ 30 pax)</td>
</tr>
</tbody>
</table>

Figure 5.11: Motor coach service costs per passenger.
As it can be seen, the cost per passenger of renting a Minibus and a Charter Bus are very similar, as they offer the same amenities. As expected, Executive Buses and Limobuses offer a higher level of comfort, and therefore have a higher cost per passenger. Furthermore, one can see in figure 5.10 how the number of executive limobuses offered is really small (only a 5%), compared to the existing offer of Minibuses and Charter Buses. Thus, it is not likely that there is enough motor coaches demand to finish the cheap motor coach supply (95% of total offer).

The costs computed in 5.11 assume that each motor coach will be used for two passenger reroutings, meaning that the motor coaches should be able to travel back and forth two times between the airports. As it has been displayed previously, driving times between the airports involved in the Bay Area are close to the hour, therefore this assumption seems feasible. Nevertheless, congestion near SFO due to bottlenecks caused by rubbernecking and emergency vehicles may increase this driving times.

It can be concluded that the cost per passenger of renting motor-coaches to use them in the inter-modal services, noted in the mathematical model as CostBV, will be 11$ per passenger.

### 5.4.3 Summary of approach I

The following figure summarizes the values of travel times and trip fees to compute the total costs, in order to determine for every diverted airport which rerouting option is most cost-efficient:

<table>
<thead>
<tr>
<th></th>
<th>SJC to SFO</th>
<th>OAK to SFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>113 min</td>
<td>54 min</td>
</tr>
<tr>
<td>Passenger time value</td>
<td>53,9 €</td>
<td>25,7 €</td>
</tr>
<tr>
<td>Trip fee</td>
<td>12,4 €</td>
<td>11,0 €</td>
</tr>
<tr>
<td>Total cost</td>
<td>66,3 €</td>
<td>36,7 €</td>
</tr>
</tbody>
</table>

*Driving times have been estimated using googlesheets.com

Figure 5.12: Summary of transportation possibilities within the Bay Area.

The analysis shows how the use of motor-coaches as private transportation is the most cost efficient measure of applying an inter-modal substitution to reroute passengers within the Bay Area to SFO. Nevertheless, the operational costs of
giving transport vouchers are not substantially different to those of contracting motor-coaches, and rerouting passengers through the underground rail network could help to diminish the impact of the crash in the road network.

5.5 Approach II: Complete inter-modal substitution

As explained previously, a complete inter-modal substitution would imply that the passengers are rerouted by surface means of transport from the diverted airports where they got stuck. The airports from which a complete inter-modal substitution is feasible are:

- Oakland International Airport (OAK), 30 miles from SFO.
- Mineta San Jose International Airport (SJC), 50 miles from SFO.
- Sacramento International Airport (SMF), 100 miles from SFO.
- Reno Tahoe International Airport (RNO), 230 miles from SFO.
- Los Angeles International Airport (LAX), 390 miles from SFO.
- McCarran International Airport (LAS), 565 miles from SFO.

Having the 5 airports presented above in mind, there are two possible ways of rerouting passengers through surface means of transport:

- **Public transportation:** Use the bus and train networks to connect the passengers with their final destination SFO.
- **Private transportation:** Use private motor coaches to reroute the passengers.

Both possibilities have been assessed, in order to decide which surface transportation mode will be implemented in the rerouting optimisation model.

5.5.1 Public transportation outside the Bay Area

5.5.1.1 Overview of public transportation: Railway system in California.

Although long distance public transportation it is still in the US not always an optimal solution, both possibilities will be assessed for all the airports, and
then the most cost-effective rerouting option will be chosen. In order to get a
sense of the railway network in California, the following picture shows the National
Railroad Passenger Corporation (Amtrak) lines in California.

![AMTRAK railway system](image)

**Figure 5.13: AMTRAK railway system.**

In the map shown in figure 5.13 the two largest routes of the National Rail-
road Passenger Corporation (AMTRAK) are the Pacific Surfliner (green) and San
Joaquin (blue). Other AMTRAK routes in California are shown in black, and the
Capitol Corridor is shown in red. Non-AMTRAK commuter rail lines are shown
in yellow.

Analysing the network in detail, starting from the Pacific Surfliner, one can
observe how is the major commuting route in Southern California. The entire
length of the line runs from San Luis Obispo in the north, down to San Diego in
the south. The San Joaquin line operates twelve trains each day between Bakers-
field and Stockton. From Stockton, four trains from Bakersfield continue west
to Oakland, whilst two trains proceed north to the state capital of Sacramento.
Finally, the Capitol Corridor route runs north from San Jose through the East
Bay to Oakland and Richmond, then east through the Delta communities of Martinez and Suisun City, and the Sacramento Valley. One Capitol Corridor train per day continues east of Sacramento crossing the state to Auburn and Reno cities in Nevada.

As one can observe, Amtrak railway network connects the cities involved in this system of study; Sacramento, Los Angeles and the Bay Area. Although is not present in the map, as it has been previously mentioned, Reno is also connected through Amtrak to Sacramento and the Bay Area.

5.5.1.2 Connection SMF to SFO

It has been seen in figure 5.17 how Sacramento International Airport (SMF) is the closest airport to the Bay Area, being located within only 100 miles from SFO. The following figure shows the rerouting proposed to transport passengers by public modes of transport from SMF to SFO.

Figure 5.14: Rerouting from SMF to SFO using public transportation.

The above presented rerouting would take an overall journey of 4h and 49’, involving 3 transport transfers to connect door-to-door SMF with SFO. Passengers would have to take a YOLOBUS to go from SMF to Sacramento city center, with a cost of 2.00$. Then, they would transfer to AMTRAK train with a ticket fare
of 32.00$ with destination Richmond in the Bay Area, and then finally transfer to Bay Area Rapid Transport (BART) to reach SFO, with a ticket fare of 9.85$. The transitions between different public transport modes would make passengers walk up to 17 min. Long walking times can impact on the passengers perception of delay cost, as it is unpleasant to walk long ways carrying heavy luggage with them, reason why the routes have been designed trading-off between having few transport transfers and the least possible walking times.

In the case of Sacramento International Airport, the total cost of this first rerouting would be 43.85$ per passenger, with a total journey time close to 5 hours.

5.5.1.3 Connection RNO to SFO

Figure 5.17 shows how Reno Tahoe International Airport (RNO) is the second closest airport to the Bay Area, after SMF, as it is located within only 230 miles from SFO. The following figure shows the rerouting proposed to transport passengers by public modes of transport:

![Map showing rerouting from RNO to SFO using public transportation.](image)

Figure 5.15: Rerouting from RNO to SFO using public transportation.

The above presented rerouting would take an overall journey of 10h and 11 minutes, involving 4 transport transfers to connect door-to-door SMF with SFO. Passengers would have to take a Regional Transportation Commission bus to go
from RNO Airport to the Reno AMTRAK station, with a cost of 2.00$ [24]. Then, passengers would take the AMTRAK train with a ticket fare of 56.00$ with destination Richmond in the Bay Area, and then transfer to Bay Area Rapid Transport (BART) to reach SFO, with a ticket fare of 9.85$. The transitions between different public transport modes would make passengers walk up to 13 min, that can be annoying on the passengers view if they are carrying heavy luggage with them.

Thus, the total cost of this first rerouting would be 67.85$ per passenger.

5.5.1.4 Connection LAX to SFO

When analysing the possibility of giving public transport vouchers to passengers, Los Angeles Intl. starts to be an extreme case scenario. Due to a lack of fast and efficient surface rail transportation, the transportation times between these two cities become really high. The following figure explains in detail the public transport route between the two cities.

![Figure 5.16: Rerouting from LAX to SFO using public transportation.](image)

The above presented rerouting would take an overall journey of 11h and 18’, involving 5 transport transfers to connect door-to-door LAX with SFO. The first
two transfers belong to *Metro Los Angeles bus* service, and serve the passengers
to connect the LAX airport with the *Bundu Bus* station, with a ticket fare of
1.50$. This transfers could be avoided placing a shuttle bus sending people from
the airport to the bus station in the city center. *Bundu Bus* offers a straight 7h
and 40 min bustrip connecting LAX and SFO, with a fare of 58.00$ per person.
The destination station is 1 min by foot far from a Bay Area Rapid Transport
(BART) station in Montgomery street, from which passengers can take a straight
30 min trip to the airport, with a ticket fare of 8.65$ per person.

Thus, the total cost of this rerouting would be 66.15$. The critical problem with
this rerouting is that the Los Angeles to San Francisco *Bundu Bus* service is offered
only once a day departuring at 12pm, therefore, most of the passengers could miss
the bus and would have to wait until the next day departure. Furthermore, the
trip times raise up to more than 8 hours, reason why most of the passengers would
rather prefer to stay in the airport waiting for another flight, or overnight in a
nearby hotel, than to spend 8 hours seating in a train.

### 5.5.1.5 Connection from LAS, PHX, SLC, DEN and MSP to SFO

Las Vegas Intl. Airport established the extreme case scenario for public trans-
portation, as the trip time reaches 8 hours. The rest of the airports located within
more than 400 miles to SFO have infeasible rail and public bus transportation
options, as they take more than one day travel. For instance, Mc Carran Intl.
Airport, located within 560 miles from SFO, has no straight transportation time
to SFO. This means that passengers should take a train to Los Angeles and trans-
fer to another mode to reach SFO, taking a total trip time of 1 day and 9 hours
(estimated by google maps). In the case of Phoenix Sky Harbor Intl. Airport,
located within 750 miles from SFO, the trip time would be of 2 days and 15 hours.
Naturally, the travel times keep raising even further for the airports in Salt Lake
City, Denver or Mississipi, which absorbed also diversions during the 4 day period
of study.

Therefore, after analysing the public transportation possibilities from the di-
verted airports to SFO, it can be concluded that there is only a feasible public
transport route from SMF, RNO and LAX to SFO. The next section will assess
if the public transportation option is more cost-effective than using motor-coaches
for the rerouting of passengers.
5.5.2 Private transportation outside the Bay Area

5.5.2.1 Overview of private transportation: Motor-coaches.

The main problem of inter-modal substitution is that it is not cost effective for long distance substitution. It has been seen in the public transportation overview how, although San Francisco is well connected to the alternative airports in California and to Reno in Nevada by Caltrain network, transport times reach levels were passengers would likely prefer to overnight in a hotel and wait for a morning flight.

Evidently, private transportation is no exception, and therefore after analysing all the airports that were involved in the diversions triggered by the ASIANA crash, it is clear that some of them could not apply inter-modal substitution. The following figure shows the airports used to absorb diversions.

One can observe how airports like Minneapolis St. Paul International Airport (MSP) or Denver International Airport (DEN), are over 1,300 miles far away from San Francisco, meaning the surface transport time would be over a day. Such a journey would not be accepted by passengers, therefore MSP and DEN will not be considered for the inter-modal substitution rerouting option.
Analysing further the map, it can be distinguished a second layer of airports, that includes Salt Lake City International Airport (SLC), Phoenix Sky Harbor (PHX) and Las Vegas McCarran International Airport (LAS). All three airports are located within more than 570 miles from SFO. Passengers, in this case, would perceive a rerouting journey of over 10 hours in the best scenario, making inter-modal substitution also highly unlikely for SLC, PHX and LAS.

Finally, it can be observed a third cluster of airports outside the Bay Area, that includes Los Angeles International (LAX), Reno Tahoe International Airport (RNO) and Sacramento International Airport (SMF). These 3 airports are located within less than 400 miles from SFO. LAX is the airport in greater distance to SFO, implying a 6 hours road journey to reach SFO. Driving times would diminish to 4,5 hours in the case of RNO, or to 2,5 hours in the case of SMF. These driving times are more likely to be accepted by diverted passengers, thus LAX, SMF and RNO are the 3 airports outside the Bay Area from where it will be assessed an inter-modal substitution as a rerouting option.

It has been seen in 5.4.2 the private transportation analysis for the Bay Area, therefore the next analysis will focus in public and private modes of transport available to connect these 3 selected airports with SFO. The study will conclude for the 3 airports above detailed which transportation option is more cost effective for an inter-modal complete substitution.

5.5.2.2 Private transportation from SMF to SFO

The case of SMF is the best scenario for complete inter-modal substitution from diverted airports outside the Bay Area. Being located within only 100 miles from SFO, the door-to-door driving time is estimated to be of 1h and 50 minutes.

From Sacramento International airport, the journey would mainly involve I-5 N motorway, afterwards the I-80W motorway and finally merging onto US-101 S. On the crash day, due to congestion generated by rubbernecking and emergency vehicles, the US-101 part that is attached to SFO there was a considerable road congestion. A good way to ensure passengers do not perceive larger delays, could be to send them straight to San Francisco downtown instead of ending the trip in SFO airport. Passengers could be left at a Taxi or Bay Area Rapid Transport (BART) station in San Mateo county, saving the time they would spend going back and forth to SFO in order to reach their final destination.

Therefore, the private transportation rerouting from SMF to SFO would have
a total estimated travel time close to the two hours. One can now analyse if there is enough offer in Sacramento to fulfill the possible inter-modal service demand in highly disruptive situations. Figure 5.18 shows the available charter-compaines in Sacramento:

### Area: Sacramento and Elk Grove

<table>
<thead>
<tr>
<th>Type of Bus</th>
<th>Capacity range</th>
<th># of charter companies</th>
<th># of motor coaches</th>
<th>Range of all-day rental cost</th>
<th>Variable cost (US $ / mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minibus</td>
<td>37</td>
<td>3</td>
<td>7</td>
<td>$600 - $700</td>
<td>n/a</td>
</tr>
<tr>
<td>Charter Bus</td>
<td>47 - 58</td>
<td>4</td>
<td>17</td>
<td>$700 - $800</td>
<td>n/a</td>
</tr>
<tr>
<td>Executive \ Limobus</td>
<td>30</td>
<td>1</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Source: Busrates.com, last accessed in June 2014.

Figure 5.18: Charter companies available in Sacramento area.

As one can observe in figure 5.18, the charter companies analysed were located either in Sacramento area or in Elk Grove area. Elk Grove is a small town located in the suburbs of Sacramento city, in which the charter companies find cheaper storing garages and can still serve the Sacramento offer. Only 8 charter companies have been found with base in Sacramento, offering a total of 25 motor coaches. The 70% of the motor coaches available are Charter Buses, with a passenger capacity between 47 and 58 passengers, and an all-day renting fare of 750$ on average. The second greatest amount of motor coaches available are from the Minibus type, with an average capacity of 37 passengers and an average fare of 650$. Finally there is one charter company offering a Limobus, without renting cost details.

Therefore, according to the data available, the total reroutable passengers at SMF would be of 1.173 passengers, considering that each motor coach can perform only one substitution. Computing the costs of the inter-modal service in Sacramento, the results are shown in figure 5.19:

### SMF: Cost per passenger and day

<table>
<thead>
<tr>
<th>Type of Bus</th>
<th>Cost per day</th>
<th>Passengers per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minibus</td>
<td>$22</td>
<td>(~ 30 pax)</td>
</tr>
<tr>
<td>Charter Bus</td>
<td>$21</td>
<td>(~ 40 pax)</td>
</tr>
<tr>
<td>Executive \ Limobus</td>
<td>$47</td>
<td>(~ 20 pax)</td>
</tr>
</tbody>
</table>

Figure 5.19: Costs of motor coaches renting in SMF area.
Comparing the renting costs to the ones of charter companies in the Bay Area, one can see how costs are slightly lower in SMF, probably due to a lower market demand. Additionally, one should have in mind that these costs have been computed considering every motor coach does only one substitution, although is rented all day. As SMF is located within 2 hours drive time from SFO, it could be assumed that the motor coaches would be able to make one trip in the morning and another during the afternoon, lowering the costs a 50%. Nevertheless, it is probable that in highly disruptive situations there is a peak of diversions during the late morning, reason why, having the passenger value of time in mind, it would be more cost effective to use motor coaches as long as passengers arrive to the airport.

5.5.2.3 Private transportation from RNO to SFO

In the case of Reno Tahoe International Airport, the 230 miles road distance to SFO would mean a door-to-door driving time of 3h and 45 minutes.

The journey would mainly elapse in I-580 N motorway, afterwards merging onto I-80W motorway and finally taking the US-101 S to reach SFO. As it has explained before for the SMF assessment, on the crash day, the US-101 section attached suffered considerable congestions. As for a rerouting from SMF, passengers could be left in a Bay Area Rapid Transport (BART) station or Taxi station at San Mateo or San Francisco counties, in order to ensure passengers do not perceive larger delays.

Therefore, the private transportation rerouting from SMF to SFO would have a total estimated travel time close to the four hours. One can now analyse if there is enough offer in Reno to fulfill the possible inter-modal service demand. The following figure shows the available charter-compaines in Reno:

As one can observe in the figure, the charter companies offer in Reno is limited to 2 charter companies, offering a total of 54 motor coaches. A 93% of the motor coaches available are Charter Buses, with a passenger capacity between 47 and 58 passengers. The remaining 7%, corresponds to 4 minibuses, with capacity of 37 passengers. Therefore, according to the data available, the total reroutable passengers at RNO would be of 2,598 passengers, considering that each motor coach can perform only one substitution.

There is no data available on all-day service costs, as both companies do not
offer details on renting fees. It will be assumed the costs of motor coach service in RNO to be similar to the ones at Sacramento, as RNO is probably serving other populations in Nevada, and it does not have high demand itself. Therefore, costs will be assumed to be the following:

<table>
<thead>
<tr>
<th>Area: Reno (Nevada)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Bus</strong></td>
</tr>
<tr>
<td>Minibus</td>
</tr>
<tr>
<td>Charter Bus</td>
</tr>
<tr>
<td>Executive</td>
</tr>
</tbody>
</table>

Source: Busrates.com, last accessed in June 2014.

Figure 5.20: Charter companies available in Reno area.

In the case of Reno Tahoe, as the driving time would reach the 4 hours, it is infeasible that motor coaches can do more than one substitution, in order to lower the fixed costs. Airlines would thus have to contract the service for all day, and start rerouting passengers as soon as they reach RNO.

5.5.2.4 Private transportation from LAX to SFO

In the case of Los Angeles International Airport, the 390 miles road distance to SFO would mean a door-to-door estimated driving time of 6h and 30 minutes.

The journey would mainly elapse in I-405 N motorway to leave Los Angeles area, then transfer to I-5 for 260 miles, and finally merging onto the US-101 S motorway to reach SFO. As it has explained in the previous airport assessments, on the crash day, the US-101 section attached suffered considerable congestions. As for a rerouting from SMF, passengers could be left in a Bay Area Rapid Transport (BART) station or Taxi station at San Mateo or San Francisco counties, in order to ensure passengers do not perceive larger delays.
Therefore, the private transportation rerouting from LAS to SFO would have a total estimated travel time close to the 6h and 30 minutes, taking into account the delay minutes due to the US-101 congestion close to SFO. One can now analyse if there is enough offer in Reno to fulfill the possible inter-modal service demand. Figure 5.22 shows the available charter-companies in Reno:

<table>
<thead>
<tr>
<th>Los Angeles</th>
<th>Range of seating capacity</th>
<th># of available charter</th>
<th># of available motor-</th>
<th>Range of all-day rental cost (US)</th>
<th>Range of variable cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minibus</td>
<td>20 - 37</td>
<td>30</td>
<td>257</td>
<td>$575 - $775</td>
<td>n/a</td>
</tr>
<tr>
<td>Charter Bus</td>
<td>45 - 58</td>
<td>38</td>
<td>515</td>
<td>$775 - $950</td>
<td>n/a</td>
</tr>
<tr>
<td>Executive / Limobus</td>
<td>9 - 28</td>
<td>15</td>
<td>75</td>
<td>$450 - $1550</td>
<td>n/a</td>
</tr>
</tbody>
</table>


Figure 5.22: Charter companies available in Los Angeles area.

As one can observe in figure 5.22, the charter companies available in Los Angeles area is extremely high. This is due to the fact that many town villages surrounding Los Angeles (within less than 50 miles), offer tour guides visiting the california south cost, San Diego and Los Angeles. A 30% of the motor coaches available are Mini Buses, with a passenger capacity between 20 and 37 passengers. The most abundant type of buses available is the Charter Buses (60%), with a capacity range of 38 to 53 passengers. Finally, there is a relatively short supply of Executive or Limo Buses, only a 10 % of the offer, with a range capacity of 9 to 28 passengers. Therefore, according to the data available, the total reroutable passengers from LAX to SFO would be of 29,810 passengers, assuming the charter companies have no pre-commitments on the crash weekend.

The data available on all-day service costs was low, as some of the charter companies do not offer details on renting fees online, nevertheless the price range already serves as a reference to estimate an average renting fee per motor-coach. Thus, the contracting costs have been estimated to be the following:

<table>
<thead>
<tr>
<th>LAX: Cost per passenger and day</th>
<th>Minibus</th>
<th>$23 (≈ 30 pax)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charter Bus</td>
<td>$22 (≈ 40 pax)</td>
<td></td>
</tr>
<tr>
<td>Executive / Limobus</td>
<td>$45 (≈ 20 pax)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.23: Costs of motor coaches renting in Los Angeles area.
In the case of LAX, as the driving time would reach up to 6 hours, it is infeasible that motor coaches can do more than one substitution, in order to lower the fixed costs. Airlines would thus have to contract the service for all day, and start rerouting passengers as soon as they reach RNO. Therefore, the operational cost of renting motor-coaches for inter-modal service from LAX will be assumed as shown in figure 5.23.

5.5.2.5 Private transportation from LAS, PHX, SLC, DEN and MSP to SFO

As it has already been explained in the public transportation analysis, Las Vegas Intl. Airport established the extreme case scenario for public transportation, as the driving time reaches 8 hours and 30 minutes. The rest of the airports located within more than 560 miles to SFO have infeasible motor-coach transportation options, as the travel times raise to more than one day travel.

Therefore, after analysing the private transportation possibilities from the diverted airports to SFO, it can be concluded that there is only a feasible motor-coach passengers’ rerouting from SMF, RNO, LAX and LAS to SFO.

5.5.3 Summary of Approach II. Comparison and selection of the most cost-effective mode of transport.

The following figure summarizes the values of travel times and trip fees to compute the total costs, in order to determine for every diverted airport which rerouting option is most cost-efficient:

In order to summarize the values, it has been assumed that Las Vegas area would have a level of supply of charter companies comparable to the one in Los Angeles, due to the high level of tourists that travel there for recreational objectives or to visit the Grand Canyon area. The analysis shows how the use of motor-coaches as private transportation is the most cost efficient measure of applying an inter-modal substitution to reroute passengers from closer airports outside the Bay Area to SFO. The operational cost of using private transportation raise, but even in a great way raise the trip times, impacting directly in the passengers journey back home.
5.6 Further operational issues in inter-modal substitution

5.6.1 Motor-coach operational handling alternatives

As Hansen & Zhang distinguished in [21], there are three roles in supplying motor coach service, a combination of which make up 3 alternatives of handling motor-coaches service. The main roles in supplying motor coach service are:

1) Owning the vehicles.
2) Operating and maintaining the vehicles.
3) Provide airport facilities.

According to these roles, the alternatives that airlines have in handling the motor-coaches service, as part of their inter-modal operations, are summarized in the table below:

As one can observe in the table, the first alternative would be to purchase a fleet of vehicles, and dedicate them for inter-modal operations. From airlines’ point of view, the advantages of owning the vehicles would be that airlines could customize them and furnish the vehicles with flights’ similar amenities, such as beverage, entertainment or more luggage space, in order to help retain passengers’ loyalty and reduce their customers’ perceived costs of inter-modal substitution. Furthermore, airlines would be in position of operating the fleet by themselves, so
that they can have control of vehicles dispatch, and what’s more, ensure an efficient integration of airside and landside operations. Despite these advantages, this alternative could barely be economical, as the inter-modal substitution proposed in this study is an operational measure conceived to be implemented in highly disruptive situations, which occur infrequently.

The second alternative presented in table 5.25 could be to own the fleet but outsource the operating and maintenance. The advantages of this second alternative would be that airlines could use the fleet for internal operations, or obtain an extra revenue source by offering a surcharge charter service, during the days without inter-modal operations. The days with inter-modal service then, airlines could contract part-time drivers that serve on-call demands, and outsource the operating and maintenance of the fleet to a third party with access to professional charter services and who agrees to give top priority to airline inter-modal service requests. This second alternative would help to control the labor cost of inter-modal operations, that is a major component of motor coach operating cost. Although this alternative would definitely lower the costs of the service, still leaving the vehicle fleet idle on the days without inter-modal operations can be inefficient.

Finally, the third alternative for airlines would be to contract with existing local charter companies to supply service whenever the inter-modal operations are needed, with a negotiable economic incentive if companies had previously arranged commitments. This alternative implies that the local companies would own, operate and maintain the vehicle fleet. The main advantage of this option is that it would require low investment and no fixed costs (such as vehicle fleet amortization), and would enable airlines have a first experience with inter-modal operations without making a large commitment nor great investment.

In order to have an overview of the 3 alternatives proposed, the following table summarizes the advantages and disadvantages of each alternative:
As it can be seen in figure 5.26, the optimal alternative for inter-modal substitution operations in highly disruptive situations, would be alternative 3. Disruptive situations where an inter-modal substitution is the most cost-effective rerouting are not frequent, and thus it is difficult to assess if airlines would be the party that would initiate the inter-modal operations. The third alternative would be a good way to ensure a smooth introduction of the inter-modal concepts, and then, perhaps airlines would more likely develop further the service by implementing one of the two first alternatives.

### 5.6.2 Time response to urgent service requests

According to the conclusions in 5.6.1, the alternative in motor coaches handling that seems more feasible for airlines to implement is alternative 3. Then, if airlines would more likely outsource the motor-coaches handling operations to local companies, contracting them for the inter-modal services in an on-call basis, the ability of such companies to respond in a timely manner to requests for service, which will be evidently urgent and unpredictable, is critical.

Hansen & Zhang conducted in [21] a research on charter companies’ response to service inter-modal service requests.
To get a general idea about how promptly charter companies could respond to service requests, Hansen & Zhang conducted a telephone survey for ten randomly picked charter companies for six regions in the US: San Francisco, Los Angeles, New York, Chicago, Miami and Texas. All of the regions are supposed to have a charter companies’ offer comparable, if not bigger in some cases, to San Francisco. They constructed a scenario motivating an urgent request for a motor coach service at an airport, and asked for a motor coach that could accommodate at least 30 passengers and their personal belongings and be available for at least 6 hours.

The following table reprinted from [21] shows the results of the survey conducted:

<table>
<thead>
<tr>
<th></th>
<th>San Francisco</th>
<th>Los Angeles</th>
<th>New York</th>
<th>Chicago</th>
<th>Miami</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SFO</td>
<td>LAX</td>
<td>JFK</td>
<td>ORD</td>
<td>MIA</td>
<td>DFW</td>
</tr>
<tr>
<td>Not available</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>1-1.5 hours</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>3 - 4 hours</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 5.27: Survey on time response to inter-modal service request.

The results in figure 5.27 show how about a 30% of the charter companies did not have vehicles or drivers available at the time of the request. For companies who can provide the service, a 50% can get to the airport within one and half hours, while the other half need about three to four hours.

The problem lays in the fact that many charter companies hire part-time drivers and schedule their work load according to reservations. For urgent requests, they need to check the availability of drivers and reorganize their shifts.

While being interviewed by Hansen & Zhang, some charter companies asked if the surveyor had a business relationship with their company, implying that they might respond more quickly if this were the case. Furthermore, they interviewed a customer service manager of United Airlines at ORD about her experiences working with local charter companies. The manager stated that United could obtain motor coaches within one hour of making the request. This evidences that if airlines could establish a long-term relation with local charter companies, contracting them for whenever an inter-modal service is required, that could ensure a timely response of the charter companies.
Although the project had no resources to conduct equivalent surveys for Reno and Sacramento local charter companies, the Hansen & Zhang results can be extrapolated to this study. According to 5.27 a 33% of the randomly picked charter companies in San Francisco could not respond to an urgent service request. From the remaining 66% of charter companies surveyed, a 22% could deliver motor coaches within 1 and 1.5 hours, and a 44% could deliver motor coaches within 3 to 4 hours.

One could consider that the Bay Area is an extension of the San Francisco region considered in Hansen & Zhang survey, and therefore the same proportions would apply for the local charter companies that this study has considered in the 3 areas of the Bay Area distinguished in 5.4.2.1.

Furthermore, assuming the random sample used in the survey to be representative of the population, and analysing the proportions of time responses within the same regions:

<table>
<thead>
<tr>
<th></th>
<th>SFO</th>
<th>Los Angeles</th>
<th>New York</th>
<th>Chicago</th>
<th>Miami</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not available</td>
<td>33%</td>
<td>22%</td>
<td>33%</td>
<td>56%</td>
<td>44%</td>
<td>44%</td>
</tr>
<tr>
<td>1-1.5 hours</td>
<td>22%</td>
<td>33%</td>
<td>44%</td>
<td>22%</td>
<td>33%</td>
<td>22%</td>
</tr>
<tr>
<td>3 - 4 hours</td>
<td>44%</td>
<td>56%</td>
<td>33%</td>
<td>33%</td>
<td>33%</td>
<td>44%</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>36%</td>
<td>27%</td>
<td>37%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.28: Summary of the survey on time response to inter-modal service request.

In order to be conservative with the estimations, it will be assumed that Reno and Sacramento local charter companies, have average time responses in relation to the sample of study. Therefore, as displayed in the figure 5.28 a 36% of the charter companies will not be able to provide the service, whilst the 64% remaining will be able to attend the inter-modal service urgent request. A 27% of the charter companies will be able to attend the request within 1 and 1.5 hours, and a 37% will provide the service within 3 and 4 hours from the request.

Therefore, as it has been estimated in 5.29 with a weighted average, the time response of the local charter companies in Reno and Sacramento will be assumed to be of 2 hours and 35 minutes. Evidently, this average time response has been only assumed for the percentage of local charter companies that will be able to provide service in Reno and Sacramento. It is difficult to assess whether charter companies with more motor coaches are able to respond to the request faster. Furthermore,
it is also difficult to assess to which extent the charter companies can be overbooked. Therefore, it will be assumed that the total number of buses displayed in figure 5.8 is evenly distributed between all the charter companies. Therefore, and as estimated in figure 5.29 only a 64% of the charter companies will be able to attend the request, and the service will be provided within 2.55 hours.

After the estimations performed, one can conclude that the value of the coefficient $BWT$ used as input in the mathematical programming will be 175 minutes.

### 5.6.3 Passengers perception of inter-modal substitution

Compared to flying, the surface modes of transport are sometimes considered inferior, not only in terms of service, but also in terms of speed. The implementation of inter-modal operations therefore must take into account the customer reaction when reassigned to surface modes of transport, as it is expected that some of the passengers may offer resistance to such reaccommodation.

As the survey to SFO passenger displayed in table 5.3 shows, a total of approximately 16% use either door-to-door van services, private scheduled bus or free hotel shuttle. That means, a 16% of the SFO customers are used to involve a motor coach transport as part of their journeys to move inside the leave or reach SFO. This is due to the fact that most of the customers of SFO live in counties that are located within 20 to 50 miles of SFO, and such distances are admissible to be made by surface modes of transport. The problem will raise with passengers reassigned to motor coaches from SMF or RNO back to SFO, when traveling times are higher.

In any case, a good way to deal with such resistance could be to offer the
inter-modal substitution as an extra option, and retain the right to be reassigned to a later flight instead if passengers prefer to. Airlines should notify that refusing the substitution could lead to long delays, making passengers awareness of the consequence an inducement to accept the substitution.

If passengers still prefer to be retained at their diverted airports, the airline policy could be to rebook them in a way that the cost incurred is no more than that of reassigning them in a motor coach. This may result in severe delays, as airlines will prioritize to accommodate passengers who have been involuntarily disrupted. Furthermore, as airlines have limited obligations to provided compensations to passengers if their disruption is caused by adverse weather or emergency accidents, the passengers that are aware of this would thus accept the substitution as the less disruptive rerouting to end their journeys.

5.6.4 Security issues

Inter-modal substitution as an option for rerouting diverted passengers raise new security questions. These passengers, who have been reassigned from flights to ground transportation, will enter or leave the airport system (with their luggage), and therefore the inter-modal operation must ensure they are processed through security as well. As diversions mostly occur last minute, the flight might be forced to land in airports that have less traffic, meaning they might not have the optimal facilities to handle the security check of inter-modal passengers. The main problem appears if there are international flights involved in the inter-modal operations, as these passengers must go through custom borders and special security checkpoints.

For instance, during the 6th of July Salt Lake City International Airport (SLC) absorbed most of the international flights, instead of San Jose or Oakland. SLC was the closest airport with an international custom able to process this international flights diverted, as OAK and SJC had no such facilities ready.

![Tweet reporting OAK not ready for international customs.](image)

Figure 5.30: Tweet reporting OAK not ready for international customs.
Some international flights had no chance to be diverted to international hubs such as Seattle or Phoenix, due to low fuel reserves or other aircraft security issues. Therefore, some of them were forced to land in Sacramento, which had no custom checkpoints available, forcing the custom officers to move to the aircrafts to proceed with the security checks, as figure 5.31 shows.

Figure 5.31: Tweet reporting custom officers being called onto flights.

Zhang proposes in [21] two process passengers transferred to surface modes of transport securely:

- **Transfer between modes in a secured area inside the airport**
  - Passengers are loaded and unloaded inside the airport secure area, in which only airport and airline employees, as well as passengers who have gone through security screening, are allowed to stay.
  - Motor-coaches carrying the airline passengers would enter the secure area to load and unload passengers and luggage.

- **Transfer between modes outside the airport secure**
  - Motor-coaches do not enter the airport secured area. Passengers are loaded and unloaded outside.
  - Implies an increase of workload, as resources should be allocated outside the common area of work, but eliminates possible threads.
  - No further screenings needed to ensure that the motor coaches have not been altered since they were loaded at the spoke airport.

Both options proposed in [21] have been summarized above, and may be good ways to ensure an efficient integration of inter-modal operations, as well as a secure transfer of passengers between modes.
Chapter 6

Mathematical programming - Airport pairs optimisation model

6.1 Introduction

The optimisation model proposed here aims to assess the possibility of inter-modal substitution as a rerouting option in the reaccommodation of diverted flights. The validity of the model will be implemented in an Asiana crash Case Study, in which the mathematical programming will determine the most cost-effective reaccommodation of the diverted passengers that were not able to reach SFO with their original flights.

If one recalls, Asiana Airlines Flight 214 was a scheduled transpacific passenger flight from Incheon International Airport near Seoul, South Korea to San Francisco International Airport (SFO) in the United States. On the morning of Saturday, July 6, 2013, the Boeing 777-200ER aircraft operating the flight crashed on final approach into SFO. As a consequence, two runways had to be closed on the 6th and remain not operative on the 7th of July, triggering severe cancellations and delays on the flights that were supposed to land in SFO on the 6th to 9th of July.

The novelty of the mathematical modeling lies in:

- The implementation of inter-modal operations in airline schedule recovery from highly disruptive situations.

- The passenger-centric modeling of the rerouting costs, meaning the cost of rerouting not only will take into account the operational costs that airlines
will perceive, but also the monetary translation of delay times that passengers will perceive.

The rerouting model is defined over pairs of airports (SFO - DivertedAirport_n), and the optimisation implementation has been performed over the busiest airports involved in the diversions triggered by Asiana Crash. Thus, the mathematical programming will analyse the diverted flights that landed in one specific airport, and then, according to the non-cancelled departure flights and surface modes of transport available, the model will propose the most cost-effective rerouting configuration, taking into account both passenger travel times and operational costs.

6.2 Nomenclature used in the model

This airport focused optimisation will use as input data the set of diverted flights, departure flights and available resources (motor coaches and aircrafts) at one specific airport. The following section will define the variables that are included along the mathematical optimisation problem:

6.2.1 Index variables

- $\mathcal{F}$ : Set of departure flights from the diverted airport to the Bay Area (SFO, OAK, SJC) = \{f_1, f_2, ..., f_n\}
- $\mathcal{\Gamma}$ : Set of discrete time periods = \{t_1, t_2, ..., t_T\}
- $\mathcal{P}$ : Set of diverted passengers = \{p_1, p_2, ..., p_P\}
- $A$: Set of aircraft available to affrete in the diverted airport
  \{ a_1, a_2, ..., a_{MaxAircraft} \}
- $B$: Set of available buses for inter-modal substitution in the diverted airport
  \{ b_1, b_2, ..., b_{MaxBuses} \}

6.2.2 Input time and delay variables:

- $AT_f$ : Scheduled arrival time of flight $f$
- $DT_f$ : Scheduled departure time of flight $f$
• $PaxAT_p$ : Scheduled arrival time of passenger $p$ previous to the diversion.
• $ActualDivAT_p$ : Arrival time of passenger $p$ to the diverted airport.
• $BDT_{OAK}$ : Bus transportation time from OAK to SFO
• $BDT_{SJC}$ : Bus transportation time from SJC to SFO
• $BDT_{DivAirport}$ : Bus transp. time from the diverted airport to SFO
• $FlightTime_{DivAirport}$ : Flight time from the diverted airport to SFO

6.2.3 Input capacity variables:

• $Pax_f$ : Total number of passengers on departure flight $f$.
• $Cap_f$ : Maximum passengers capacity of flight $f$.
• $CapAircraft_a$ : Maximum passengers capacity of chartered flight $a$.
• $CapBus$ : Maximum passengers capacity of buses available for inter-modal substitution.

6.2.4 Input cost coefficients:

• $CostAffrete$ : Cost of chartering a new aircraft. Defined in [ $/ hour \cdot passenger$ ] in order to be able to scalate the cost of placing bigger aircrafts, without having to separate the cost per type of aircraft.
• $CostBV$ : Variable cost of utilizing ground transportation per passenger [ $/ passenger$ ].
• $CostP$ : Passenger delay cost per one time unit [ $/ hour \cdot passenger$ ].

6.2.5 Other input coefficients:

• $Beta_{Wait}$ : Weight coefficient for passenger waiting times.
• $Beta_{Transp}$ : Weight coefficient for passenger transportation times.
• $MinloadBus$ : Percentage of the total bus capacity that establishes the minimum passenger load to be ready to leave.
• $MinloadAffrete$ : Percentage of the total aircraft capacity that establishes the minimum passenger load of an chartered flight to be ready to leave.
• TimeFactor: Conversion factor used to convert time periods into minutes.
• MaxBuses: Maximum number of buses available to substitute flights.
• MaxAircraft: Maximum number of aircraft available to be chartered.

6.2.6 Binary variables

6.2.6.1 Input binary variables:

\[
OAK_f = \begin{cases} 
1 & \text{if the destination of departure flight } f \text{ is OAK} \\
0 & \text{otherwise} 
\end{cases}
\]  
(6.1)

\[
SJC_f = \begin{cases} 
1 & \text{if the destination of departure flight } f \text{ is SJC} \\
0 & \text{otherwise} 
\end{cases}
\]  
(6.2)

6.2.6.2 Output binary variables:

The first type of output binary variables are \( Squeeze_{t(p,f)} \), \( Subst_{t(p,b)} \) and \( Affrete_{t(p,a)} \). These three variables that assign passengers to one of the three possible rerouting options:

\[
Squeeze_{t(p,f)} = \begin{cases} 
1 & \text{if passenger } p \text{ is squeezed into flight } f \text{ in time period } t \\
0 & \text{otherwise} 
\end{cases}
\]  
(6.3)

\[
Subst_{t(p,b)} = \begin{cases} 
1 & \text{if passenger } p \text{ is rerouted with motor – coach } b \text{ in time period } t \\
0 & \text{otherwise} 
\end{cases}
\]  
(6.4)
The mathematical programming uses the following auxiliary binary variables: $y_1$, $y_2$, $y_3$, and $y_4$.

### 6.3 Objective function

The objective of the mathematical model is to minimize the cost of reaccommodation of diverted passengers who were stuck in their respective diverted airports and could not reach SFO. Thus, it will be used as input data the final ASIANA crash schedule (e.g. what flights were diverted, which flights were cancelled and which ones could reach SFO), and the model will only assess the more cost-effective rerouting back to SFO.

The rerouting options evaluated in the mathematical programming are as follows:
(A) Squeeze the diverted passengers into flights to SFO
(B) Squeeze the diverted passengers into flights to OAK or SJC
(C) Ferry back the passengers to SFO by chartering a new aircraft
(D) Apply an inter-modal substitution from the diverted airport

In the rerouting options enumerated above, Option (B) implies rerouting passengers to the alternative airports in the Bay Area, and then implementing a short inter-modal commute, transporting the passengers back to SFO by surface means of transport. Furthermore, Option (D) implies that passengers are rerouted with motor-coaches from the diverted airport back to SFO.

The following figure represents the four rerouting options for a given pair of airports, in this case, from LAX to SFO:

![Figure 6.1: Possibilities of rerouting from LAX.](image)

LAX airport is one of the 4 airports from which a complete inter-modal substitution is feasible, in the rerouting to SFO. Please notice that for diverted airports
other than Reno Tahoe, Sacramento or McCarran Las Vegas, the complete inter-modal substitution may be infeasible, therefore figure A.1 could slightly differ.

6.3.1 Model Input Data

The input data for the mathematical programming is the following:

1. Set of diverted passengers to the airport of study.
2. Set of departure flights $\mathcal{F}$ from the diverted airport of study, with destination either to SFO, OAK or SJC.
3. Number of passengers booked and maximum capacity of each flight $f$.
4. Scheduled departure and arrival times of each flight $f$.
5. Actual departure and arrival times of all the flights previously mentioned.
6. Surface transportation times between the diverted airport and SFO.
7. Remaining arrival flight capacities at SJC and OAK.
8. Remaining departure flights capacity in the diverted airport.

The following tables describe in detail the input matrix that will have to be uploaded in matlab in order to be able to run the computations.

6.3.1.1 Diverted passengers data

The first input table contains the data regarding the diverted flights. Each row of the table represents a diverted passenger. The data has to be formatted as follows:

As it is described in 6.2, the data includes:

- Day of arrival: Integer from 1 to 4, corresponding to the 4-day period of study (6th of July to 9th of July).
6.3.1.2 Departure flights data

The following input table corresponds to the data on the flights, that were not cancelled, connecting the diverted airport to either SFO, SJC or OAK.

<table>
<thead>
<tr>
<th>Day of arrival</th>
<th>Tail #</th>
<th>Flight #</th>
<th>Cap_f</th>
<th>Pax_f</th>
<th>Destination</th>
<th>DT_f</th>
<th>ActualDT_f</th>
<th>AT_f</th>
<th>ActualAT_f</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_1</td>
<td>1</td>
<td>xxxx</td>
<td>Cap_1</td>
<td>Pax_1</td>
<td></td>
<td>d_1</td>
<td>xxxx</td>
<td>xxxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>f_2</td>
<td>1</td>
<td>xxxx</td>
<td>Cap_2</td>
<td>Pax_2</td>
<td></td>
<td>d_2</td>
<td>xxxx</td>
<td>xxxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>f_n</td>
<td>4</td>
<td>xxxx</td>
<td>Cap_f</td>
<td>Pax_f</td>
<td></td>
<td>d_f</td>
<td>xxxx</td>
<td>xxxx</td>
<td>xxxx</td>
</tr>
</tbody>
</table>

Figure 6.3: Input table with the information of the departure flights.

Table 6.3 contains the data regarding the departure flights, as specified previously. Each row of the table represents a departure flight f. The data includes:

- Day of arrival: Integer from 1 to 4, corresponding to the 4-day period of study (6th of July to 9th of July).
- Tail #: Tail number of the diverted flight in which passenger p arrived.
- Flight #: Flight number of the diverted flight in which they arrived.
- \( Cap_f \): Passenger capacity of flight \( f \).
- \( Pax_f \): Passengers booked in flight \( f \).
- Destination Airport: Integer from 1 to 3, corresponding to SFO, OAK or SJC respectively.
- \( DT_f \): Departure time of flight \( f \).
- \( ActualDT_f \): Actual departure time of flight \( f \).
- \( AT_f \): Scheduled arrival time of flight \( f \).
- \( ActualAT_f \): Scheduled arrival time of flight \( f \).

### 6.3.1.3 Airport destination binary variables

The two following tables correspond to the two binary variables that will be used as input data for the model.

\[
\begin{array}{ccc}
 & SJC_f & OAK_f \\
\hline
f_1 & 0 & f_1 & 0 \\
f_2 & 0 & f_2 & 0 \\
\vdots & \vdots & \vdots & \vdots \\
f_n & 0 & f_n & 0 \\
\end{array}
\]

Figure 6.4: Input binary variables stating the landing airport of flight \( f \).

The value of the above represented binary variables, as described in \([A.2.6]\), is equal to 1 if flight \( f \) has destination SJC (in case of \( SJC_f \) variable) or destination OAK (in case of \( OAK_f \) variable).

### 6.3.1.4 Capacity of aircraft available for chartering

The following table corresponds to the variable \( CapAircraft_a \) that will be used as input data for the model.

The value of the above represented variables, as described in \([A.2.3]\), is equal to the maximum number of passengers that can be chartered into flight \( a \).
### 6.3.2 Model assumptions

Airlines' operations are complicated to optimize as a whole due to the interaction of many factors and feasibility constraints of different resources. Four main constraints affect the feasibility of airline planning and disruption management, including aircraft maintenance checks, pilot work rules, fleet assignment and passenger accommodation.

Therefore, the following assumptions regarding concrete modelisation aspects have been made, in order to ensure an admissible problem complexity.

1. Connecting passengers will connect to their final destination from the Bay Area.
2. When chartering new aircraft, there are limited amount of aircraft available, and it has been assumed there is remaining arrival capacity for them at SFO.
3. When the rerouting is done through the alternative airports in the Bay Area, it has been assumed a 100% of the passengers will be transported to SFO.
4. The model will not take into account aircraft maintenance checks and pilot work rules, as these two constraints are less critical for disruption management than they are for airline planning.

### 6.3.3 Costs to optimize

The cost-effectiveness of the new solution of reaccommodation will take into account the following costs:

- **Passengers delay cost**
• **Squeezing cost:** Cost of squeezing passengers into flights to either SFO, SJC or OAK.

• **Chartering cost:** Cost of placing a new aircraft to ferry back diverted passengers.

• **Inter-modal substitution cost:** Cost of transporting passengers with motor-coaches, either from the diverted airport, or just within the Bay Area.

The mathematical programming will set the mix of squeezed passengers, passengers rerouted with inter-modal substitution, and passengers reaccommodated in an chartered aircraft, that will minimizes the total rerouting cost.

### 6.3.4 Objective function

The optimisation problem will minimize the value of the following objective function:

\[
[MIN] z = \sum_t \sum_p \left[ C_{Squeeze}^t_p + C_{Subst}^t_p + C_{Affrete}^t_p + C_{Stuck}^t_p \right]
\]  

As it can be seen in the formula above displayed, the mathematical programming will evaluate at every time period \( t \), if passenger \( p \) should be rerouted being squeezed into a flight \( f \), rerouted by complete inter-modal subsitution in a bus \( b \), ferried back with an chartered flight \( a \), or otherwise continue stuck at the diverted airport. The optimization will balance the cost of leaving the passengers stuck and rerouting them with every option. At the end of the chosen time horizon, no diverted passengers must remain in the diverted airport.

The following sections will describe how the costs attached to each rerouting option are computed.
6.3.4.1 Cost of squeezing passengers into departure flights

\[ CSqueeze^t_p = \sum_f Squeeze^t_{p,f} \times [ (DT_f - DivAT_p) \times \beta_{\text{wait}} \times CostP + \]
\[ + (FlightTime_{DivAirp} + BDT_{OAK} \cdot OAK_f + BDT_{SJC} \cdot SJC_f) \times \beta_{\text{transp}} \times CostP + \]
\[ + CostBV \times (SJC_f + OAK_f) ] \]

(6.9)

In the computation of \( CSqueeze^t_p \), the first term calculates the passengers waiting time for being rerouted, translated to economic terms with the passenger value of time (\( CostP \)) and weighted with the variable \( BetaWait \). The second term evaluates the economic value of the transportation times, weighted in this case with the variable \( BetaTransp \). Finally, the third term adds the operational costs of using motor-coaches, in case the passenger is squeezed into flights to the alternative airports in the Bay Area.

6.3.4.2 Cost of complete inter-modal substitution

\[ CSubst^t_p = \sum_b Subst^t_{p,b} \times [ (t \cdot TimeFactor - DivAT_p) \times \beta_{\text{wait}} \times CostP + \]
\[ + ( BDT_{DivAirp} \times \beta_{\text{wait}} \times CostP ) + CostBV ] \]

(6.10)

Equation (6.10) displayed above, represents the operating cost of applying a complete substitution of a flight, straight from the diverted airport. The first term of the equation computes the cost of passengers waiting time, according to the passenger value of time (\( CostP \)). The time of arrival to the diverted airport \( DivAT_p \) is substracted to the time of the assignment to the motor coach, time \( t \). The second term computes the cost of passenger transportation time, by multiplying the bus transportation time \( BDT_{Div} \) per the passenger value of time (\( CostP \)), weighted by the coeficient \( Beta_{transp} \). Finally, the third term of the equation computes the cost per passenger of contracting the motor coach service (\( CostBV \)).
6.3.4.3 Cost of chartering an aircraft

\[
CA_{\text{ffrete}}^t_p = \sum_b A_{\text{ffrete}}^t(p,a) \times \left[ (t \cdot \text{TimeFactor} - \text{DivAT}_p) \times \beta_{\text{wait}} \times \text{CostP} + (\text{FlightTime}_{\text{DivAirp}} \times \beta_{\text{transp}} \times \text{CostP}) + \text{CostAffrete} \right]
\]

Equation A.14 represents the total cost per passenger of chartering an aircraft to ferry diverted passengers to SFO from the diverted airport. The first term of the equation computes the cost of passengers waiting time, according to the passenger value of time (CostP), weighted by the coefficient Beta\text{wait}. The time of arrival to the diverted airport DivAT\_p is subtracted to the time of the assignment to the aircraft a, time t. The second term computes the cost of passenger transportation time, by multiplying the flight transportation time FlightTime\_DivAirp per the passenger value of time (CostP), weighted by the coefficient Beta\text{transp}. Finally, the third term of the equation computes the cost per passenger of chartering an aircraft (CostAffrete). This cost coefficient CostAffrete, as explained in section 6.2.4, has been defined in US$ per passenger.

Additionally, it has been assumed in this particular rerouting option:

- There is a limited amount of aircrafts available to affrete, as defined in re-\text{flimitations with the variable MaxAircraft.}
- All the aircraft placed are assumed to transport the passengers to SFO and fly back to their orginal airport, although they could remain in SFO until the end of the period of study.

6.3.4.4 Cost of passengers remaining in the diverted airport

\[
C_{\text{Stuck}}^t_p = \alpha \times \text{CostP} \times (t \cdot \text{TimeFactor} + \text{DivPaxAT}_p) \times \left( 1 - \sum_{\tau=1}^{t} \sum_f S_{\text{squeeze}}^t(p,f) - \sum_{\tau=1}^{t} \sum_b S_{\text{Subst}}^t(p,b) - \sum_{\tau=1}^{t} \sum_a A_{\text{ffrete}}^t(p,a) \right)
\]

(6.12)
Equation A.15 represents the cost of delay that passengers perceive if they remain in the diverted airport for long time periods. It has only one term, corresponding to the cost of passenger delay. The delay time is computed as the subtrac tion between the time period \( t \) in minutes \((t \cdot TimeFactor)\) and the arrival time of passengers to the diverted airport \(DivPaxAT_p\). The variable \(CStuck^t_p\) can only have a value greater than zero if the passenger has not been assigned to any mode yet. The constraints ensure that once the passenger has been assigned to one rerouting option, the variable \(CStuck^t_p\) will permanently be zero.

6.3.5 Constraints

6.3.5.1 Constraints of squeezing passengers into scheduled flights

1) The number of passengers squeezed into flight \( f \) in time period \( t+1 \), should be less or equal to the number of remaining available seats in flight \( f \) at time \( t+1 \):

\[
\sum_p Squeeze^{t+1}_{(p,f)} \leq Cap_f - Pax_f - \sum_{\tau=1}^{t} \sum_p Squeeze^\tau_{(p,f)} \quad \forall t, \forall f \tag{6.13}
\]

2) The passengers can not be squeezed into flight \( f \), if the flight has already departed:

\[
(t \cdot TimeFactor - DT_f) \times Squeeze^{t}_{(p,f)} \leq 0 \quad \forall t, \forall f, \forall p \tag{6.14}
\]

6.3.5.2 Constraints of the complete inter-modal substitution option

1) The number of passengers assigned to each motor coach must be less or equal to the motor-coach capacity, at every time slot:

\[
\sum_p Subst^{t+1}_{(p,b)} \leq CapBus - \sum_{\tau=1}^{t} \sum_p Subst^\tau_{(p,b)} \quad \forall b, \forall t \tag{6.15}
\]
2) The motor coach $b$ contracted for inter-modal substitution can only departure if it is filled up to a minimum bus load (MinloadBus), as explained in \[A.2.5\]. This restriction is guaranteed through 2 pairs of constraints:

**Part A:** Serves to fix the condition in which the bus must not departure.

\[
\begin{align*}
\text{MinloadBus} \cdot \text{CapBus} - \sum_{\tau=1}^{t} \sum_{p} \text{Subst}_{(p,b)}^{\tau} &< 0 + M_1 \cdot (1 - y_1) \\
\text{DTBus}_b^t - M_1 \cdot y_1 &\leq 0
\end{align*}
\]

(6.16)

Equation \[A.19\] must be valid $\forall b, \forall t$. $M_1$ is a very large number, and $y_1$ is an auxiliar binary variable. The underlying logic of the above presented statement is as follows:

- (IF) $\sum_{\tau=1}^{t} \sum_{p} \text{Subst}_{(p,b)}^{\tau} \geq \text{MinloadBus} \cdot \text{CapBus}$
  
  (THEN) $y_1 = 0$ or $y_1 = 1$
  
  [y=0] implying $\text{DTBus}_b^t \leq 0$. Then $\text{DTBus}_b^t = 0$
  
  [y=1], implying $\text{DTBus}_b^t \leq M_1$. Then $\text{DTBus}_b^t = 1$ or 0
  
  (The bus can departure)

- (IF) $\sum_{\tau=1}^{t} \sum_{p} \text{Subst}_{(p,b)}^{\tau} < \text{MinloadBus} \cdot \text{CapBus}$
  
  (THEN) $y_1 = 0$, implying $\text{DTBus}_b^t \leq 0$. Then $\text{DTBus}_b^t = 0$
  
  (The bus must not departure)

**Part B:** Serves to fix the conditions for which the bus must departure.

\[
\begin{align*}
\sum_{\tau=1}^{t} \sum_{p} \text{Subst}_{(p,b)}^{\tau} - \text{MinloadBus} \cdot \text{CapBus} &\leq 0 + M_2 \cdot (1 - y_2) \\
\text{DTBus}_b^t + M_2 \cdot y_2 &> 0
\end{align*}
\]

(6.17)

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Equation A.20 must be valid \( \forall b, \forall t \). \( M_2 \) is a very large number, and \( y_2 \) is an auxiliar binary variable. The underlying logic of the above presented statement is as follows:

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^\tau \leq MinloadBus \cdot CapBus \)
  (THEN) \( y_2 = 0 \) or \( y_2 = 1 \)
  
  \([y_2 = 0]\) implying \( DTBus_b^t > 0 \). Then \( DTBus_b^t = 1 \)
  
  \([y_2 = 1]\), implying \( DTBus_b^t \leq M_2 \). Then \( DTBus_b^t = 1 \) or \( 0 \)
  (The bus can departure)

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^\tau > MinloadBus \cdot CapBus \)
  (THEN) \( y_2 = 1 \)
  
  \([y_2 = 0]\) implying \( DTBus_b^t > 0 \). Then \( DTBus_b^t = 1 \)
  (The bus must departure)

3) Passengers can only be assigned to a certain bus at the time slot that the bus departures:

\[
M_1 \cdot DTBus_b^t \geq \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^\tau \quad \forall b, \forall t \quad (6.18)
\]

4) The motor coach \( b \) can departure at one time slot only, in between the starting time slot to the time horizon:

\[
\sum_t DTBus_b^t \leq 1 \quad \forall b \quad (6.19)
\]

6.3.5.3 Constraints corresponding to chartering a new aircraft

1) The number of passengers assigned to each new chartered aircraft must be less or equal to the aircraft capacity, at every time slot:
6 – Mathematical programming - Airport pairs optimisation model

\[ \sum_p \text{Affrete}^{t+1}_{(p,a)} \leq \text{CapAircraft}_a - \sum_{\tau=1}^{t} \sum_p \text{Affrete}^\tau_{(p,a)} \quad \forall a, \forall t \quad (6.20) \]

2) The aircraft a chartered can only departure if it is filled up to a minimum aircraft load (\(\text{MinloadAircraft}\)), as explained in [A.2.5]. This restriction is guaranteed through two pairs of constraints:

**Part A:** Serves to fix the situations in which the new chartered aircraft \(a\) must not departure.

\[
\text{MinloadAircraft} \cdot \text{CapAircraft}_a - \sum_{\tau=1}^{t} \sum_p \text{Affrete}^\tau_{(p,a)} < 0 + M_1 \cdot (1 - y_3)
\]

\[DT\text{Affrete}^t_a - M_1 \cdot y_3 \leq 0\]

Equation [A.24] must be valid \(\forall a, \forall t\). \(M_1\) is a very large number, and \(y_3\) is an auxiliar binary variable. The underlying logic is the equivalent to the one explained for equation [A.19].

**Part B:** Serves to fix the situations in which the chartered aircraft must departure.

\[
\sum_{\tau=1}^{t} \sum_p \text{Subst}^\tau_{(p,a)} - \text{MinloadAircraft} \cdot \text{CapAircraft}_a \leq 0 + M_2 \cdot (1 - y_4)
\]

\[DT\text{Affrete}^t_a + M_2 \cdot y_4 > 0\]

Equation [A.25] must be valid \(\forall a, \forall t\). \(M_2\) is a very large number, and \(y_4\) is an auxiliar binary variable. The underlying logic is equivalent to the previously explained for equation [A.20].

3) Constraint that ensures that passengers are assigned to chartered aircrafts in the time slot that the Aircraft departures:
\[ M_1 \cdot DT\text{Affrete}_a^t \geq \sum_{\tau=1}^{t} \sum_{p} Affrete_{(p,a)}^\tau \quad \forall a, \forall t \quad (6.23) \]

4) Every aircraft chartered \((a)\), can departure at one time slot only, between the starting time slot and the time horizon:

\[ \sum_t DT\text{Affrete}_a^t \leq 1 \quad \forall a \quad (6.24) \]

### 6.3.5.4 Passenger conservation constraints

1) Each passenger can be assigned only to one of the rerouting options in every time period:

\[ \sum_f Squeeze_{(p,f)}^t + \sum_b Subst_{(p,b)}^t + \sum_a Affrete_{(p,a)}^t \leq 1 \quad \forall p, \forall t \quad (6.25) \]

2) Each passenger must be assigned to only one rerouting option (Squeeze, Substitution or chartering) in all the time period of study. The equation also ensures that no passengers will continue stuck at the time horizon.

\[ \sum_t [ \sum_f Squeeze_{(p,f)}^t + \sum_b Subst_{(p,b)}^t + \sum_a Affrete_{(p,a)}^t ] = 1 \quad \forall p \quad (6.26) \]

3) Passengers can start to be assigned to the rerouting options only 30 minutes after their landing in the diverted airport:

\[ [ t \cdot TimeFactor - (30 + ActualDivAT_p) ] \times \times ( Squeeze_{(p,f)}^t + Subst_{(p,b)}^t + Affrete_{(p,a)}^t ) \geq 0 \quad \forall p, \forall t, \forall f, \forall b, \forall a \quad (6.27) \]

Underlying logic:
• (IF) \( t \cdot \text{TimeFactor} \geq (30 + \text{ActualDivAT}_p) \)
  (THEN) \[ Squeezed^t_{(p,f)} + \text{Subst}^t_{(p,b)} + Affretel^t_{(p,a)} = 0 \) or 1
  (the passenger can be assigned to one rerouting option)

• (IF) \( t \cdot \text{TimeFactor} \leq (30 + \text{ActualDivAT}_p) \)
  (THEN) \[ Squeezed^t_{(p,f)} + \text{Subst}^t_{(p,b)} + Affretel^t_{(p,a)} = 0 \]
  (the passenger can not be assigned to a rerouting option)

### 6.4 Cost coefficients determination

#### 6.4.1 Approaches in cost impact estimation of imperfect operations

The current practices in estimating the cost impact of imperfect operational performance on airlines can be classified into two approaches: Cost factor approach and aggregate cost approach.

As Hansen & Zou explained in [27] the cost factor approach is based on assigning unite costs to different categories of delay based on estimates of the resources consumed when a given category of delay occurs. The total cost factor \( C \), is equal to the sum of the cost in each category:

\[
C = \sum_i P_i \cdot X_i \quad (6.28)
\]

Where \( P_i \) denotes the unit cost per minute for delay in the ith category, and \( X_i \) represents the corresponding total delay minutes.

Determining cost factors rests on the assumption that delay causes additional consumption of largely the same inputs as the airlines’ normal line production process. Judgement must be made about which cost components (e.g. fuel, labor, capital, airport charges) need to be included for a specific type of delay, and the unit cost per delay minute for each cost component.

To determine these, two methods are most commonly adopted, both involving some uncertainties due to the lack of flight-level cost data. One is to use more
aggregated cost factors, e.g. cost for 1-min ground delay given an aircraft type, often based upon aircraft block hour cost data. Such estimates may be highly influenced by accounting conventions that often have little empirical basis. A second approach relies on expert opinion. However experienced, the views of these individuals are inherently subjective. Respondents will tend to incorporate cost impacts that are obvious to them while neglecting those that are not directly visible.

The other cost approach is the aggregate cost approach. This second venue is built upon firm or industry level relationships between total operating cost and delay. A simple version of this approach assumes that airline operating costs are proportional to the total aircraft operating time, and estimates delay cost as the fraction of total aircraft operating time that results from delay, multiplied by the total airline operating cost.

This avoids the difficult task of determining cost factors, and only requires straightforward calculation of the aggregate delay time and the total operating cost. Since overhead cost is part of the total operating cost, including not only fuel, crew salaries, maintenance, and depreciation, but also advertising, ticket agents, landing fees, legal fees, and other items that may be relatively insensitive to delays, this simple version generally produces higher delay cost estimates than the cost factor approach.

In order to estimate the value of the cost coefficients used as input in the model, it has been applied the aggregated cost approach in the cases there was rigorous data available. Estimations of the passengers value of time and the operational costs of inter-modal substitution have been done using the aggregate cost approach. Nevertheless, it has been used the cost factor approach in order to estimate the operational costs of chartering a new aircraft, based on the study described in [7] by the Economic counsel to the Transportation Industry, released in 2004.

The following sections summarize the computations of each cost coefficient included in the mathematical programming.
6.4.2 Model cost coefficients estimation

6.4.2.1 Passenger value of time

First it will be addressed how to translate the impact of delays on passengers into monetary terms. Time is a valuable economic resource that may be devoted to work or leisure activities. Because traveling consumes time, it imposes an opportunity cost equal to the individual value of time in the forgone work or leisure activity.

The Department of Transportation proposes in [7] an approach to measure the hourly values of travel time for aviation passengers. These values are used by the Federal Aviation Administration (FAA), and are not to be updated for changes in price levels.

The following table shows the recommended hourly values of travel time savings, proposed by the Department of Transportation (DOT) upon guidance furnished by the Office of the Secretary of Transportation of the United States of America (OST).

<table>
<thead>
<tr>
<th>Category</th>
<th>Recommendation</th>
<th>Sensitivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Air Carrier:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal</td>
<td>$23,30</td>
<td>$20,00</td>
</tr>
<tr>
<td>Business</td>
<td>$40,10</td>
<td>$32,10</td>
</tr>
<tr>
<td>All Purposes</td>
<td>$28,60</td>
<td>$23,80</td>
</tr>
<tr>
<td>General Aviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal</td>
<td>$31,50</td>
<td>NR</td>
</tr>
<tr>
<td>Business</td>
<td>$45,00</td>
<td>NR</td>
</tr>
<tr>
<td>All Purposes</td>
<td>$37,20</td>
<td>NR</td>
</tr>
</tbody>
</table>

Figure 6.6: Recommended values for aviation passenger travel time.

As there is no specific data available on the travel purpose of the diverted passengers, one will assume that all the passengers in the study can be embraced by the category "air carrier, all purposes". Therefore, one can conclude that the cost coefficient $CostP$ that will be used in the mathematical model, to represent the diverted passengers value of time, will be equal to 28,60 US$. 

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6.4.2.2 Cost of chartering a new aircraft

In order to get a sense of the costs of chartering a new aircraft, it has been used the estimations of aircraft operating costs done by the Economic counsel to the Transportation Industry in [7]. The guide proposes cost data defined for air carrier and general aviation aircraft as variable or fixed. Variable costs change in proportion to aircraft usage, and include fuel and oil, maintenance and crew costs. One could assume that crew costs are fixed in the short run, especially in the case for entities that operate one or a small number of aircraft, but as the airlines involved in the study are big air carriers, the cost of crew will be left as variable.

The U.S. airline industry has undergone considerable financial restructuring following the events of September 11, 2001. This, coupled with a shift in the business cycle, caused severe losses for U.S. air carriers, and a situation where the supply of seats in the industry well exceeded demand at existing price levels. In response, carriers reduced fares to maintain traffic levels, or took aircraft out of service. This in turn reduced airline revenues and caused carriers to enter into significant cost reduction programs. Some carriers reorganized their finances and obligations through the bankruptcy process. During this time, the "old line" carriers actually reduced their level of output while the "low cost carriers" increased market share.

Since then, the trend in air carriers shows the direct operating expenses to be below the 50 percent of total costs for major air carriers. To support this fact, the following table provides a perspective on overall carrier costs and the relative magnitudes of each category of costs. The air carrier costs are shown per block hour by objective grouping. The data is divided into passenger and all cargo carriers and then into the groupings of Major, National, and Regional carriers. Major air carriers have annual revenues of more than $1 Billion; whilst national carriers have annual revenues of more than $100 million.

The source of cost data for carriers used in [7] was the Bureau of Transportation Statistics (BTS) Form 41 and Form 298-C. Form 41 data covers large air carriers (generally those with annual revenues of at least $100 million), although some carriers have exemptions from reporting Form 41. Form 298-C data cover smaller air carriers (generally smaller carriers operating under FAR 121 and / or FAR 135). FAR 121 is a section of 14 CFR (Code of Federal Regulations). Basically, airlines fall under FAR 121 regulations if they are a regularly scheduled air carrier. This
is compared to FAR 135 operators (generally on-demand charter-type services), or Part 91 operators (general operators).

As shown in figure 6.7, the focus will be the category "Passengers", as they are mainly the air carriers involved in the study. The last row of figure 6.7 summarizes the total operating costs of aircraft per block hour, specified per type of air carrier (Major, National or Regional). In the mathematical model, the cost coefficient that represents the cost of operating a new aircraft chartered, \( Cost_{Affreting} \), is defined per passenger. The reason for specifying the cost of chartering per passenger is that it enables the model to escalate the cost of chartering an aircraft. A great number of passengers will mean a linear greater cost, and thus embracing a wider range of aircraft type that can be chartered without having to specify them previously, as there is no data regarding which aircraft were available at every time slot.

It will be assumed in the model that all the aircraft used for affreting will be "passenger" aircraft from "Major" air carrier type. Therefore, one can observe how the cost of chartering the aircraft will be 6.445 US$ per hour. Then, in

<table>
<thead>
<tr>
<th>Expense Category</th>
<th>Passenger</th>
<th>All Cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Majors</td>
<td>Nationals</td>
</tr>
<tr>
<td>General Management Personnel</td>
<td>$30</td>
<td>$44</td>
</tr>
<tr>
<td>Flight Personnel</td>
<td>$816</td>
<td>$329</td>
</tr>
<tr>
<td>Maintenance Labor</td>
<td>$238</td>
<td>$94</td>
</tr>
<tr>
<td>Aircraft and Traffic Handling</td>
<td>$480</td>
<td>$183</td>
</tr>
<tr>
<td>Other Personnel</td>
<td>$252</td>
<td>$89</td>
</tr>
<tr>
<td>Total Salaries</td>
<td>$1,817</td>
<td>$739</td>
</tr>
<tr>
<td>Total Fringe Benefits</td>
<td>$768</td>
<td>$256</td>
</tr>
<tr>
<td>Total Salaries and Benefits</td>
<td>$2,584</td>
<td>$995</td>
</tr>
<tr>
<td>Total Material</td>
<td>$1,136</td>
<td>$617</td>
</tr>
<tr>
<td>Total Services</td>
<td>$1,131</td>
<td>$701</td>
</tr>
<tr>
<td>Landing Fees</td>
<td>$138</td>
<td>$73</td>
</tr>
<tr>
<td>Rentals</td>
<td>$570</td>
<td>$510</td>
</tr>
<tr>
<td>Depreciation</td>
<td>$362</td>
<td>$98</td>
</tr>
<tr>
<td>Amortization</td>
<td>$42</td>
<td>$4</td>
</tr>
<tr>
<td>Other</td>
<td>$120</td>
<td>$141</td>
</tr>
<tr>
<td>Transport Related Expenses</td>
<td>$291</td>
<td>$17</td>
</tr>
<tr>
<td>Total Operating Expenses</td>
<td>$6,375</td>
<td>$3,156</td>
</tr>
<tr>
<td>Total Non-Operating Expenses</td>
<td>$70</td>
<td>$110</td>
</tr>
<tr>
<td>Total Expenses ($/hour)</td>
<td>$6,445</td>
<td>$3,267</td>
</tr>
</tbody>
</table>
order to make the chartering cost scalable, it has been assumed an average aircraft passenger capacity. The average passenger capacity of aircraft will depend of every airport, as airport facilities (such as runway length or taxi facilities) condition the size of aircraft that can be operated in each airport. Nevertheless, it will be established an average passenger capacity of 120 seats, roughly estimated according to the aircraft type volume operated at SFO.

One can conclude finally that the CostAffreting coefficient that will be used in the model, will be calculated dividing the 6.445 US$ per hour, per an estimated average passenger capacity of 120 seats. Thus, CostAffreting coefficient it is estimated as 53.70 US$ per passenger.

6.4.2.3 Cost of inter-modal substitution

It was analysed previously in the report "Operational issues in inter-modal substitution" how the inter-modal substitution would be operated. Two separate assessments were done, first the assessment of a partial inter-modal substitution, within the Bay Area, and secondly a complete inter-modal substitution, applying the substitution straight from the diverted airports to SFO. The objective of the assessments was to be able to compute the coefficients CostBV_{BayArea} and CostBV_{DivAirport}, that are needed as input data for the mathematical programming developed.

The inter-modal substitution within the Bay Area, as explained in the previous report, would take part if passengers are squeezed into flights to the alternative airports in the Bay Area (San Jose or Oakland), from where passengers would be sent to SFO by surface means of transport. The conclusions of the assessment showed how the most cost-effective substitution, in terms of passenger time savings and airline operational costs, would be to contract local charter-companies for the inter-modal service in an on-call basis. The variable cost estimated was of 7.50 US$ per passenger. Regarding the service fixed costs, one could think airlines would have to pay a fixed amount to charter companies, in order to ensure charter companies would prioritize the airlines demands in case they had already been booked. Nevertheless, as it has not been possible to conduct surveys with local charter companies to ask which fare would be charged, it will be assumed in the model that the only cost of inter-modal service is the variable cost.

Therefore, one can conclude, that the cost coefficient CostBV_{BayArea} used for the model will be of 11 US$ per passenger.
The second approach analysed the most cost-effective substitution corresponding to the complete inter-modal substitution. If one recalls, only the Los Angeles Intl. Airport, Reno Tahoe Intl. Airport and Sacramento Intl. Airport presented feasible complete inter-modal substitutions, therefore only the operational costs for these 3 airports were computed. The assessment showed how the operational costs of the inter-modal service at these 3 airports were similar to those in the Bay Area. The difference resides in the frequency for which the same motor coach could be used. For instance, within the Bay Area each motor coach was estimated to be able to perform 3 substitution per day, whilst in Sacramento, motor coaches could be used only for two substitutions. In the case of Reno Tahoe or Los Angeles, each motor coach could perform only one substitution, due to greater driving distances to SFO. Evidently, a higher service frequency will lower the costs, making the inter-modal service a better option for the airports that are closer to SFO.

Furthermore, the assumption on fixed costs of the inter-modal service would apply, as there was no possibility of conducting surveys with local charter companies at Sacramento, Reno or Los Angeles.

Therefore, as for the study presented in previous reports, one can conclude how the cost coefficient $CostBV_{DivAirport}$ would have the following values for the 3 airports in which this rerouting option is feasible:

- $CostBV_{Sacramento} = 11$ US $ per passenger.
- $CostBV_{Reno} = 22$ US $ per passenger.
- $CostBV_{LosAngeles} = 22$ US $ per passenger.

### 6.4.2.4 Summary of cost coefficient estimations

After analysing each cost coefficient used in the mathematical programming separately, one can now summarize all the values in the following table, in order to have them present for the model implementation.

One can observe how the cost coefficients give us a sense of the cost-effectiveness of each rerouting option. As expected, the operational costs of inter-modal service are lower than the operational costs of chartering a new aircraft.
However, one must have in mind that the mathematical programming will balance the operational costs (associated with the cost coefficients shown in figure 6.8), with the cost savings that a lower delay may generate (associated with the passenger value of time). Therefore, low operational costs will not always be an indicator of the most cost-effective rerouting.

### 6.5 Representation of cost behaviour in rerouting options

The following section will show, according to the cost coefficients previously summarized, how the programming will trade-off the different costs in order to decide which rerouting option is the most cost effective. As an example, two scenarios have been built, to show two different situations that may arise during the rerouting of diverted passengers:

All the scenarios will be assumed to be reroutings from Reno Tahoe International airport (RNO). Flights connecting RNO and SFO have an estimated length of 55 minutes, whilst the bus driving time is about 120 minutes. The scenarios do not include the option of being squeezed into flights to the alternative airports in the Bay Area (SJC or OAK) and then transported through surface means of transport to SFO. Having these assumptions in mind one can start analysing the 2 scenarios represented below.
6.5.1 Scenario 1 - All airlines’ ressources available

The first scenario represents a diverted passenger being rerouted as soon as he is available in the diverted airport. The cost representation of this scenario shows the evolution with time of the cost per passenger attached to every rerouting option. The scenario assumes that there are available buses for inter-modal substitution, available aircraft to be chartered (and remaining capacity at SFO for their landing), as well as available seats for the passenger to be squeezed into flights either to SFO or the Bay Area.

![Figure 6.9: Rerouting scenario 1](image)

Please notice in figure 6.9 how the time value $t$ starts the moment in which the passenger lands in the diverted airport ($t = 0$). As it can be observed the passenger is not available for being reaccomodated after 30 minutes after his landing ($t = 30$). This is due to the fact that it takes approximately 30 minutes for passengers to get out of the aircraft, pick their luggage, and follow the instructions to go to the next boarding gate.

As it has been previously stated, the figure represents the evolution with time...
of the cost per passenger attached to every rerouting option. If one recalls from Chapter 5, the rerouting options that passengers have are:

- Squeezing into flights to SFO
- Squeezing into flights to OAK or SJC
- Reaccommodation with an chartered aircraft
- Substitution from the diverted airport to SFO
- Remain stuck at the diverted airport

Figure 6.9 shows how in this first scenario, squeezing the passenger into a flight to SFO is the most cost effective, as this rerouting option involves no additional cost other than the passenger delay cost. The second most cost effective solution would be to squeeze the passenger into a flight to either SJC or OAK, then would come the complete inter-modal substitution, and finally the least cost effective option would be to affrete an aircraft to send passengers to SFO.

The mathematical model developed performs the trade-off between the different options and will select the rerouting that is more cost-effective. Paying closer attention to figure 6.9, the linear behaviour of each cost function can be understood when having in mind the costs that every rerouting option has attached:

- **Squeezing into flights to SFO**: Linear function. Only computes the cost of passenger delay (time dependent).
- **Squeezing into flights to OAK or SJC**: Linear function with a fixed cost. Computes the cost of passenger delay (time dependent), and adds the operational cost of contracting motor-coaches (fixed amount per passenger).
- **Reaccommodation with an chartered aircraft**: Linear function. Computes the cost of passenger delay (time dependent), and adds the operational cost of chartering an aircraft (modeled time dependent to be scalable).
- **Substitution from the diverted airport to SFO**: Linear function with a fixed cost. Computes the cost of passenger delay (time dependent), and adds the operational cost of contracting motor-coaches (fixed amount per passenger).
- **Remain stuck at the diverted airport**: Linear function. Only computes the cost of remaining stuck in the diverted airport (time dependent).
As it has previously been stated, this Scenario assumes that the airline would have all the resources necessary to implement the 5 rerouting options at \( t = 30 \). This hypothesis is rarely true, and therefore some rerouting options would require longer waiting time for passengers, and thus an increase in the delay cost component. The next scenario shows this situation.

### 6.5.2 Scenario 2 - Not all airlines’ resources available

The first scenario represented a diverted passenger being rerouted as soon as he is available in the diverted airport, as it has been hypothesized that Airlines’ had all the resources needed for each rerouting option (motor coaches, chartered aircrafts, remaining capacity in outgoing flights to the Bay), thus they had only to pick the most cost-effective one. Nevertheless, this situation is not realistic.

The second scenario represents a new situation, in which the airline does not dispose of all these mentioned resources at the arrival of the diverted passenger. For instance, scenario 2 assumes the following lack of resources:

- There are no resources available from \( t = 0 \) to \( t = 120 \).
- At \( t = 120 \) the airline disposes of an aircraft to affrete, and a motor-coach to perform a complete inter-modal substitution.
- At \( t = 180 \) two flights departure with remaining capacity for diverted passengers to be squeezed in, one with destination to SFO and the other with destination OAK.

According to the resources’ availability previously detailed, it can be observed how in Scenario 2, the minimum waiting time for this diverted passenger will be 2 hours. After the two hours the passenger has the possibility to be reaccomodated into an chartered aircraft or a contracted motor-coach. Furthermore, if the passenger prefers to wait 3 hours, he/she could be squeezed into a flight either to SFO or to OAK.

The following figure shows how the computing of the costs would be in Scenario 2, taking into account the previously detailed resources’ availability.
It can now be observed how the change in the resources’ availability modifies the whole picture. In Scenario 2, the most cost effective option would be to squeeze the passenger in the flight with destination to SFO, although it would involve the passenger to wait for 3 hours in the diverted airport. The second most cost-effective option would be to reaccomodate the passenger in a motor-coach with destination SFO. The third option would be to squeeze the passenger into a flight to OAK, and finally the least cost-effective option would be to reaccomodate the passenger in an chartered aircraft.

In this new Scenario, the mathematical programming will reaccomodate the passenger in the squeezed flight, as it is the most cost-effective rerouting option. Nevertheless, it can also be seen how the passenger would perceive a longer trip in this option, and would have to be stuck a longer period in the airport, than if he/she is rerouted with a contracted motor-coach.

### 6.5.3 Scenarios conclusion

First, the two different scenarios show how the mathematical programming will select the rerouting option that is most cost-effective, according to the resources
available in that particular time period.

Secondly, the cost representation shows how the cost of each rerouting option will be a trade-off between the cost of passengers’ delay and the operational costs attached to that particular rerouting option. For instance, a faster rerouting will mean less delay costs but it may involve also greater operational costs, transforming it into a not so efficient rerouting option.
Chapter 7

Implementation Analysis

7.1 Introduction

The objective of the implementation performed was to; first give a better understanding of how the model parameters interact in the decision-making of the rerouting of passengers, through a sensitivity analysis on some of the parameters of the model. Secondly, and most important, was to prove how an efficient and systematic inter-modal rerouting could help airlines to recover their schedules faster in critical situations. In order to correctly understand the implementation scenarios, two main assumptions must be defined:

- **The rerouting of passengers will be aggregated.** In such disruptive situations as Asiana Crash, where SFO remained nearly closed for more than one day and where more than 7,000 passengers must be rerouted, airlines may be obliged to collaborate even out of their alliances, in order to ensure a cost-efficient recovery from the disruptions. Therefore, no distinction between airlines has been performed in the rerouting of passengers, imposing the rule First-Arrived-First-Served.

- **BTS represents a realistic set of flight data.** Although BTS data does not contain information regarding international flights, as the number of international diverted flights as consequence of Asiana Crash was low, it has been assumed that the data provided by the Bureau of Transportation Statistics is representative enough to ensure a realistic implementation of the mathematical model developed.

- **Rerouting of the flights that could not reach SFO.** According to the BTS data, the implementations will only take into account the flights that
had as scheduled destination SFO, but after being diverted have no reported arrival to SFO.

- **One-day rerouting.** In coherence with the airlines behaviour in the rerouting of passengers, the inter-modal and charter rerouting options have only been taken into account within the day of arrival of the passengers. The overnight of passengers in hotels to wait for next day flights has not been considered.

As for the analysis performed on the feasibility of an inter-modal substitution between the airports involved in the absorption of diverted flights during the 4-day period of study, the implementation has only been performed in the four airports for which it was feasible. Due to a extremely high driving times to SFO, the rerouting from Phoenix, Denver, Salt Lake City, Seattle and Mississippi has not been performed. Therefore, the implementations that will be shown in this chapter are as follow:

1. **Reno Tahoe Intl. Airport**
   - Sensitivity analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources
   - Sensitivity analysis on Minimum Aircraft and Bus passenger loads.

2. **Sacramento Intl. Airport**
   - Sensitivity analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources

3. **Reno Tahoe Intl. Airport**
   - Sensitivity analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources
   - Comparison with a non-intermodal rerouting

4. **Mc Carran Intl. Airport (Las Vegas)**
   - Sensitivity analysis on available resources
   - Comparison with a non-intermodal rerouting

The different implementation scenarios have been defined to grow in the number of rerouted passengers and available resources, being able to apply the feedback of the implementations of smaller samples to the greater reroutings. The objective of the implementation scenarios can be understood as follows:
The first implementation performed was the rerouting from Reno Tahoe Intl. Airport, located 230 miles from SFO and absorbing only two diverted flights. It was aimed basically to give a better understanding of the correct performance of the model, and a first insight on a sensitivity analysis, although the low volume was not very representative. Secondly, the rerouting from Sacramento Intl. Airport has been performed, to give a broader insight on the sensitivity analysis after the conclusions from the first implementation.

The third rerouting optimised has been from Los Angeles Intl. Airport, with a greater amount of passengers diverted, and a diverse scope of resources available, with the objective of giving a real image of the trade-off between modes in the decision-making process of the mathematical model. Finally, the last optimisation has been from Mc Carran Intl. Airport, aims to give a Worst Case Scenario due to its distance to SFO, in order to understand how higher driving times influence the prioritisation for air modes of transportation.
7.2 Case Scenario 1: Rerouting from Reno-Tahoe International Airport

7.2.1 Input Data

7.2.1.1 Set of diverted flights

The model implementations have been performed on a real set of data, as specified in Chapter 1. The first implementation corresponds to the rerouting of the diverted passengers to Reno-Tahoe International Airport (RNO).

As it has been introduced in Chapter 1, during the 4 day period of study, RNO International Airport only absorbed diversions the 6th of July, which accounted for a 4% of the total diverted flights on the date. Furthermore, these flights were not able to reach their final destination (SFO) after the diversion to RNO. Therefore, the mathematical programming will try to assess the most cost-effective solution for the rerouting of these diverted passengers back to SFO. Extracted from the database available from BTS, the following table shows the set of flights with destination SFO that were diverted to RNO. The table has been also used as input data for the optimizations.
7 – Implementation Analysis

Figure 7.2: Set of diverted flights to RNO

<table>
<thead>
<tr>
<th>DAY</th>
<th>TAIL_NUM</th>
<th>FL_NUM</th>
<th>Pass. load</th>
<th>DT</th>
<th>ActualDT</th>
<th>AT</th>
<th>ActualDivAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N76523</td>
<td>1085</td>
<td>170</td>
<td>12:34</td>
<td>12:34</td>
<td>15:17</td>
<td>14:30</td>
</tr>
<tr>
<td>1</td>
<td>N593ML</td>
<td>6345</td>
<td>41</td>
<td>11:49</td>
<td>11:45</td>
<td>13:19</td>
<td>13:00</td>
</tr>
</tbody>
</table>

Where the columns of the table correspond to:

- DAY: Day of the 4-day period of study. In this case 6th of July.
- TAIL_NUM: Tail number of the diverted flight.
- FL_NUM: Flight number of the diverted flight.
- Pass. load: Estimated passenger load.
- DT: Departure time.
- ActualDT: Actual departure time.
- AT: Scheduled arrival time.
- ActualDivAT: Actual arrival time to the diverted airport.

As it can be observed, only two flights were diverted to RNO on the 6th of July, landing between 1pm and 2:30 pm. The total number of passengers that will need to be rerouted is 211 passengers.

7.2.1.2 Set of departure flights to the Bay Area

The first rerouting possibility of diverted passengers, as seen in Chapter 5, is to be squeezed into flights to the Bay Area. Particularly, Reno-Tahoe is a small airport with no flights connecting to OAK or SJC, but only with SFO. The following figure shows the set of flights that have been used as input data.

Most of the columns of table 7.3 contain the same variables as the input data for the diverted flights. Additionally, the following data is provided specifically for departure flights:

- DEST: Destination airport of the departure flight.
- Capacity: Maximum passenger capacity of the aircraft assigned to the tail number.
- ActualAT: Actual arrival time of the departure flight.
7.2.1.3 Aircraft and bus capacities

The last input data required by the mathematical programming is the passenger capacities of the aircraft available to be affreted, as well as for the motor coaches used for inter-modal substitution.

After the study performed on the operational issues in inter-modal substitution, please see section Chapter 5, it has been assumed that all the motor-coaches available for inter-modal substitution have the same capacity: 40 passengers. Regarding the passenger capacity of the aircraft affreted, as it is impossible to know which aircraft were available at every time period for the 4-day period of study, it has been assumed that there is a mixture of the more commonly used aircraft in domestic flights. The following table shows passenger capacity of the fleet assumed to be available:

<table>
<thead>
<tr>
<th>FL_DATE</th>
<th>TAIL_NUM</th>
<th>FL_NUM</th>
<th>Capacity</th>
<th>Pass. load</th>
<th>DEST</th>
<th>DT</th>
<th>ActualDT</th>
<th>AT</th>
<th>ActualAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>N982SW</td>
<td>5628</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>5:30</td>
<td>5:32</td>
<td>638</td>
<td>6:34</td>
</tr>
<tr>
<td>06/07/2013</td>
<td>N984CA</td>
<td>6484</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>9:35</td>
<td>9:29</td>
<td>10:52</td>
<td>10:37</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>N768SK</td>
<td>6484</td>
<td>78</td>
<td>71</td>
<td>SFO</td>
<td>9:34</td>
<td>10:00</td>
<td>10:51</td>
<td>12:14</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>N962SW</td>
<td>6336</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>10:53</td>
<td>11:30</td>
<td>12:10</td>
<td>13:16</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>N978SW</td>
<td>5528</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>17:23</td>
<td>20:08</td>
<td>18:30</td>
<td>21:15</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>N917SW</td>
<td>5628</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>5:30</td>
<td>5:36</td>
<td>638</td>
<td>6:41</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>N962SW</td>
<td>6454</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>14:16</td>
<td>16:43</td>
<td>15:23</td>
<td>17:51</td>
</tr>
<tr>
<td>08/07/2013</td>
<td>N978SW</td>
<td>6484</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>9:39</td>
<td>9:36</td>
<td>10:56</td>
<td>10:53</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>N983SW</td>
<td>5628</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>5:30</td>
<td>5:24</td>
<td>638</td>
<td>6:43</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>N913SW</td>
<td>6454</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>14:16</td>
<td>17:35</td>
<td>15:23</td>
<td>19:03</td>
</tr>
<tr>
<td>09/07/2013</td>
<td>N980SW</td>
<td>6484</td>
<td>50</td>
<td>46</td>
<td>SFO</td>
<td>9:39</td>
<td>11:38</td>
<td>10:56</td>
<td>12:58</td>
</tr>
</tbody>
</table>

Figure 7.3: Set of departure flights from RNO to the Bay Area

In figure 7.21, the aircraft with a maximum capacity of 60 passengers could correspond to a Bombardier CL-600-2C10 Regional Jet in a small configuration,
typically operated by Sky West Airline. Aircraft with maximum load of 70 passengers could correspond to the Bombardier model CL-600-2D15 (Regional Jet Series 705) or a CL-600-2C10 in a large configuration. Finally, the aircraft with seating capacity of 120 passengers represent the Airbus A319, typically operated by Virgin America, United Airlines or US Airways, or the Boeing 737, typically operated by SouthWest Airlines, United Airlines, Delta or US Airways.

7.2.2 Implementation Scenario

Because the linear program formulation grows almost linearly with the number of passengers, it has been decided to perform an implementation using passenger aggregation by batches. In this first implementation, passengers have been grouped in batches of 10 passengers. This measure reduces 10 times the number of variables of the program, and therefore the computational time required to optimize every scenario, making feasible a sensitivity analysis on a larger number of cases.

7.2.2.1 General optimization context

The optimization scenario has the following general input variables:

<table>
<thead>
<tr>
<th>Scenario context - Rerouting Reno</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization starting time slot (11 am)</td>
<td>44</td>
</tr>
<tr>
<td>Optimization horizon (12 pm)</td>
<td>96</td>
</tr>
<tr>
<td>Time slot length</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Bus driving time RNO - SFO</td>
<td>300 minutes</td>
</tr>
<tr>
<td>Bus driving time OAK - SFO</td>
<td>75 minutes</td>
</tr>
<tr>
<td>Bus driving time SJC - SFO</td>
<td>50 minutes</td>
</tr>
<tr>
<td>Flight time RNO - SFO</td>
<td>105 minutes</td>
</tr>
<tr>
<td>Minimum bus load</td>
<td>100%</td>
</tr>
<tr>
<td>Minimum aircraft load</td>
<td>90%</td>
</tr>
</tbody>
</table>

Figure 7.5: General optimization input variables.

7.2.3 Sensitivity Analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources

The first implementation analysis has been to perform a sensitivity analysis over the input variables $\beta_{\text{Wait}}$, $\beta_{\text{Transp}}$, Max $\text{buses}$ and Max $\text{Affrète}$. The aim of this first sensitivity analysis was to analyse how these variables condition
the assignment to the rerouting options in this first RNO based scenario. The optimization has been performed on 539 different scenarios, in which previously described input values were modified according to the following ranges:

- $\beta_{\text{Wait}}$: From 0.5 to 1.35 in steps of 0.05
- $\beta_{\text{Transp}}$: From 1.5 to 0.65 in steps of 0.05. ($\beta_{\text{Transp}} = 2 - \beta_{\text{Wait}}$)
- $\text{Max}_Buses$: From 5 to 10 in steps of 1
- $\text{Max}_Affrete$: From 1 to 5 in steps of 1

In this second analysis, all the scenarios were feasible. The results for every optimization were computed and can be summarized in the following figure:

![Figure 7.6: Feasibility analysis of the optimizations](image)

As one can observe in figure 7.6, only a 20% of the optimizations had a feasible solution. This is due to the fact that in the rerouting of RNO passengers the 6th of July, the available departure flights to squeeze in passengers had already departed before diverted passengers landed. Furthermore, the restrictions in the minimum bus and aircraft load make some scenarios infeasible, as there is no configuration in which the buses and aircraft can be filled up to its minimum load and reroute the 100% of the passengers at the same time. The following figure shows how only feasible solutions were obtained for the scenarios with 5 aircraft available to be affreted, in which the mathematical programming finds an optimal solution by rerouting passengers through two aircraft carrying a total of 130 passengers and 2 buses loaded with 80 passengers in total.
Figure 7.7: Cost objective function against number of buses and aircraft available.

Figure 7.7 shows how the value of the cost objective for the different optimizations differs. Nevertheless, one can observe how the value is constant for any given maximum number of buses. This is due to the fact that the optimal solution computed uses only two buses. Furthermore, one can see how there are only feasible solutions when airlines have 5 aircraft available. This is a result of the combination of the input data displayed in figure 7.21 and the minimum load for aircraft (90%) and bus (100%). The following figure displays the rerouting departure times of the diverted passengers in the different modes to which they were assigned.

As it has been mentioned previously, all the feasible solutions provided the same rerouting configuration due to the minimum load constraints, as figure 7.8 shows. Nevertheless, figure 7.7 denotes how the objective function value obtained differs for the different feasible scenarios differs. This is result of the variation of $\beta_{\text{wait}}$ and $\beta_{\text{transp}}$ values.

The following figure shows the distribution of the objective function values obtained for the feasible scenarios, against $\beta_{\text{wait}}$. 
As it can be inferred from this first sensitivity analysis, the influence of $\beta_{\text{wait}}$ and $\beta_{\text{transp}}$ in the assignment to the different rerouting modes is constrained by the minimum loads of the buses and aircraft affreted. Furthermore, as this first rerouting involved only 210 passengers, the margin for variations of the optimal solutions was very low. Thus, another sensitivity analysis has been performed in the RNO rerouting case scenario, to try to assess the influence of the variables $\text{MinimumBusLoad}$ and $\text{MinimumAircraftLoad}$.
7.2.4 Sensitivity Analysis on minimum Aircraft and Bus loads

This second sensitivity analysis has been performed over the input variables \( \text{MinimumBusLoad} \) and \( \text{MinimumAircraftLoad} \). The aim of this second sensitivity analysis was to analyse how these variables condition the assignment to the rerouting options in this first RNO based scenario by fixing \( \beta_{\text{wait}} \), \( \beta_{\text{transp}} \), \( \text{Max\_buses} \) and \( \text{Max\_Affrete} \) values. The optimization has been performed on 12 different scenarios, in which the previously described input values were modified according to the following ranges:

- \( \beta_{\text{Wait}} = 1 \) (Fixed)
- \( \beta_{\text{Transp}} = 1 \) (Fixed)
- \( \text{Max\_Buses} = 6 \) (Fixed)
- \( \text{Max\_Affrete} = 7 \) (Fixed)
- \( \text{MinimumBusLoad} \): Vary from 80% to 100% in steps of 10%.
- \( \text{MinimumAircraftLoad} \): Vary from 85% to 100% in steps of 5%.

The results now show certain variation in the assignment of passengers:

As it can be observed, two different rerouting configurations are obtained for the corresponding input data. In this case, as the value of \( \beta_{\text{wait}} \) and \( \beta_{\text{transp}} \) is fixed to be equal to one, the difference between the values of the cost objective function is only attributed to the allocation of more resources. The two optimal solutions that were obtained in this new analysis are presented in the following histograms:

As it can be observed in figure 7.11a, the first optimal rerouting allocates two buses with a total of 80 passengers, and two affreted aircraft with 60 and 70 passengers respectively, whilst the second optimal configuration shown in figure 7.11b, the mathematical programming allocates one bus filled with 40 passengers and two aircraft with a total of 170 passengers.

Although this second sensitivity cost analysis has been performed on a small sample, only 12 optimization scenarios, it can still be inferred how the minimum bus and aircraft loads impact in the assignment of passengers in the different modes.
Figure 7.10: Cost objective distribution against the minimum bus and aircraft loads

Figure 7.11: Optimal solutions of the sensitivity cost over the minimum bus and aircraft loads.

Airlines could for instance prioritize the time of their passengers, by letting buses leave being not fully booked, or otherwise they could decide to lower the rerouting costs to the maximum level, by not permitting the buses or aircraft leave unless they have been fully filled with diverted passengers.
7.2.5 Conclusions

From the first sensitivity analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources no relevant conclusions can be extracted. The low number of diverted passengers, added to the restriction of the minimum bus and aircraft loads, make infeasible to obtain many different rerouting configurations. Nevertheless, it can be inferred how the variation of $\beta_{\text{wait}}$ and $\beta_{\text{transp}}$ influence the value of the cost objective function.

The second sensitivity analysis, performed on minimum aircraft and bus loads, shows how the minimum passenger load to departure conditions in an earlier departure of the vehicles, as well as in the rerouting configuration. As shown in the results, a lower minimum bus loads impacts in the assignment of less passengers to chartered aircrafts.
7.3 Case Scenario 2: Rerouting from Sacramento International Airport

7.3.1 Input Data

7.3.1.1 Set of diverted flights

The second rerouting scenario corresponds to the reaccommodation of the diverted passengers from Sacramento International Airport (SMF). SMF is located 100 miles from SFO, northwest from the Bay Area. SMF absorbed 676 diverted passengers in 7 flights. The first 5 flights landed in SMF the 6th of July, with a total passenger load of 540 passengers, whilst the other two flights landed the 9th of July, with a passenger load of 136 passengers. Only the flights in the 6th of July were not able to reach their final destination SFO, therefore this scenario will reaccommodate efficiently the 540 passengers that were not able to reach SFO on the 6th of July.

![Location of Sacramento International Airport](image)

Figure 7.12: Location of Sacramento International Airport

Extracted from the database available from BTS, the following table shows the set of flights with destination SFO that were diverted to SMF, and could not reach SFO. The table has been also used as input data for the optimizations.
7.3.1.2 Set of departure flights to the Bay Area

The first rerouting possibility of diverted passengers, as seen in Chapter 5, is to be squeezed into flights to the Bay Area. In this case, Sacramento is a medium airport with low traffic. Half of their flights account for South West Airlines, and they do not operate to SJC or OAK. Furthermore, there is a low frequency of flights connecting SMF with SFO. The 6th of July there were only 45 available seats for passengers to be squeezed spread in 3 flights, and all of them took off before the diverted passengers landed at SFO.

7.3.1.3 Aircraft and bus capacities

The Aircraft and Bus capacities used as input data are the equal to the input data used for the Reno-Tahoe scenario (section 7.2.1).
7.3.2 Implementation Scenario

In the case of Sacramento implementation, it has been decided to perform an implementation using passenger aggregation by batches. In this third implementation, passengers have been grouped in batches of 5 passengers.

7.3.2.1 General optimization context

The optimization scenario has the following general input variables:

<table>
<thead>
<tr>
<th>Scenario context - Rerouting SMF</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization starting time slot (11 am)</td>
<td>44</td>
</tr>
<tr>
<td>Optimization horizon (12 pm)</td>
<td>96</td>
</tr>
<tr>
<td>Time slot length</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Bus driving time SMF - SFO</td>
<td>150 minutes</td>
</tr>
<tr>
<td>Bus driving time OAK - SFO</td>
<td>75 minutes</td>
</tr>
<tr>
<td>Bus driving time SJC - SFO</td>
<td>50 minutes</td>
</tr>
<tr>
<td>Flight time SMF - SFO</td>
<td>60 minutes</td>
</tr>
<tr>
<td>Minimum bus load</td>
<td>90%</td>
</tr>
<tr>
<td>Minimum aircraft load</td>
<td>90%</td>
</tr>
</tbody>
</table>

Figure 7.15: General optimization input variables.

7.3.3 Sensitivity Analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$, and available ressources

The analysis performed over the input variables $\beta_{\text{wait}}$, $\beta_{\text{transp}}$, Max_\textit{Buses} and Max_\textit{Affrete}. In order to distinguish closely how the number of the variables impact the distribution between modes, they have been modified according to the following ranges:

- $\beta_{\text{Wait}} =$ From 0.5 to 1.5 in steps of 0.2
- $\beta_{\text{Transp}} = 2 - \beta_{\text{Wait}}$
- Max_\textit{Buses} : From 10 to 14 in steps of 1
- Max_\textit{Affrete}: From 0 to in steps of 5

The scenarios with no aircraft available and 10 or 11 buses available were not feasible, accounting for an 8% of the optimizations performed. The following figure shows the percentual distribution between modes in every scenario, in order
to distinguish how the rerouting costs are taken into account when assigning the rerouting mode.

As the available flights to the Bay Area had already departed when the diverted passengers landed, no passengers have been squeezed. Furthermore, it can be
observed how the more aircraft available are placed, the passengers are assigned to
the new affreted aircraft increases, to the detriment of the substitution passengers.
The next figure shows how the amount of passengers assigned to each rerouting mode:

Figure 7.17: Number of passengers assigned to each rerouting mode

128
Once analysed the distribution between modes, the impact of the betas in the allocation of resources has also been analysed. The following figure shows the objective function values grouped by the $\beta_{\text{wait}}$ value used in each implementation:

![Objective function value per BetaWait groupings](image)

Figure 7.18: Objective function value per BetaWait groupings

As mentioned previously, the scenarios with only 1 Aircraft and 10 to 11 buses are not feasible, as no passengers can be squeezed. It can also be inferred how the cost increases the scenarios were the number of buses available is increased and the number of aircraft available is low. The rerouting costs ranges from a minimum of $26,341 with 14 buses and 5 aircraft available, to a maximum of $64,772 with 1 aircraft and 12 to 14 buses available.

### 7.3.4 Conclusions

This second rerouting shows the best case scenario for the inter-modal substitution, as is the closest airport to SFO. Furthermore the sensitivity analysis on $\beta_{\text{wait}}, \beta_{\text{transp}}$ and available resources on a rerouting of a greater amount of passengers, in relation to the previous implementation, permits to extract the following consequences:

- $\beta_{\text{wait}}$ and $\beta_{\text{transp}}$ have apparently no influence in the assignment of passengers to rerouting modes.
• The increase in the available aircraft to be chartered directly increases the affreting passengers.

• The passenger value of time is considerably high, making the rerouting through surface modes of transport a less cost-effective option, due to the longer travel times.

The second sensitivity analysis, performed on minimum aircraft and bus loads, shows how the minimum passenger load to departure conditions in an earlier departure of the vehicles, as well as in the rerouting configuration. As shown in the results, a lower minimum bus loads impacts in the assignment of less passengers to chartered aircrafts.
7.4 Case Scenario 3: Rerouting from Los Angeles International Airport

7.4.1 Input Data

7.4.1.1 Set of diverted flights

The third rerouting scenario corresponds to the reaccomodation of the diverted passengers from Los Angeles International Airport (LAX). LAX is the airport within the largest distance from SFO, and therefore the trade-off of the costs between the different modes of transportation will be notorious. Furthermore, LAX absorbed more than 1100 passengers on the 6th of July, making the rerouting within the same day particularly challenging.

![Figure 7.19: Location of Los Angeles Intl. Airport](image)

As it has been shown in Chapter 2, during the 4 day period of study, LAX International Airport only absorbed diversions the 6th of July, which accounted for a 11% of the total diverted flights on the date. Furthermore, these flights were not able to reach their final destination (SFO) after the diversion. Therefore, the mathematical programming will try to assess the most cost-effective solution for the rerouting of these diverted passengers back to SFO.
Extracted from the database available from BTS, the following table shows the set of flights with destination SFO that were diverted to LAX, and could not reach SFO. The table has been also used as input data for the optimizations.

<table>
<thead>
<tr>
<th>DAY</th>
<th>TAIL_NUM</th>
<th>FL_NUM</th>
<th>Pass. load</th>
<th>DT</th>
<th>ActualDT</th>
<th>AT</th>
<th>ActualDiv/AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N76055</td>
<td>72</td>
<td>220</td>
<td>6:25</td>
<td>6:19</td>
<td>14:28</td>
<td>14:26</td>
</tr>
<tr>
<td>1</td>
<td>N567UA</td>
<td>419</td>
<td>167</td>
<td>10:38</td>
<td>10:34</td>
<td>12:40</td>
<td>12:25</td>
</tr>
<tr>
<td>1</td>
<td>N212UA</td>
<td>724</td>
<td>312</td>
<td>12:30</td>
<td>13:12</td>
<td>20:23</td>
<td>21:25</td>
</tr>
<tr>
<td>1</td>
<td>N323AA</td>
<td>179</td>
<td>152</td>
<td>10:30</td>
<td>10:30</td>
<td>13:45</td>
<td>13:04</td>
</tr>
<tr>
<td>1</td>
<td>N3BFAA</td>
<td>1267</td>
<td>152</td>
<td>11:55</td>
<td>11:52</td>
<td>13:30</td>
<td>16:43</td>
</tr>
<tr>
<td>1</td>
<td>N3HXAA</td>
<td>1745</td>
<td>152</td>
<td>10:45</td>
<td>10:42</td>
<td>13:15</td>
<td>16:17</td>
</tr>
</tbody>
</table>

Figure 7.20: Set of diverted flights to LAX

All the columns of table 7.20 represent the same variables as for the previous scenarios (please see section 7.2.1). As it can be observed, all the flights were diverted to LAX on the 6th of July, landing between 1pm and 9pm. In this case scenario, the total number of passengers that will need to be rerouted is 1,156 passengers.

7.4.1.2 Set of departure flights to the Bay Area

The first rerouting possibility of diverted passengers, as seen in Chapter 5, is to be squeezed into flights to the Bay Area. In this case, Los Angles int'l. aiport has a great frequency of connecting flights to the Bay Area. Particularly, 45 flights departured the 6th of July with destination the Bay Area. After estimating their passenger loads, and extracting the flights passenger capacity from FAA registry, it could be computed the remaining capacity of the flights. The 6th of July there were 835 available seats for passengers to be squeezed, although a some part of the flights took off before the diverted passengers landed at SFO.

7.4.1.3 Aircraft and bus capacities

The last input data required by the mathematical programming is the passenger capacities of the aircraft available to be affereted, as well as for the motor coaches used for inter-modal substitution.

In this third rerouting scenario, as stated in section 7.2.1 all motor-coaches
available for inter-modal substitution will also be defined to have 40 seats capacity. Regarding the aircraft affreted, the assumption as for the previous two scenarios will apply. The following table shows the passenger capacity of the fleet assumed to be available:

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
</tr>
</tbody>
</table>

Figure 7.21: Aircraft data used as input for LAX rerouting scenario.

As explained in section 7.2.1, the aircraft with a maximum passenger capacity of 60 passengers intend to resemble the capacity of a Bombardier CL-600-2C10 Regional Jet in a small configuration, aircraft with capacity of 70 passengers represent the Bombardier model CL-600-2D15 (Regional Jet Series 705) or a CL-600-2C10 in a large configuration, and finally, the aircraft with a seating capacity of 120 passengers represent the Airbus A319 or Boeing 737.

7.4.2 Implementation Scenario

As for the previous implementation scenarios, it has been decided to perform an implementation using passenger aggregation by batches. In this third implementation, passengers have been grouped in batches of 5 passengers.

7.4.2.1 General optimization context

The optimization scenario has the following general input variables:

7.4.3 Sensitivity Analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources

In the first implementation analysis, a sensitivity analysis over the input variables $\text{Max}_\text{buses}$ and $\text{Max}_\text{Affrete}$ has been performed. The aim of this first analysis was to assess the trade-off between transportation modes in a greater passenger sample. In order to distinguish closely how the number of Buses and Aircraft available affect the distribution between modes, $\beta_{\text{Wait}}$ and $\beta_{\text{Transp}}$ have been fixed to 1. The optimization has been performed on 12 different scenarios,
in which the previously described input values were modified according to the following ranges:

- $\beta_{\text{Wait}} = 1$ (fixed)
- $\beta_{\text{Transp}} = 1$ (fixed)
- $\text{Max\_Buses}$: From 20 to 30 in steps of 5
- $\text{Max\_Affrete}$: From 0 to 6 in steps of 2

All the scenarios were feasible. The results for every optimization were computed and can be summarized in the following figure:

As it can be inferred, the allocation of more aircraft lowers the cost of the rerouting. This is due to the fact that LAX is located approximately 400 miles from SFO, making a rerouting through surface means of transport little expensiver than the rerouting through affreted aircraft. In order to clearly identify the distribution between modes in this first LAX rerouting analysis, the following figure has been computed:

As stated previously, it can be observed how the more aircraft available are placed, the passengers are assigned to the new affreted aircraft increases, to the detriment of the substitution passengers. Furthermore, it can be observed in figure 7.24 how the amount of passengers squeezed remains approximately constant. This is due to the fact that the squeezing option has no operational cost added, and therefore is most of the times the most cost-effective option.
Nevertheless, some of the departure flights already took off when the diverted passengers landed in LAX, and another group of flights departed in the late afternoon, making some times cost-effective to reaccomodate the diverted passengers in other modes.
7.4.4 Comparison of rerouting times with a non inter-modal rerouting

In order to correctly compare to a realistic airline rerouting, and having in mind that no data regarding the actual rerouting of Asiana Crash diverted passengers was available, two assumptions have been performed, in order to analyse two possible scenarios:

- **Hypothesis A**: Best case scenario. Diverted passengers will be squeezed in the first seat available, without taking into account if the rerouting is performed with the same operator.

- **Hypothesis B**: Realistic case scenario. Diverted passengers will only be squeezed into available seats from their arrival flights’ airline

Both analysis have been performed previously for RNO and SMF reroutings, but the figures were alarming due to a low frequency of flights between these
airports and the Bay Area, reason why airlines may had to proceed with special operations. Nevertheless, the same analysis for LAX airport shows a different picture, as every given day there are 50 to 60 flights scheduled to the Bay Area, making the rerouting definitely faster.

7.4.4.1 Hypothesis A: Rerouting in first seat available

In order to correctly assess the effectiveness of the mathematical model developed, the comparison must be performed under the same conditions. As it has been stated in the assumptions of the implementation, please see Chapter 6, the implementation has been performed under an aggregated rerouting, meaning the rerouting has not been grouped by airlines. Thus, the results obtained with the model should be compared to a non inter-modal rerouting under the above presented hypothesis A.

In this case, the route between LAX and SFO is highly operated, making LAX a good candidate for the diversion of flights with destination SFO. After analysing the schedule between these two cities in the 4-day period of study, it can be observed how there was a high daily traffic between LAX and the Bay Area, with 48 flights scheduled and not cancelled on the 6th of July, and raising a 16% up to 63 flights on the 7th of July. The available seats to squeeze in passengers has been computed according to the estimated load factors provided by BTS, for departure flights from LAX during July 2013. The next figure shows the estimated load factors separated by airline:

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>90.70%</td>
</tr>
<tr>
<td>UA</td>
<td>89.76%</td>
</tr>
<tr>
<td>OO</td>
<td>82.72%</td>
</tr>
<tr>
<td>WN</td>
<td>84.25%</td>
</tr>
<tr>
<td>VX</td>
<td>82.51%</td>
</tr>
<tr>
<td>DL</td>
<td>90.20%</td>
</tr>
<tr>
<td>MQ</td>
<td>76.65%</td>
</tr>
</tbody>
</table>

Figure 7.26: Estimated load factors separated by airline.

According to the previously shown estimated load factors (7.26), the following figure shows the available slots in the departure flights to squeeze in passengers,
together with the arrival of the diverted flights, in order to get a sense of the possibilities of rerouting that airlines had on the 6th of July.

![Scheduled and diverted flights per time slot on the 6th of July.](image)

Figure 7.27: Scheduled and diverted flights per time slot on the 6th of July.

It can be observed in figure 7.27 a high concentration of available seats during the afternoon. In the time bracket 4pm to 10pm the 65% of the available seats are placed. Nevertheless, approximately a 30% of the flights had already departed when the diverted passengers landed in LAX, making the entire rerouting on the 6th of July infeasible. Therefore, airlines probably offered hotel vouchers for their passengers to overnight nearby the airport and wait until the 7th of July to be rerouted. The following figure shows the available slots during the 7th of July:
Then, once the available slots are computed, if the diverted passengers are aggregated at their arrival to LAX and rerouted with the first flight available, the total delays can be computed. The results obtained are as follows:

Then, computing the weighted average block delays for all the diverted passengers, the results are as follows:

As one can observe, the average delay minutes incurred by the diverted passengers that landed in LAX, under the hypothesis that they were rerouted on the first flight flying back to the Bay Area, is 10 hours 24 minutes.

It must be taken into account, that the delay minutes computed do not take into account the additional trip time that the passengers rerouted through SJC and OAK would perceive, as they would have to take another mean of transport to get to their final destination that was SFO. Thus, having in mind that this is the best scenario possible, as passengers are squeezed into flights independently to their origin airline flight and that they are sent to the Bay Area and not straight
### 7.4.4.2 Hypothesis B - Passengers rerouted with flights within the same airline

Although in highly critical situations airlines may be forced to collaborate, in order to succeed in a fast recovery from the disruption, hypothesis A differs from the normal operational behaviour of airlines in schedule disruptions. Therefore, as airlines may not likely let their competitors reroute the diverted passengers to SFO, 10h and 24 minutes is a very high delay.
using their flights, hypothesis B has also been computed to offer a more realistic approach of the Asiana crash situation. Thus, the following results show a non-collaborative and non-inter-modal rerouting, meaning that passengers will only be squeezed into flights of the same airline, and having in mind also that airlines placed no new aircrafts to ferry back the passengers to SFO.

In the case of diversions to LAX, the affected air carriers were United Airlines, American Airlines and Sky West Airlines. Thus, the analysis will be performed case-by-case, looking at the flights that each airline company had scheduled for the Bay Area on the 4-day period of study, and computing the available slots in each of them, to assess if the rerouting would have been possible. In the case of American Airlines:

<table>
<thead>
<tr>
<th>FL_DATE</th>
<th>CARRIER</th>
<th>TAIL_NUM</th>
<th>FL_NUM</th>
<th>Aircraft</th>
<th>Pass. load Available</th>
<th>ORIGIN</th>
<th>DEST</th>
<th>DIV_AR</th>
<th>CRS_DEP</th>
<th>CRS_ARR</th>
<th>CRS_ARH</th>
<th>DIV_AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/07/2013</td>
<td>AA</td>
<td>NIGHAA*</td>
<td>1921</td>
<td>737-400</td>
<td>132</td>
<td>14</td>
<td>LAX</td>
<td>SFO</td>
<td>-</td>
<td>7:10</td>
<td>7:00</td>
<td>8:35</td>
</tr>
<tr>
<td>07/07/2013</td>
<td>AA</td>
<td>NSJAA*</td>
<td>737-400</td>
<td>132</td>
<td>14</td>
<td>LAX</td>
<td>SFO</td>
<td>-</td>
<td>7:18</td>
<td>7:04</td>
<td>8:35</td>
<td>8:31</td>
</tr>
</tbody>
</table>

Figure 7.31: American Airlines scheduled flights.

It can be observed how AA diverted one flight on the 6th of July with an estimated load of 152 passengers, whilst it had only scheduled 2 flights from LAX to the Bay Area on the 6th and 7th of July. In this case the flights went straight to SFO, but their estimated available seats to squeeze in diverted passengers was 28 seats. Furthermore, the diverted flight landed in LAX at noon, and at that time the first AA flight had already departed. That means that only a 11% of the diverted passengers could be rerouted in less than 1 day, and consequently the 90% remaining will suffer a more than 2 days delay if another AA flight is not placed to reroute them.

With only one scheduled flight per day, the rerouting will last so long that one can conclude how the hypothesis B seems totally unfeasible for American Airlines carrier. Let’s analyse United Airlines now:

The case of United Airlines is also delicate, as one of the flights that were diverted was a Boeing 777 carrying an estimated number of 312 passengers, making the total number of diverted passengers for UA raise up to 492 passengers. Analysing the scheduled flights for the 6th and 7th of July, one can observe how only a 38% of the diverted passengers could have been rerouted with UA flights with less than 1 day delays. Consequently, more than a 60% of the passengers would have to stay in a hotel for 2 days or more waiting for another flight. It can also conclude how the hypothesis B seems also unfeasible for United Airlines if no other UA flights are placed to reroute the remaining passengers.
### Implementation Analysis

**Figure 7.32: United Airlines scheduled flights.**

Finally, if analysing the same situation for Sky West Airlines case:

**Figure 7.33: Sky West Airlines scheduled flights.**

Sky West Airlines is in the best position between the affected airlines at LAX, having 22 scheduled flights from LAX to the Bay Area after their one and only
diverted flight landed in LAX the 6th of July. Furthermore, the diverted flight was a Bombardier CL-600-2B19 with an estimated load of only 41 passengers, thus the amount of disrupted passengers was significantly lower than for UA and AA.

Figure 7.34: Sky West Airlines rerouting flights.

Analysing the schedule, it can be observed how within less than 4h all the diverted passengers would have been on their way to the Bay Area, with a total average delay of 5 hours and 15 minutes.

Therefore, under hypothesis B, only in the Sky West case it would make probably economic sense not to do a multimodal substitution for the rerouting, and even then passengers would perceive an average of 5 hours and 15 minutes delay without taking into account the transportation time between OAK or SJC and SFO, in the respective cases. In the cases of UA and AA, the passengers would perceive extremely high delays, reason why these airlines may had to apply critical measures to ensure a less disruptive journey.

7.4.5 Conclusions of the implementation

This third rerouting offers a broader picture of the model behaviour, as the rerouting is performed over a greater passenger sample, enabling the model to try more configurations within the rerouting constraints. Thus, the following conclusions can be extracted from the sensitivity analysis on $\beta_{\text{wait}}$, $\beta_{\text{transp}}$ and available resources:

- Even in greater passenger samples, $\beta_{\text{wait}}$ and $\beta_{\text{transp}}$ have apparently no influence in the assignment of passengers to rerouting modes.

- The passenger time value has a high weight in the rerouting costs, making even in some cases the squeezing option non-optimal, as it holds passengers in the diverted airport longer periods than other faster but operationally more expensive rerouting options.

- The increase in the available aircraft to be chartered directly increases the affected passengers, diminishing proportionally the number of substituted passengers.
The inter-modal service is not the most cost-effective due to the long distance between LAX and SFO.

Furthermore, the comparison with a non-inter-modal rerouting gives a reference of the effectiveness of the model. From the comparative analysis the following conclusions can be extracted:

- Hypothesis A, (collaborative rerouting and non-inter-modal rerouting), shows an average delay close to the 11 hours, making the inter-modal rerouting a good solution for most disrupted passengers.
- Hypothesis B, (non-collaborative rerouting and non-inter-modal rerouting), shows how most of the airlines may be forced to apply new solutions such as inter-modal operations, to ensure their diverted passengers do not have to overnight and suffer such unpleasant delays.
7.5 Case Scenario 4: Rerouting from McCarran International Airport

7.5.1 Input Data

7.5.1.1 Set of diverted flights

The fourth rerouting scenario corresponds to the reaccomodation of the diverted passengers from McCarran International Airport (LAS). LAS is located more than 550 miles from SFO, southwest from the Bay Area, and absorbed a 10% of the diverted flights during the 6th of July, with a total passenger load of 571 passengers.

In the case of LAS, including it in the Regional Airport System of SFO would mean to increase the range only up to 560 miles as one can observe in figure 7.35. Up to this moment the greater distance from SFO had been given by LAX, which is 400 miles from SFO, thus LAS will give us a reference of the maximum distance for cost-effectiveness in this multimodal substitution within the SFO Regional Airport System. The mathematical programming will trade-off the travel times for surface means of transport and their lower operational costs, against squeezing or affreting aircrafts, which would higher the operational costs but considerably lower the rerouting times.

Figure 7.35: Location of McCarran International Airport
7 – Implementation Analysis

Extracted from the database available from BTS, the following table shows the set of flights with destination SFO that were diverted to LAS, and could not reach SFO. The table has been also used as input data for the optimizations.

<table>
<thead>
<tr>
<th>DAY</th>
<th>TAIL_NUM</th>
<th>FL_NUM</th>
<th>Pass. load</th>
<th>DT</th>
<th>ActualDT</th>
<th>AT</th>
<th>ActualDivAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N519UA</td>
<td>499</td>
<td>152</td>
<td>9:51</td>
<td>10:51</td>
<td>12:17</td>
<td>12:19</td>
</tr>
<tr>
<td>1</td>
<td>N596UA</td>
<td>580</td>
<td>152</td>
<td>10:00</td>
<td>10:04</td>
<td>13:07</td>
<td>13:07</td>
</tr>
<tr>
<td>1</td>
<td>N848VA</td>
<td>23</td>
<td>144</td>
<td>10:30</td>
<td>10:35</td>
<td>13:50</td>
<td>13:47</td>
</tr>
</tbody>
</table>

Figure 7.36: Set of diverted flights to LAS

All the columns of table 7.36 represent the same variables as for the previous scenarios (please see section 7.2.1). As it can be observed, the total number of passengers that will need to be rerouted is 570 passengers.

7.5.1.2 Set of departure flights to the Bay Area

LAS is the 9th busiest airport in the US in terms of total passenger boardings, and has a high frequency of flights to SFO, reaching the 15 to 26 daily flights per day in peak seasons. Furthermore, the airlines operating in LAS also offer flights connecting with SJC and OAK. The following figure shows the total departure flights connecting LAS and the Bay Area during the 6th of July.

7.5.1.3 Aircraft and bus capacities

The last input data required by the mathematical programming is the passenger capacities of the aircraft available to be affreted, as well as for the motor coaches used for inter-modal substitution. In this McCarran Intl. Airport based scenario, the bus and aircraft capacities implemented are equal to the input data used for the other implementations (please see section 7.2.1).

7.5.2 Implementation Scenario

As for the previous implementation scenarios, it has been decided to perform an implementation using passenger aggregation by batches. In this third implementation, passengers have been grouped in batches of 5 passengers.
7.5.2.1 General optimization context

The optimization scenario has the following general input variables:

<table>
<thead>
<tr>
<th>Scenario context - Rerouting LAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization starting time slot (11 am)</td>
</tr>
<tr>
<td>Optimization horizon (12 pm)</td>
</tr>
<tr>
<td>Time slot length</td>
</tr>
<tr>
<td>Bus driving time LAS - SFO</td>
</tr>
<tr>
<td>Bus driving time OAK - SFO</td>
</tr>
<tr>
<td>Bus driving time SJC - SFO</td>
</tr>
<tr>
<td>Flight time LAS - SFO</td>
</tr>
<tr>
<td>Minimum bus load</td>
</tr>
<tr>
<td>Minimum aircraft load</td>
</tr>
</tbody>
</table>

Figure 7.38: General optimization input variables.
As it can be observed, the bus driving time from LAS to SFO is over 8 hours, making the rerouting through surface means of transport a not so efficient option. Moreover, the flight time between both airports, including boarding times, is expected to be of 135 minutes, making a huge difference with the substitution option. Presumably, the affreting and squeezing options will take an important role in this rerouting scenario, reducing the amount of passengers rerouted by inter-modal substitution.

7.5.2.2 Results of sensitivity Analysis on available resources

The analysis performed over the input variables $\beta_{\text{wait}}$, $\beta_{\text{transp}}$, Max$_{\text{buses}}$ and Max$_{\text{Affrete}}$. In order to distinguish closely how the number of the variables impact the distribution between modes, they have been modified according to the following ranges:

- $\beta_{\text{Wait}} = 1$ (Fixed)
- $\beta_{\text{Transp}} = 1$ (Fixed)
- Max$_{\text{Buses}}$: From 10 to 14 in steps of 2
- Max$_{\text{Affrete}}$: From 0 to 6 in steps of 2

Therefore, 16 scenarios have been implemented for McCarran Intl. Airport rerouting optimization, all of them being feasible. The results for every optimization were computed and can be summarized in the following figure:

As it can be inferred, the allocation of more aircraft lowers the cost of the rerouting. This is due to the fact that LAS is located 560 miles from SFO, making a rerouting through surface means of transport expensiver than the rerouting through affreted aircraft. In order to clearly identify the distribution between modes, the following figure has been computed:

As stated previously, it can be observed how if the number of aircraft available is increased, the number of passengers assigned to these new chartered aircraft proportionally increases, to the detriment of the substitution passengers. This situation already was shown in the rerouting scenario of Los Angeles International Airport, and it is even more persistent in the LAS scenario due to the greater distance to SFO. Furthermore, it can be observed in figure 7.40 how the amount of passengers squeezed does not remain constant. Although the squeezing option has no operational cost added, in this case scenario the available departure flights
had late departures, increasing the passenger waiting cost, and making more cost-effective an earlier rerouting through other modes.

As it can be observed, the number of passengers squeezed fluctuates between 285 and 345 passengers. The number of passengers substituted has the minimum
Figure 7.41: Number of passengers assigned to each rerouting mode

at 280 passengers, in the scenario with 6 aircraft available, and rises up to 800 passengers for the scenario with no aircraft available. Contrary, the number of affreting passengers reaches the maximum at 560 passengers, and the minimum with 0 passengers.

As it has been previously mentioned, McCarran Las Vegas is an extreme case scenario, due to its long distance with respect to San Francisco, therefore, the passengers rerouted through surface means of transport are particularly impacted. It is clear that the inter-modal substitution enables a fast and systematic rerouting, making the passengers perceive the least time stuck at the airport with no clue of how will they be rerouted, nevertheless the average rerouting time grows due to the use of slower modes of transport. The next figure shows the rerouting departure times against the arrival times of the diverted passengers at LAS:
Figure 7.42: Departure against arrival times of las vegas diverted passengers

As it can be observed, the rerouting times raise up to an average of 8 hours and 6 minutes, whilst the average waiting time is little over 30 minutes. Although it must be taking into account that this is a worst case scenario, as LAS is located 560 miles from SFO, resulting in approximately 9 hours of motor-coach driving times, this difference raise the question about what is more important; do passengers perceive less disruptions if they are quickly set into their way home? or passengers would rather prefer to overnight and wait over a day to be rerouted in a more pleasant mode of transport? Customer experience in inter-modal services differ within age and economic power, nevertheless this study still shows how passengers would suffer no irritation while waiting for a response as they would be quickly and systematically be placed again into their journey back home.
7.5.3 Comparison of rerouting times with a non inter-modal rerouting

Being McCarran International Airport an extreme case scenario, it is particularly interesting to compare the optimal rerouting computed with the mathematical programming, with how the rerouting would have been with no aircraft nor buses available for the rerouting of passengers. As it has been previously stated for LAX rerouting case scenario, two hypothetical airline scenarios have been computed:

- **Hypothesis A**: Best case scenario. Diverted passengers will be squeezed in the first seat available, without taking into account if the rerouting is performed with the same operator.

- **Hypothesis B**: Realistic case scenario. Diverted passengers will only be squeezed into available seats from their arrival flights’ airline

First, the following figure shows the cumulative rerouting of diverted passengers in the optimal rerouting configuration computed by the mathematical programming, against a passenger rerouting computed under hypothesis A.

The optimised rerouting shown in figure 7.43 corresponds to the optimization scenario #14, in which airlines would have 16 buses and 2 aircraft available for the rerouting of their diverted passengers. It can be observed how the inter-modal rerouting would enable passengers to be rerouted within the same day, whilst under Hypothesis A, although it is a best case scenario, as passengers would be rerouted independently to their origin ticket provider, passengers would have to wait more than two days to be rerouted back to SFO.

Again, it must be emphasized that the average travel time with the inter-modal rerouting would raise up to 8 hours, whilst a conventional rerouting would have an average of 2 hours travel times. Nevertheless, the passengers would suffer 20 hours more delay if they are hold in the diverted airport waiting for an available seat in the subsequent flights. As mentioned previously, this difference raises the question about what is less disruptive for passengers; do passengers find less irritating to avoid to overnight nearby the airport, although it would mean longer travel times? or passengers would rather prefer to wait on average 30 hours to be rerouted in a more pleasant mode of transport?
Mc Carran Las Vegas Intl. Airport is not the best candidate for inter-modal operations with destination SFO, but still the effectiveness of the implementation of this new rerouting option must be taken into account.

What is more, performing the same analysis but applying hypothesis B, meaning passengers will only be squeezed into flights from their original flight operator, the delays perceived by passengers are even greater. The following figure shows the available seats in the airlines involved in the diversions to LAS on the 6th of July.

Having in mind that the airlines involved in the diversions to LAS had on average close to 140 passengers on board, it can be inferred how only Virgin America would have been able to squeeze all their diverted passengers within two days from the Asiana Crash. Moreover, it can be observed how some of the airlines had all their flights canceled during the 6th of July, and a low flight frequency on the 7th of July, directly impacting in the rerouting possibilities of the diverted passengers. It can be concluded that the delays that most of the passengers would
perceive are inadmissible, and thus airlines must have applied crisis measures to solve the problem, therefore may this situation serve as a prove of how inter-modal reroutings offer an efficient and necessary measure to help airlines recover from operational disruptions.
Chapter 8

Suggestions for further research

There is many research performed in flight delay management, or optimisation of aircraft and crew schedulings, but few research has been on passenger-centric recovery from highly disruptive situations. Until great disruption events as the Eyjafjallajokull volcanic eruption in 2010, the low frequency of highly disruptive situations supported the fact that few researchers focused in the efficient handling of these situations. Nevertheless, as the airlines’ trend is to optimise the flight schedules to leave the minimum idle time possible, when such huge disruptions occur, airlines are surpassed, ressources are inefficiently allocated, and the impact of the disruption snowballs becoming very costly for airlines.

Since some decades airports realized the importance of an optimal Access Intermodality, putting efforts to integrate rail transportation and shuttle bus services to efficiently connect airports with the city centers. These measures have helped to reduce congestion in roads close to the airports, as a result of the permanently increasing air transportation demand, and have enabled to smoothly link airports to the real final destination of the passengers. Nevertheless, the implementation of inter-modal operations at a network level is starting to be tackled recently by academia, since disruption recovery is becoming increasingly difficult for airlines, due to the planification of flight schedules with the minimum idle time possible.

It is reasonable to decide to use buses in highly disruptive situations, nevertheless, airlines are performing reactively in these cases, without a systematic way to integrate airfield and ground operations. Thus, the mathematical programming proposed in chapter 6 aims to offer a optimisation model that may serve as a future tool to ensure a cost-efficient network integration of inter-modal operations in the rerouting of diverted passengers, after highly disruptive situations. Nevertheless,
the model proposed has been built as an airports pairs model, where the optimisation of the rerouting is performed over the pairs SFO - $DivertedAirport_{n}$, and not optimising at a whole network level.

Although the optimality of a rerouting may be understood as the most cost-efficient transportation of passengers from the diverted airport to their original destination, if the model was expanded to a whole network level, the optimisation could open more possibilities for airlines to manage their diverted passengers. For instance, some airlines may want to prioritise their international passengers, although placed in diverted airports further than their original destination. Furthermore, working at whole network level could be assess with more realistic capacity time constraints.

In Appendix 1 a first whole network optimisation model is proposed, built upon an expansion of the first model presented in chapter 6, with the objective of rerouting all the diverted passengers in the airports involved in the asiana crash at the same time. Therefore, the author of this master thesis proposes the further development of this whole network optimisation model, that may serve as a starting point for the development of a real tool for airline control centers, with the ultimate objective that airlines start to apply inter-modal operations to systematically and cost-efficiently recover from highly disruptive situations.
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Appendices
Appendix A

Whole Network Rerouting Model

A.1 Introduction

The optimisation model proposed here aims to assess the possibility of inter-modal substitution as a rerouting option in the reaccommodation of diverted flights. The validity of the model will be implemented in an Asiana crash Case Study, in which the mathematical programming will determine the most cost-effective reaccomodation of the diverted passengers that were not able to reach SFO with their original flights.

This second mathematical modeling is motivated by the previous model Airport-pairs rerouting optimisation. Therefore, this new model proposed will expand the previous model to embrace the rerouting from all the diverted airports involved in the Asiana Crash disruption at the same time.

The novelty of the mathematical modeling lies in:

- The implementation of inter-modal operations in airline schedule recovery from highly disruptive situations.

- The passenger-centric modeling of the rerouting costs, meaning the cost of rerouting not only will take into account the operational costs that airlines will perceive, but also the monetary translation of delay times that passengers will perceive.

- The optimisation of the rerouting of diverted passengers from a global network perspective.
The rerouting is performed from all the diverted airports of study to SFO. Thus, the mathematical programming will analyse the diverted flights that landed at every airport, and then, according to the non-cancelled departure flights and surface modes of transport available, the model will propose the most cost-effective rerouting configuration, taking into account both passenger travel times and operational costs.

A.2 Nomenclature used in the model

The optimisation will not try to assess if the diversions and cancellations could have been better handled, but will focus on finding the most cost-effective solution to reroute the passengers that were diverted. The input data corresponds to the current diversions situation in the period of study, and then, knowing the flights that were cancelled, diverted and the ones that could follow the schedule, the programming will find the most cost-effective.

I will now define the variables that will build the mathematical optimization problem:

A.2.1 Index variables

- $\mathcal{F}$: Set of departure flights from the diverted airports to the Bay Area (SFO, OAK, SJC) = \{\(f_1, f_2, ..., f_n\)\}
- $\Gamma$: Set of discrete time periods = \{\(t_1, t_2, ..., t_T\)\}
- $\mathcal{P}$: Set of diverted passengers = \{\(p_1, p_2, ..., p_P\)\}
- $\mathcal{O}$: Set of diverted airports of study = \{\(o_1, o_2, \ldots\)\}
- $\mathcal{D}$: Set of destination airports of departure flights $f = \{d_1, d_2, \ldots\}$
- $\mathcal{A}$: Set of aircraft available to affrete in the diverted airport
  \{\(a_1, a_2, \ldots, a_{\text{MaxAircraft}}\)\}
- $\mathcal{B}$: Set of available buses for inter-modal substitution in the diverted airport
  \{\(b_1, b_2, \ldots, a_{\text{MaxBuses}}\)\}
A.2.2 Time and delay input variables:

- $AT_f$: Scheduled arrival time of flight $f$
- $DT_f$: Scheduled departure time of flight $f$
- $PaxAT_p$: Scheduled arrival time of passenger $p$ in his original flight
- $ActualDivAT_p$: Arrival time of passenger $p$ to the diverted airport
- $BDT_o$: Bus transportation time from the diverted airport $o$ to SFO
- $FlightTime_o$: Flight time from the diverted airport $o$ to SFO

A.2.3 Input capacity variables:

- $Pax_f$: Total number of passengers on departure flight $f$.
- $Cap_f$: Maximum passengers capacity of flight $f$.
- $CapAircraft_a$: Maximum passengers capacity of affreting flight $a$.
- $CapBus_b$: Maximum passengers capacity of buses available for inter-modal substitution.

A.2.4 Input cost coefficients:

- $CostAffrete$: Cost of affreting a new aircraft. Defined in [ $ / hour \cdot passenger$ ] in order to be able to scale the cost of placing bigger aircrafts, without having to separate the cost per type of aircraft.
- $CostBV$: Variable cost of utilizing ground transportation per passenger [ $ / passenger$ ].
- $CostP$: Passenger delay cost per one time unit [ $ / hour \cdot passenger$ ].
A.2.5 Other input coefficients:

- $Beta_{Wait}$: Weight coefficient for passenger waiting times.
- $Beta_{Transp}$: Weight coefficient for passenger transportation times.
- $MinloadBus$: Percentage of the total bus capacity that establishes the minimum passenger load to be ready to leave.
- $MinloadAffrete$: Percentage of the total aircraft capacity that establishes the minimum passenger load of an affreted flight to be ready to leave.
- $TimeFactor$: Conversion factor used to convert time periods into minutes.

A.2.6 Binary variables

A.2.6.1 Input binary variables:

The following binary variables define if the departure flights $f$ have as destination the alternative airports in the Bay Area (SJC, OAK), or otherwise they will land in SFO.

$$OAK_f = \begin{cases} 
1 & \text{if the destination of departure flight } f \text{ is OAK} \\
0 & \text{otherwise}
\end{cases} \quad \text{(A.1)}$$

$$SJC_f = \begin{cases} 
1 & \text{if the destination of departure flight } f \text{ is SJC} \\
0 & \text{otherwise}
\end{cases} \quad \text{(A.2)}$$

The following binary variables define which is the origin airport of the departure flights $f$, contracted motor-coaches $b$, or affreted aircrafts $a$.

$$\text{OriginFlight}_o^f = \begin{cases} 
1 & \text{if airport } o \text{ is the origin airport of flight } f \\
0 & \text{otherwise}
\end{cases} \quad \text{(A.3)}$$
A.2.6.2 Output binary variables:

The first type of output binary variables are $Squeeze_{(p,f)}^t$, $Subst_{(p,b)}^t$ and $Affrete_{(p,a)}^t$. These three binary variables define the rerouting option to which the passengers are assigned, if it is the case, in every time slot:

$$Squeeze_{(p,f)}^t = \begin{cases} 
1 & \text{if passenger } p \text{ is squeezed into flight } f \text{ in time period } t \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (A.6)

$$Subst_{(p,b)}^t = \begin{cases} 
1 & \text{if passenger } p \text{ is rerouted with motor – coach } b \\
in time period } t \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (A.7)

$$Affrete_{(p,a)}^t = \begin{cases} 
1 & \text{if passenger } p \text{ is rerouted in affreted flight } a \\
in time period } t \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (A.8)

The second group of output binary variables are $DTBus_{b}^t$ and $DTAffrete_{a}^t$. These two binary variables define the time period in which the contracted motor-coaches $b$ or affreted aircraft $a$ departure:
A – Whole Network Rerouting Model

\[ DT_{Bus}^b_t = \begin{cases} 
1 & \text{if bus } b \text{ departs in time period } t \\
0 & \text{otherwise} 
\end{cases} \quad (A.9) \]

\[ DT_{Affrete}^a_t = \begin{cases} 
1 & \text{if affreted aircraft } a \text{ departs in time period } t \\
0 & \text{otherwise} 
\end{cases} \quad (A.10) \]

Additionally, the mathematical programming uses the following auxiliary binary variables: \( y_1, y_2, y_3, \) and \( y_4. \)

### A.3 Objective function

The objective of the mathematical model is to minimize the cost of reaccommodation of diverted passengers who were stuck in their respective diverted airports and could not reach SFO. Thus, it will be used as input data the final ASIANA crash schedule (e.g. what flights were diverted, which flights were cancelled and which ones could reach SFO), and the model will only assess the more cost-effective rerouting back to SFO.

The rerouting options evaluated in the mathematical programming are as follows:

(A) Squeeze the diverted passengers into flights to SFO
(B) Squeeze the diverted passengers into flights to OAK or SJC
(C) Ferry back the passengers to SFO by affreting a new aircraft
(D) Apply an inter-modal substitution from the diverted airport. (Only feasible from some diverted airports)

In the rerouting options enumerated above, Option (B) implies rerouting passengers to the alternative airports in the Bay Area, and then implementing a short
inter-modal commute, transporting the passengers back to SFO by surface means of transport. Furthermore, Option (D) implies that passengers are rerouted with motor-coaches from the diverted airport back to SFO.

The following figure represents the rerouting from all the airports that absorbed diversions as a result of the Asiana Crash in SFO.

![Figure A.1: Rerouting from all the diverted airports of study to SFO.](image)

### A.3.1 Model Input Data

The mathematical programming will have as input the following data:

1) Set of diverted passengers in the operational day of study.
2) Set of departure flights $F$ taking off from diverted airports of study, with destination either to SFO, OAK or SJC.
3) Number of passengers booked and maximum capacity of each flight $f$.
4) Scheduled departure and arrival times of each flight $f$. 

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5) Actual departure and arrival times of all the flights previously mentioned.
6) Surface transportation times between the diverted airport and SFO.
7) Remaining arrival flight capacities at SJC, OAK and SFO.
8) Remaining departure flights capacity in the diverted airport.

The following tables describe in detail the input matrix that will have to be uploaded in matlab in order to be able to run the computations.

### A.3.1.1 Diverted passengers data

The first input table contains the data regarding the diverted flights. Each row of the table represents a diverted passenger. The data has to be formatted as follows:

<table>
<thead>
<tr>
<th>Day of arrival</th>
<th>Tail #</th>
<th>Flight #</th>
<th>DivAirp&lt;sub&gt;p&lt;/sub&gt;</th>
<th>DT&lt;sub&gt;p&lt;/sub&gt;</th>
<th>ActualDT&lt;sub&gt;p&lt;/sub&gt;</th>
<th>AT&lt;sub&gt;p&lt;/sub&gt;</th>
<th>ActualDivAT&lt;sub&gt;p&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>p₁</td>
<td>1</td>
<td>xxxx</td>
<td>1</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
</tr>
<tr>
<td>p₂</td>
<td>1</td>
<td>xxxx</td>
<td>5</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>pₚ</td>
<td>4</td>
<td>xxxx</td>
<td>2</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>xxx</td>
</tr>
</tbody>
</table>

Figure A.2: Input table with the information of the diverted passengers.

As it is described in [A.2], the data includes:

- Day of arrival: Integer from 1 to 4, corresponding to the 4-day period of study (6th of July to 9th of July).
- Tail #: Tail number of the diverted flight in which passenger p arrived.
- Flight #: Flight number of the diverted flight in which they arrived.
- DivAirp<sub>p</sub>: Airport to which the passenger p has been diverted. - DT<sub>p</sub>: Departure time of the flight in which passenger p arrived.
- ActualDT<sub>p</sub>: Actual departure time of the flight in which passenger p arrived.
- PaxAT<sub>p</sub>: Scheduled arrival time of the flight in which passenger p arrived.
- ActualDivAT<sub>p</sub>: Scheduled arrival time of the flight in which passenger p arrived.
A.3.1.2 Departure flights data

The following input table corresponds to the data on the flights, that were not cancelled, connecting the diverted airport to either SFO, SJC or OAK.

![Input table with the information of the departure flights.](image)

Table 6.3 contains the data regarding the departure flights, as specified previously. Each row of the table represents a departure flight $f$. The data includes:

- Day of arrival: Integer from 1 to 4, corresponding to the 4-day period of study (6th of July to 9th of July).
- Tail #: Tail number of the diverted flight in which passenger $p$ arrived.
- Flight #: Flight number of the diverted flight in which they arrived.
- $Pax_f$: Passengers booked in flight $f$.
- $Cap_f$: Passenger capacity of flight $f$.
- $OF$: Origin airport of flight $f$, defined by an integer.
- $DestF$: Destination airport of flight $f$, defined by an integer.
- $DT_f$: Departure time of flight $f$.
- $ActualDT_f$: Actual departure time of flight $f$.
- $AT_f$: Scheduled arrival time of flight $f$.
- $ActualAT_f$: Scheduled arrival time of flight $f$.

A.3.1.3 Airport destination binary variables

The two following tables correspond to the two binary variables that will be used as input data for the model.

The value of the above represented binary variables, as described in A.2.6, is equal to 1 if flight $f$ has destination SJC (in case of $SJC_f$ variable) or destination OAK (in case of $OAK_f$ variable).
A.3.1.4 Capacity of aircraft and buses available

The following input data is modeled as a table containing the information regarding the available flights to be affreted (variable \(CapAircraft_a\) and \(OAircraft_a\)).

![Table A.5: Input data on affreted aircraft’s passenger capacity.]

The value of \(CapAircraft_a\), as described in A.2.3, is equal to the maximum number of passengers that can be affreted into flight \(a\). Furthermore, \(OAircraft_a\) defines the airport in which the aircraft \(a\) is located.

As the optimization is now performed at a global network level, and in order to make the model more realistic, it must be defined also the number of buses that are available, which capacity they have, and the airport in which they are available:

![Table A.6: Input data on the motor coaches’s passenger capacity.]

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A.3.1.5  Bus distance times from the diverted airports to SFO

The following input table corresponds to the input variable $BDT_o$.

\[
\begin{array}{|c|c|}
\hline
BDT_{o_1} & XX \text{ min} \\
BDT_{o_2} & YY \text{ min} \\
\ldots & \ldots \\
BDT_{o_n} & ZZ \text{ min} \\
\hline
\end{array}
\]

Figure A.7: Bus driving times from airports $o$ to SFO

Table A.7 represents the input variable $BDT_o$, that describes the bus driving times to SFO from all the airports involved in the model (SJC, OAK and the diverted airports). Each row corresponds a one airport. This table will be uploaded as an array, corresponding each position of the array of a distance Airport$_o$ to SFO.

A.3.1.6 Flight times from the diverted airports to SFO

The following input table corresponds to the input variable $FlightTime_o$.

\[
\begin{array}{|c|c|}
\hline
FlightTime_{o_1} & XX \text{ min} \\
FlightTime_{o_2} & YY \text{ min} \\
\ldots & \ldots \\
FlightTime_{o_n} & ZZ \text{ min} \\
\hline
\end{array}
\]

Figure A.8: Flight times from airports $o$ to SFO

Table A.8 represents the input variable $BDT_o$, that describes the bus driving times to SFO from all the airports involved in the model (SJC, OAK and the diverted airports). Each row corresponds a one airport. This table will be uploaded as an array, corresponding each position of the array of a distance Airport$_o$ to SFO.

A.3.2 Model assumptions

Airlines’ operations are complicated to optimize as a whole due to the interaction of many factors and feasibility constraints of different resources. Four main constraints affect the feasibility of airline planning and disruption management, including aircraft maintenance checks, pilot work rules, fleet assignment and passenger accommodation.
In order to ensure an admissible problem complexity, the following assumptions have been made:

1. Connecting passengers will connect to their final destination from the Bay Area.

2. When affreting new aircraft, there are limited amount of aircraft available, and that they will always make the way back to the original airport from which they were placed.

3. When the rerouting is done through the alternative airports in the Bay Area, as shown in the previous inter-modal service analysis, it has been assumed only a 80% of the passengers will be rerouted to SFO.

4. The model will not take into account aircraft maintenance checks and pilot work rules, as these two constraints are less critical for disruption management than they are for airline planning.

5. The model does not take into account that pilots and crew are eligible to continue their scheduled tasks, according to FAA regulation pt. 135 maximum hours of service.

6. It is assumed there is remaining arrival flight capacity for the affreted flights.

### A.3.3 Costs to optimize

The cost-effectiveness of the new solution of reaccommodate will take into account the following costs:

- **Passengers delay cost**

- **Squeezing cost**: Cost of squeezing passengers into flights to either SFO, SJC or OAK.

- **Affreting cost**: Cost of placing a new aircraft to ferry back diverted passengers.

- **Inter-modal substitution cost**: Cost of transporting passengers with motor-coaches, either from the diverted airport, or just within the Bay Area.
The mathematical programming will set the mix of squeezed passengers, passengers rerouted with inter-modal substitution, and passengers reaccommodated in an affreted aircraft, that will minimize the total rerouting cost.

A.3.3.1 Objective function

The optimisation problem will minimize the value of the following objective function:

\[ \text{MIN} z = \sum_{t} \sum_{p} [ CSqueeze_{tp} + CSubst_{tp} + CAffrete_{tp} + CStuck_{tp} ] \] (A.11)

As one can see in the formula above displayed, the mathematical programming will evaluate at every time period, if passenger p should be rerouted by being squeezed into a flight, rerouted by complete inter-modal substitution, ferried back with an affreted flight, or otherwise continue stuck at the diverted airport. The optimization will balance the cost of leaving the passengers stuck and rerouting them with every option. At the end of the chosen time horizon, no diverted passengers should remain in the diverted airport.

A.3.3.2 Cost of squeezing passengers into departure flights

\[
CSqueeze_{tp} = \text{Squeeze}_{(p,f)} \times \sum_{f} \left[ \text{CostP} \times \beta_{\text{wait}} \times ( DT_f - DivPaxAT_p ) + \right.
\]
\[
+ \text{CostP} \times \beta_{\text{transp}} \times ( FlightTime_o \cdot OFlight_{f_o} + \right.
\]
\[
+ \sum_{o=OAK} BDT_o \cdot OAK_f + \sum_{o=SJC} BDT_o \cdot SJC_f \right) + \right.
\]
\[
+ \sum_{o=OAK} ( BDT_o \cdot CostBV_o \cdot OAK_f ) + \sum_{o=SJC} ( BDT_o \cdot CostBV_o \cdot SJC_f ) \right] \] (A.12)

In computation \( CSqueeze_{tp} \), the first term calculates the passengers delay cost, according to the passenger value of time (CostP). The calculation is divided in two, first the calculation of the delay to the flight in which the passengers were
squeezed, and then, it adds the driving time from SJC or OAK to SFO, in case it applies. The second term of the equation adds the cost of motor coaches used to transport passengers from the other airports in the Bay to SFO, in case it applies.

### A.3.3.3 Cost of complete inter-modal substitution

\[
C_{\text{Subst}}^t_p = \text{CostP} \times \sum_b \left[ \text{Subst}_{(p,b)}^t \times (DT_{\text{Bus}}^t_b \cdot t \cdot \text{TimeFactor} + \right. \\
\left. + \sum_o \sum_b BDT_o \cdot \text{OBus}_o^b \cdot \text{DivPaxAT}_p ) \right] \\
+ \sum_b \sum_o \text{CostBV}_o \cdot \text{OBus}_o^b \cdot \sum_b \text{Subst}_{(p,b)}^t
\]

(A.13)

The equation above represents the operating cost of applying a complete substitution of a flight, straight from the diverted airport. The first term of the equation computes the cost of passengers delay, according to the passenger value of time (CostP). The delay is computed by adding the departure time of the bus \( b \) plus the bus driving time from the diverted airport to SFO, and then subtracting the scheduled arrival time of passenger \( p \). The second term of the equation computes the cost of renting the motor coaches service per passenger (CostBV).

Additionally, it has been assumed in this particular rerouting option that there is a limited amount of buses available for the inter-modal substitution, as defined in restrictions with the variable MaxBuses.

### A.3.3.4 Cost of affreting an aircraft

\[
C_{\text{Affrete}}^t_p = \text{CostP} \times \sum_a \left[ \text{Affrete}_{(p,a)}^t \times (DT_{\text{Affrete}}^t_a \cdot t \cdot \text{TimeFactor} + \right. \\
\left. + \sum_o \sum_a \text{FlightTime}_o \cdot \text{OAircraft}_o^a \cdot \text{DivPaxAT}_p ) \right] \\
+ \text{CostAffreting} \times \sum_a \text{Affrete}_{(p,a)}^t
\]

(A.14)
Equation [A.14] represents the total cost of affreting an aircraft to ferry diverted passengers back to SFO, straight from the diverted airport. The first term of the equation computes the cost of passengers’ delay, according to the passengers’ value of time \( \text{CostP} \). The delay is computed by adding the departure time of the affreted aircraft \( a \) plus an estimated \( \text{FlightTime} \) from the diverted airport to SFO, and then subtracting the scheduled arrival time of passenger \( p \). The second term of the equation computes the operating cost of placing the new aircraft. This cost coefficient \( \text{CostAffreting} \) has been defined in US$ per passenger, in order to be able to escalate the cost of placing bigger aircrafts, without having to separate the cost per type of aircraft.

Additionally, it has been assumed in this particular rerouting option:

- There is a limited amount of aircrafts available to affrete, as defined in re-fliminations with the variable \( \text{MaxAircraft} \).
- All the aircraft placed are assumed to transport the passengers to SFO and fly back to their original airport, although they could remain in SFO until the end of the period of study.

### A.3.3.5 Cost of passengers remaining in the diverted airport

\[
C_{\text{Stuck}}^t_p = \alpha \times \text{CostP} \times ( t \cdot \text{TimeFactor} + \text{DivPaxAT}_p ) \times \\
\times ( 1 - \sum_{\tau=1}^{t} \sum_f \text{Squeeze}_{(p,f)}^t - \sum_{\tau=1}^{t} \sum_b \text{Subst}_{(p,b)}^t - \sum_{\tau=1}^{t} \sum_a \text{Affrete}_{(p,a)}^t )
\]  

(A.15)

Equation [A.15] represents the cost of delay that passengers perceive if they remain in the diverted airport for long time periods. It has only one term, corresponding to the cost of passenger delay. The delay time is computed as the subtraction between the time period \( t \) in minutes \( (t \cdot \text{TimeFactor}) \) and the arrival time of passengers to the diverted airport \( \text{DivPaxAT}_p \). The variable \( C_{\text{Stuck}}^t_p \) can only have a value greater than zero if the passenger has not been assigned to any mode yet. The constraints ensure that once the passenger has been assigned to one rerouting option, the variable \( C_{\text{Stuck}}^t_p \) will permanently be zero.
**A.3.4 Constraints**

**A.3.4.1 Constraints of squeezing passengers into scheduled flights**

1) The number of passengers squeezed into flight \( f \) in time period \( t+1 \), should be less or equal to the number of remaining available seats in flight \( f \) at time \( t+1 \):

\[
\sum_p Squeeze_{(p,f)}^{t+1} \leq Cap_f - Pax_f - \sum_{\tau=1}^t \sum_p Squeeze_{(p,f)}^\tau \quad \forall t, \forall f \quad (A.16)
\]

2) The passengers can not be squeezed into flight \( f \), if the flight has already departed:

\[
(t \cdot TimeFactor - DT_f) \times Squeeze_{(p,f)}^t \leq 0 \quad \forall t, \forall f, \forall p \quad (A.17)
\]

**A.3.4.2 Constraints of the complete inter-modal substitution option**

1) The number of passengers assigned to each motor coach must be less or equal to the motor-coach capacity, at every time slot:

\[
\sum_p Subst_{(p,b)}^{t+1} \leq CapBus - \sum_{\tau=1}^t \sum_p Subst_{(p,b)}^\tau \quad \forall b, \forall t \quad (A.18)
\]

2) The motor coach \( b \) contracted for inter-modal substitution can only departure if it is filled up to a minimum bus load (MinloadBus), as explained in [A.2.5]. This restriction is guaranteed through 2 pairs of constraints:

**Part A:** Serves to fix the condition in which the bus must not departure.

\[
MinloadBus \cdot CapBus - \sum_{\tau=1}^t \sum_p Subst_{(p,b)}^\tau < 0 + M_1 \cdot (1 - y_1)
\]

\[
DTBus_{b}^t - M_1 \cdot y_1 \leq 0 \quad \text{ (A.19)}
\]
Equation [A.19] must be valid \( \forall b, \forall t \). \( M_1 \) is a very large number, and \( y_1 \) is an auxiliar binary variable. The underlying logic of the above presented statement is as follows:

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^{\tau} \geq MinloadBus \cdot CapBus \)
  (THEN) \( y_1 = 0 \) or \( y_1 = 1 \)
  \( [y=0] \) implying \( DTBus_{(p,b)}^{t} \leq 0 \). Then \( DTBus_{(p,b)}^{t} = 0 \)
  \( [y=1], \) implying \( DTBus_{(p,b)}^{t} \leq M_1 \). Then \( DTBus_{(p,b)}^{t} = 1 \) or 0
  (The bus can departure)

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^{\tau} < MinloadBus \cdot CapBus \)
  (THEN) \( y_1 = 0 \), implying \( DTBus_{(p,b)}^{t} \leq 0 \). Then \( DTBus_{(p,b)}^{t} = 0 \)
  (The bus must not departure)

**Part B**: Serves to fix the conditions for which the bus must departure.

\[
\sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^{\tau} - MinloadBus \cdot CapBus \leq 0 + M_2 \cdot (1 - y_2) \\
DTBus_{(p,b)}^{t} + M_2 \cdot y_2 > 0 \tag{A.20}
\]

Equation [A.20] must be valid \( \forall b, \forall t \). \( M_2 \) is a very large number, and \( y_2 \) is an auxiliar binary variable. The underlying logic of the above presented statement is as follows:

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^{\tau} \leq MinloadBus \cdot CapBus \)
  (THEN) \( y_2 = 0 \) or \( y_2 = 1 \)
  \( [y_2 = 0] \) implying \( DTBus_{(p,b)}^{t} > 0 \). Then \( DTBus_{(p,b)}^{t} = 1 \)
  \( [y_2 = 1], \) implying \( DTBus_{(p,b)}^{t} \leq M_2 \). Then \( DTBus_{(p,b)}^{t} = 1 \) or 0
  (The bus can departure)

- (IF) \( \sum_{\tau=1}^{t} \sum_p Subst_{(p,b)}^{\tau} > MinloadBus \cdot CapBus \)
  (THEN) \( y_2 = 1 \)
  \( [y_2 = 0] \) implying \( DTBus_{(p,b)}^{t} > 0 \). Then \( DTBus_{(p,b)}^{t} = 1 \)
  (The bus must departure)
3) Passengers can only be assigned to a certain bus at the time slot that the bus departures:

\[ M_1 \cdot DTBus^t_b \geq \sum_{\tau=1}^{t} \sum_p \text{Subst}^\tau_{(p,b)} \quad \forall b, \forall t \quad (A.21) \]

4) The motor coach \( b \) can departure at one time slot only, in between the starting time slot to the time horizon:

\[ \sum_t DTBus^t_b \leq 1 \quad \forall b \quad (A.22) \]

A.3.4.3 Constraints corresponding to affreting a new aircraft

1) The number of passengers assigned to each new affreted aircraft must be less or equal to the aircraft capacity, at every time slot:

\[ \sum_p \text{Affrete}^t_{(p,a)} \leq \text{CapAircraft}_a - t \sum_{\tau=1}^{t} \sum_p \text{Affrete}^\tau_{(p,a)} \quad \forall a, \forall t \quad (A.23) \]

2) The aircraft \( a \) affreted can only departure if it is filled up to a minimum aircraft load (MinloadAircraft), as explained in A.2.5. This restriction is guaranteed through two pairs of constraints:

**Part A:** Serves to fix the situations in which the new affreted aircraft \( a \) must not departure.

\[ \text{MinloadAircraft} \cdot \text{CapAircraft}_a - \sum_{\tau=1}^{t} \sum_p \text{Affrete}^\tau_{(p,a)} < 0 + M_1 \cdot (1 - y3) \]

\[ DT\text{Affrete}^t_a - M_1 \cdot y_3 \leq 0 \quad (A.24) \]
Equation [A.24] must be valid ∀a, ∀t. $M_1$ is a very large number, and $y_3$ is an auxiliary binary variable. The underlying logic is the equivalent to the one explained for equation [A.19].

**Part B:** Serves to fix the situations in which the affreted aircraft must depart.

$$\sum_{\tau=1}^{t} \sum_p Subst_{(p,a)}^\tau - MinloadAircraft \cdot CapAircraft_a \leq 0 + M_2 \cdot (1 - y_4)$$
$$DTAffrete_a^t + M_2 \cdot y_4 > 0$$

(A.25)

Equation [A.25] must be valid ∀a, ∀t. $M_2$ is a very large number, and $y_4$ is an auxiliary binary variable. The underlying logic is equivalent to the previously explained for equation [A.20]:

3) Constraint that ensures that passengers are assigned to affreted aircrafts in the time slot that the Aircraft departures:

$$M_1 \cdot DTAffrete_a^t \geq \sum_{\tau=1}^{t} \sum_p Affrete_{(p,a)}^\tau \quad \forall a, \forall t$$

(A.26)

4) Every aircraft affreted (a), can departure at one time slot only, between the starting time slot and the time horizon:

$$\sum_t DTAffrete_a^t \leq 1 \quad \forall a$$

(A.27)

### A.3.4.4 Passenger conservation constraints

1) Each passenger can be assigned only to one of the rerouting options in every time period:

$$\sum_f Squeeze_{(p,f)} + \sum_b Subst_{(p,b)}^t + \sum_a Affrete_{(p,a)}^t \leq 1 \quad \forall p, \forall t$$

(A.28)
2) Each passenger must be assigned to only one rerouting option (Squeeze, Substitution or Affreting) in all the time period of study. The equation also ensures that no passengers will continue stuck at the time horizon.

\[
\sum_t \left[ \sum_f Squeeze^t_{(p,f)} + \sum_b Subst^t_{(p,b)} + \sum_a Affrete^t_{(p,a)} \right] = 1 \quad \forall p \quad (A.29)
\]

3) Passengers can start to be assigned to the rerouting options only 30 minutes after their landing in the diverted airport:

\[
\left[ t \cdot TimeFactor - (30 + ActualDivAT_p) \right] \times \\
\times ( Squeezed^t_{(p,f)} + Subst^t_{(p,b)} + Affrete^t_{(p,a)} ) \geq 0 \quad \forall p, \forall t, \forall f, \forall b, \forall a \quad (A.30)
\]

Underlying logic:

- **(IF)** \( t \cdot TimeFactor \geq (30 + ActualDivAT_p) \)
  (THEN) \( \left[ Squeezed^t_{(p,f)} + Subst^t_{(p,b)} + Affrete^t_{(p,a)} \right] = 0 \) or 1
  (the passenger can be assigned to one rerouting option)

- **(IF)** \( t \cdot TimeFactor \leq (30 + ActualDivAT_p) \)
  (THEN) \( \left[ Squeezed^t_{(p,f)} + Subst^t_{(p,b)} + Affrete^t_{(p,a)} \right] = 0 \)
  (the passenger can not be assigned to a rerouting option)

### A.3.4.5 Constraints ensuring coherence in allocation of passengers to modes

1) If the passenger is diverted to airport \( o_i \), he can only be squeezed, affreted or substitution into a vehicle that departs from the same airport.

(The constraint will be replicated for Affreting and Substitution assignments:)

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\[ DivAirport_p - OFlight_f < 0 + M_1 \cdot (1 - y_5) \]
\[ 0 < Squeezed^{t}_{(p,f)} + M_2 \cdot y \]  \hspace{1cm} (A.31)

The underlying logic of the above displayed constraint is as follows:

- (IF) \( DivAirport_p - OFlight_f > 0 \)
  (THEN) \( y=0 \)
  \( [y=0] \imp (Squeezed^{t}_{(p,f)} = 1) \)

- (IF) \( DivAirport_p - OFlight_f < 0 \)
  (THEN) \( y=0 \) or \( y=1 \)
  \( [y=0] \imp (Squeezed^{t}_{(p,f)} = 1) \)
  \( [y=1] \imp (Squeezed^{t}_{(p,f)} = 0 \text{or} 1) \)

- (IF) \( DivAirport_p - OFlight_f = 0 \)
  (THEN) \( y=0 \)
  \( [y=0] \imp (Squeezed^{t}_{(p,f)} = 1) \)

**PROBLEM:** There is two cases in which squeezed is 1, and it should only be 1 in the second case.