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ENGSCI 255 Project Report: ATC Rostering

FORMUALTION OF AN EFFICIENT ROSTERING SCHEME

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Executive Summary

Auckland Airport assign Air Traffic Controllers (ATCs) to shifts. A more efficient and effective ATC shift roster leads to an efficient processing of air traffic movements, creating cost savings for Auckland Airport. A method to solve a new roster is building a model.

Data extraction from flightradar24.com using MATLAB scripts helped gauged ATC demand and decide constraints for the model.

Research into the ATC profession, New Zealand legislation, ATC working conditions and airport operations created a basis for model formulation. Underlying assumptions, based on research, helped to form the model.

An integer model was formed, solving for an initial minimum staff requirement for a 24-hour period, broken into 10 minute intervals. Simulation based on probabilities, distributions and variation refined the minimum staff requirement until an optimal solution was found.

The minimum staff requirement was converted into a daily roster. There are 4 types of shifts. A weekly roster is extrapolated from the daily roster, based on ATC working conditions research.

A financial analysis conveys the cost savings due to the roster, backed by research.

The optimal solution is 12 shifts in the roster for the 24-hour period. Auckland Airport needs to hire 16 full time ATCs and 4-part time ATCs. This roster will cover 99.85% to 99.86% of air traffic movements, saving Auckland Airport $11.06m to $18.47m NZD.

It is recommended to continue to use the model to roster ATC for the 4.5% projected air traffic movement growth at Auckland Airport. It is recommended a more comprehensive dataset fed into the model to improve the model’s realism.

Contents

Introduction

Air Traffic Controller (ATC) shift assignments are not efficient at the present time. There is a degree of viability during the management of aircraft movements, comprising of both take offs and landings. An Air Traffic controller must guide an aircraft in a time interval governing its movement, controlling up to three movements simultaneously. An aircraft is assigned one air traffic controller with preferably no handover. Flight arrivals and departures are known however delays, unfavourable weather conditions and the discovery of additional movements are not. The variability creates uncertainty on how assign air traffic controllers to a shift roster to cover all aircraft movements.

This problem creates unnecessary costs for Auckland Airport. Delays create additional costs to the Airport. Operational costs are unnecessarily higher, diminishing Auckland Airport's EBIT, net profit and profit margins. Delays contribute to the reputation of an airport. An undesirable reputation may cause Airport's bottom line to decrease. Air traffic management is crucial to Auckland Airport as underpins their entire business.

An efficient and effective shift roster needs to be scheduled. The aim of the roster is to minimise operational costs and improve delay coverage. An integer linear program will model the solution, constrained by facts and logical assumptions. Full time and part time employees are distinguishable from one another. Financial and non-financial factors are considered to deliver the best solution to Auckland Airport.

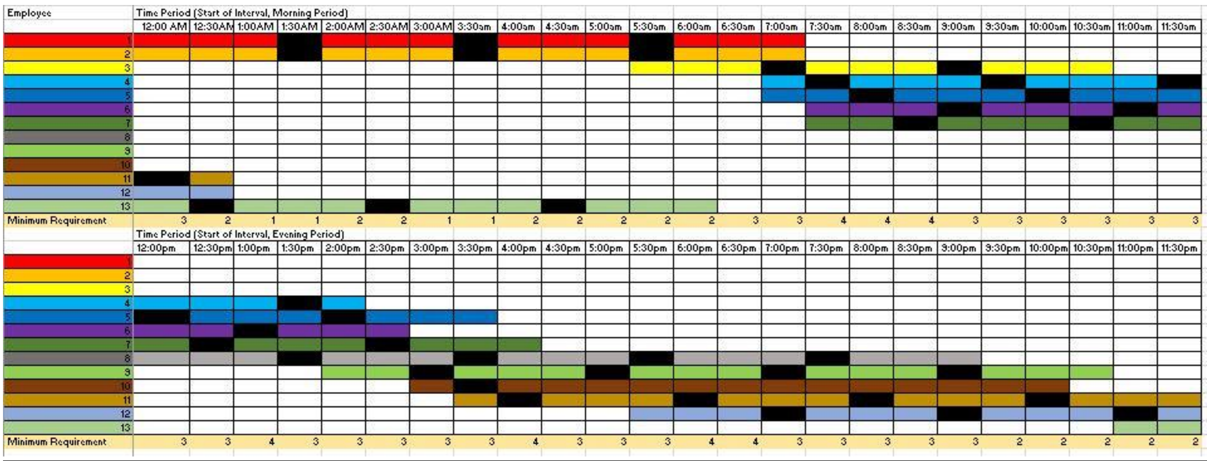

Figure 1: Potential Shift Roster

Methods

Data Collection and Processing

Before we could formulate a model, we needed data to work with. We began extracting flight data from the Auckland Airport website, looking at both arriving and departing flights for international and domestic flights. This included cargo and small plane movements. We changed our source to flightradar24.com, a source with a better representation of movements at the airport. We converted the information on the HTML webpage, relating to a specific day, into a txt file. We selected the 24-hour periods between 21st of April to 1st of May inclusive. We wrote a MATLAB script, flightradarRead.m, to collect relevant flight data. The script: Reads a file. Creates a column to store time intervals. Loops through to extract scheduled times and delays with adjustments for special cases around 12am. Counts the number of flights in each ten-minute interval. Converts delays to minutes. Excludes unknown and cancelled flights from delay calculations. Initialises delays. Counts the number of flights with different delay times and calculates the probabilities of each amount of the delay occurring. For the unknown flights, we had to make an assumption none of them were delayed as we could find no data to specify. They were included in the arrival and departure movements but not the delays. See appendix E.

```
% Loop through the lines to extract scheduled times and delays
delay = duration(0,0,0);
x = 1;
line = fgetl(fid);
while ischar(line)
    flightTime(x) = textscan(line,'%{HH:mm}D%*s'); % scheduled time
    [~] = fgetl(fid);
    [~] = fgetl(fid);
    line = fgetl(fid);

    if (~isempty(strfind(line, 'Landed')))||(~isempty(strfind(line, 'Departed')))
        temp = textscan(line,'%*s%{HH:mm}D');
        delay(x) = temp{1} - flightTime{x}; % calculate delay

        % adjust for the special case when times are near 12am
        if delay(x) > duration(22,00,00)
            delay(x) = delay(x) - hours(24);
        elseif delay(x) < duration(-22,00,00)
            delay(x) = delay(x) + hours(24);
        end
    elseif (~isempty(strfind(line, 'Canceled')))||(~isempty(strfind(line, 'Unknown')))
        delay(x) = NaN; % ignore canceled and unknown flights in delay calculation
    end
    x = x+1;
    line = fgetl(fid);
end
```

Figure 2: Excerpt of flightradarRead.m to extract scheduled times and delays.

Research

We conducted research to gather an understanding for the ATC profession and to develop linear constraints used later in our modelling. I investigated various forms of legislation. I read and extracted information from the Employment Relations Act 2000, the Health and Safety at Work Act 2015 and the Civil Aviation Act of 1990. I made assumptions including but not limited to; no strikeouts due to the airport qualifying as an essential service and breastfeeding breaks are taken in standard breaks (Employee Relations Act, 2000). I contributed to the research of ATC working conditions and air transportation processing. Aircraft need to have at least 45 seconds between runway usage is to prevent wake turbulence from impending the lift generation of the subsequent aircraft (NASA, 1997). Periods of duty must be separated by no less than 12 hours. Night duties apply to any time worked between the hours 0130 and 0529 (Civil Aviation Authority, 2014). Air Traffic Controllers are assigned sections of airspace to guide aircraft movements. These sections are either horizontal, separated by altitudes, or vertical, split into segments controlling the around the control tower. Further assumptions and research are detailed in relevant sections. See appendix B for a comprehensive set of assumptions.

Model Formulation

Our model originated starting with time intervals of 30 minutes. We switched to 10 minute intervals to improve accuracy. These time periods were applied over a 24 hours period to help develop a daily roster. We conducted further research into airport staffing patterns, preference and rostering. I gathered information from Civil Air Australian, assuming Auckland Airport being comparable to Australian Airports, as required 24-hour staffing in air traffic control. We investigated the Civil Aviation Authorities' protocol on break times, discovering a recommended 15mins for every hour on duty. We settled for 30 mins break and 90 minutes active duty in a two-hour period.

We began by referring to the integer programming section of our course book to develop an understanding of how to start modelling a staffing roster. Using the information gathered from data extraction and research, we created a basic integer linear programme, minimising the total number of staff used in the roster. The decision variable is the number of staff assigned during a 24 hours period. The objective function is the Sum of all Sum Products between employees staffed and the employee requirement at a specific time interval for each shift pattern. The integer program has two constraints. The first an ATC's serving capacity. The second is an air traffic control tower occupancy limit. The serving capacity is derived from dividing the total number of air traffic movements within the 10-minute time interval divided by the processing capacity of one ATC, a limit of 3 movements per person. The occupancy constraint addresses the physical limitations of Auckland Airport's runway. Due one runway, there is a 15-movement limit to the number of movements on the runway in the interval. We took research NASA conducted on runway occupancy times, at Fort Worth Airport, Texas. NASA discovered a 44.1 second period was the minimum runway occupancy time for both wet and dry conditions (NASA, 1997). We assumed Auckland Airport has a runway occupancy time of 1 minute due to its size, regardless of weather. Five ATC's is the maximum, processing capacity (15 movements) exceed the runway's limitations (10 movements). We need this constraint to minimise the total number of staff, even though in small periods, there is heavy overlap.

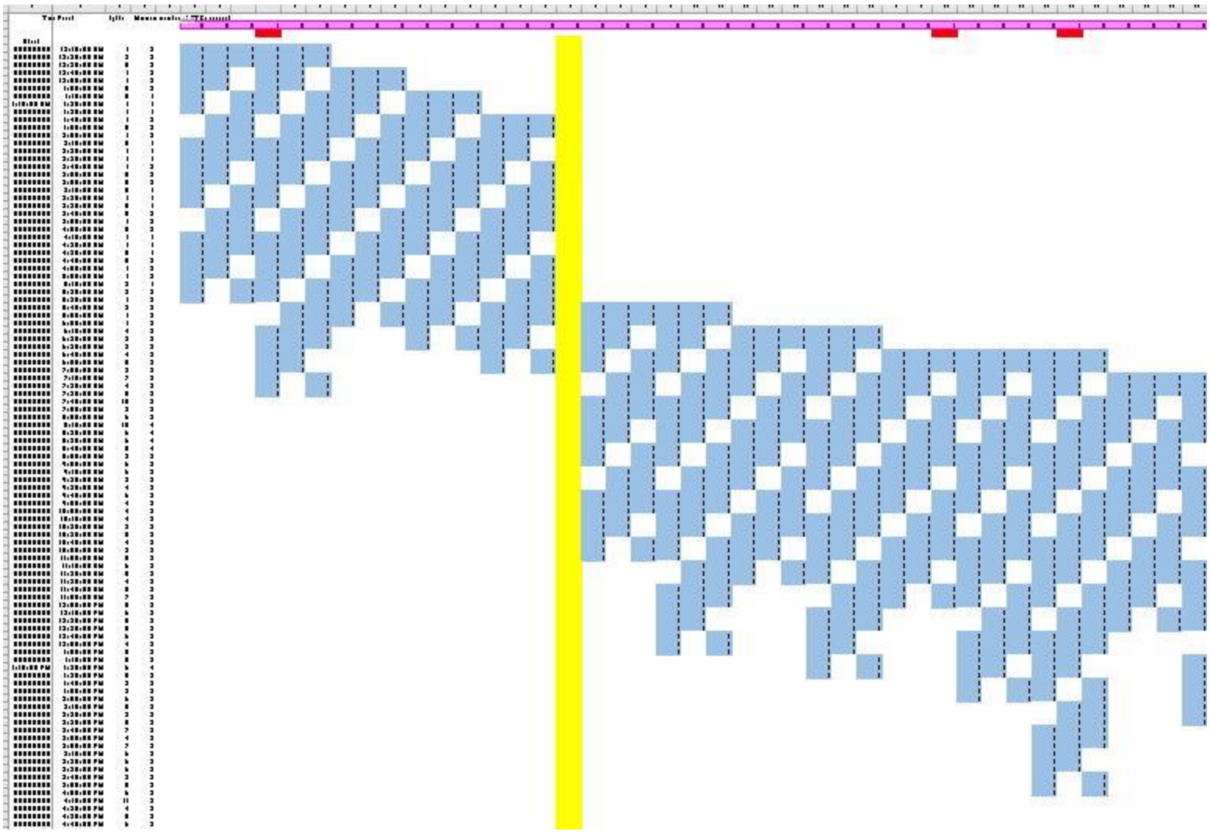

Figure 3: Model showing Shift Pattern (Blue), Integer Constraints and Employee Assignment

Simulation

We used simulation, facilitated by excel, to make our model more realistic. The simulation used both excel's inbuilt functions and our own VBA code. We performed simulations to account for delays in air traffic movements and general variation. The initial solution (ATC's assigned for each ten-minute interval) is transferred to a simulation work sheet as ATC # on Duty. The scheduled number of flights expected within each ten-minute interval is analysed. The simulation spreadsheet uses a binomial inverse distribution to estimate the probability of flights being delayed within a time interval, thus we can model delays.

-30 min	-20 min	-10 min	0 min	10 min	20 min	30 min	40 min	50 min	60 min +
0.01032368	0.0172	0.0968	0.3213	0.3176	0.1148	0.0449	0.0218	0.0349	0.0204

Figure 4: Probability of Delayed by Time Interval. Exert from Simulation Sheet

Using seed values, the binomial inverse distribution takes into account delays to calculate the actual number of air traffic movements expecting to be processed with the ten-minute intervals. The delay periods are between 30 minutes early and 60+ minutes late. We assumed it is impractical for a leave exactly on time due to the nature of boarding, thus, movements between 0 to 10 minutes are on time. A flight 30 minutes delayed leaves or arrives 30 to 40 minutes after schedule. The remaining delay periods use the same method. We used the 0 – 10 minutes on time principle to prevent the unrealistic skew of probabilities towards severe delays. Before the assumption, unrealistic delays existed. There are 3 stages to our simulation with each subsequent process using the predecessors output.

The number of unserved flights per 10-minute time interval is the first output generated. In each time interval, the flights that can be served (the number of ATC's multiplied by three) is subtracted from the actual number of flight arriving. A non-negativity constraint and runway movement limit (10 per 10-minute interval) are factored into the calculation. If the Actual arrivals exceed flights to serve by more than 10, any positive excess capacity is deferred to the next time period with no possible remedy. The first step of the iterating staff schedule uses the number of unserved to adjust the minimum staff requirements for the next iteration, leading to a decrease in the number of unserved flights after open solver resolves and the simulation has run again. See appendix C and F for model excerpts and VBA script.

Actual Arrivals	Flights to Serve	Serving Capacity	Overflow - Runway Constraints	Unserved Flights	Excess Capacity	Excess ATC's	Extra ATCs Required	Net ATC Change
2	2	12	0	0	-10	-3.333333333	0	3.333333333
0	0	12	0	0	-12	-4	0	4
2	2	12	0	0	-10	-3.333333333	0	3.333333333
2	2	9	0	0	-7	-2.333333333	0	2.333333333
2	2	9	0	0	-7	-2.333333333	0	2.333333333
1	1	9	0	0	-8	-2.666666667	0	2.666666667
0	0	6	0	0	-6	-2	0	2
1	1	6	0	0	-5	-1.666666667	0	1.666666667
2	2	6	0	0	-4	-1.333333333	0	1.333333333
0	0	6	0	0	-6	-2	0	2
1	1	6	0	0	-5	-1.666666667	0	1.666666667
0	0	6	0	0	-6	-2	0	2
0	0	6	0	0	-6	-2	0	2
0	0	6	0	0	-6	-2	0	2
0	0	6	0	0	-6	-2	0	2

Figure 5: One Random Iteration for Adjustments in Simulation

The iterative process continues to run until no further changes need to be made to the minimum staff, indicated by the adjustment coefficients. These coefficients are a percentage of flights unserved within a time interval. We aim to have the coefficients 5% or less. The excess ATC's per time interval is the simulation's second output, the excess capacity divided by 3. After the minimum staffing requirement meets the steady state, the excess staffing capacity (excess ATCs) is used to reduce overstaffing developed in the second stage on the simulation. The roster created by the minimum staffing requirements is passed through the simulation, analysing the output of the excess ATCs after 1000 simulations. One ATC is removed if overstaffed by 2 ATCs. This process continues until no further change. The product is a roster for the typical day of Auckland Airport and is place back in the simulator. 1000 simulations using the first output are run 100 times. Each time, the mean percentage of flights unserved for the 1000 simulations is calculated. These 100 values are used to construct a 95% confidence interval for the percentage of unserved flights during a typical day at Auckland Airport. This confidence interval determines the optimality of our roster.

-1.66667	-0.33333	-0.66667	-1.66667	-2	-1.66667	-1	-2.33333	-2.66667	-1.66667	-1.33333
-1.33333	-1	-1.33333	-1.33333	-1.33333	-1.33333	-2	-1	0.333333	-1.33333	-0.33333
-1.66667	-2	-1.33333	-1	-1.66667	-1.33333	-2	-1.66667	-1.66667	-1.66667	-2
-1.66667	-1.66667	-2	-1.66667	-2	-1.33333	-1.66667	-2	-1.66667	-2	-2
-2	-2	-1.66667	-1.66667	-1.66667	-2	-2	-1.33333	-1.33333	-1.66667	-1.33333
-1.66667	-1.66667	-2	-1.66667	-2	-2	-1.33333	-1.66667	-2	-2	-2
-1	-1	-0.66667	-1	-1	-0.66667	-0.66667	-1	-1	-0.66667	-0.66667
-1	-0.66667	-0.33333	-1	-1	-1	-1	-0.66667	-1	-0.66667	-0.66667
-0.33333	-0.66667	-1	-0.33333	-0.66667	-0.33333	-0.66667	-0.33333	-0.66667	-0.33333	-0.66667
-1.66667	-1.66667	-1.66667	-1.66667	-1.66667	-2	-1.66667	-2	-2	-1.66667	-1.66667
-2	-2	-2	-1.33333	-1.66667	-1.66667	-1.66667	-1.66667	-1.66667	-1.66667	-2
-2	-1.66667	-2	-2	-2	-2	-2	-2	-2	-2	-2
-0.66667	-0.66667	-0.66667	-0.66667	-0.66667	-0.66667	-1	-0.66667	-0.66667	-1	-0.66667
-1	-1	-1	-1	-0.66667	-1	-1	-0.66667	-0.33333	-1	-0.66667
-0.33333	-1	-1	-0.66667	-0.66667	-1	-0.66667	-0.66667	-0.66667	-0.66667	-1
-2	-1.66667	-1.66667	-1.66667	-2	-2	-1.66667	-1.66667	-2	-1.66667	-1.66667
-2	-2	-1.66667	-2	-2	-1.66667	-1.66667	-2	-1.66667	-2	-1.66667
-2	-2	-2	-2	-2	-1.66667	-2	-2	-2	-2	-2
-0.66667	-1	-0.66667	-1	-0.66667	-1	-1	-1	-1	-1	-1
-0.66667	-1	-0.66667	-0.66667	-0.66667	-0.66667	-0.66667	-1	-1	-0.66667	-0.66667
-1	-1	-1	-1	-1	-0.66667	-1	-0.66667	-1	-0.66667	-1

2	0.3	0.22	0.36	0.24	0.42	0.48	0.32	0.3	0.32	0.3272
9	0.471429	0.457143	0.557143	0.542857	0.414286	0.571429	0.342857	0.414286	0.471429	0.473714
6	1.14	0.96	0.98	1.38	0.92	0.66	0.78	0.8	1.06	0.9264
9	0.585714	0.557143	0.614286	0.657143	0.657143	0.657143	0.657143	0.785714	0.814286	0.678429
6	0.72	0.86	0.84	0.7	0.9	0.96	0.9	1.08	0.74	0.8318
4	0.68	0.7	0.7	0.58	0.66	0.52	0.86	0.4	0.54	0.6098
7	0.783333	0.683333	0.75	0.8	0.8	0.666667	0.783333	0.666667	0.8	0.762333
4	1.028571	0.985714	1.071429	0.985714	1.114286	0.857143	0.957143	0.885714	0.757143	0.969857
6	1.9	1.68	1.86	1.7	1.96	1.76	1.92	1.72	1.68	1.6834
5	1.38	1.65	1.56	1.7	1.63	1.71	1.5	1.75	1.74	1.5206
3	2.433333	2.516667	2.45	2.433333	2.55	2.65	2.183333	2.2	2.566667	2.416667
3	1.533333	1.533333	1.033333	1.433333	1.3	1.333333	1.433333	1.3	1.166667	1.422333
3	0.3	0.3	0.285714	0.285714	0.242857	0.357143	0.257143	0.328571	0.428571	0.351857
2	0.466667	0.566667	0.433333	0.5	0.5	0.366667	0.533333	0.333333	0.466667	0.461
5	0.225	0.2	0.25	0.1	0.225	0.125	0.175	0.175	0.125	0.2435
5	0.4125	0.375	0.325	0.25	0.3375	0.3375	0.275	0.525	0.35	0.336625
3	0.466667	0.733333	0.3	0.366667	0.433333	0.666667	0.7	0.6	0.566667	0.483667
5	0.175	0.075	0.175	0.225	0.1	0.125	0.15	0.15	0.025	0.128
7	0.1	0.116667	0.05	0.033333	0.1	0.05	0.066667	0.133333	0.15	0.079833
0	0.1	0	0.1	0.1	0.2	0.1	0	0	0	0.049
0	0	0	0	0	0	0.05	0	0	0	0.004

Figure 6 (Left): Exert of Excess ATCs per Time Interval run through 1000 simulation

Figure 7 (Right): Exert of Mean Percentage of Unserved Flights per 10-minute Interval

Rostering

I took the results generated by our model and visualised a daily roster. We modelled for the average day at Auckland Airport, assuming exceptions are made to the roster during peak periods. Christmas holidays for example. We took the roster I visualised and produced a weekly roster. We assumed the number of flights is the same on both weekend days and weekends, therefore shifts would be the same for each day.

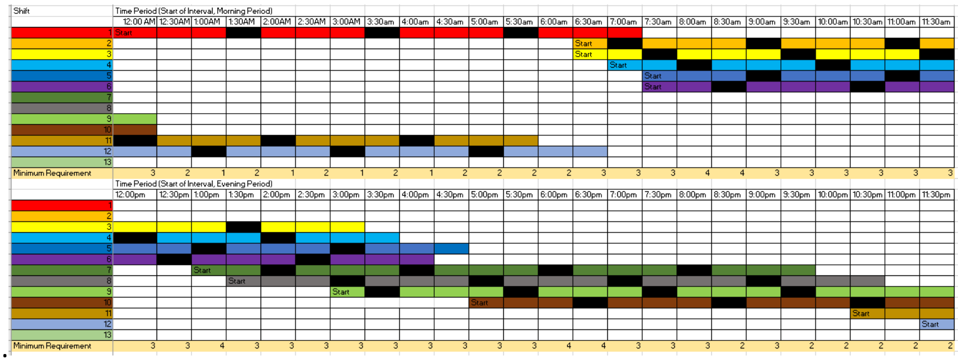

Figure 8: Final Daily Shift Roster

We conducted research to ensure our weekly roster met work related regulations and gave employees work life balance. We decided on 4 types of shifts: Night, Early, Morning and Afternoon. Each shift has a limit to the number of hours worked and time intervals specifying how to define the type. Night shifts are partly or wholly between 1:30am – 5:30am, 9.5 hours max and end by 7:30am. Early shifts start between 5:30 – 6:29am and are a max of 8 hours. Morning shifts start between 6:30am and 7:29am. Afternoon shifts are assumed to be the rest for simplicity. Over the 7-day period, employees are assigned different shifts, based on constraints used to formulate the weekly roster. Some constraints include 12 hour intervals between shifts, maximum of 50 hours of work per cycle, maximum 6-day cycle, 60-hour break after each cycle and maximum requirement to the number of shift type worked per cycle. Based on our research, assumptions and constraints, we develop two sets of cycles. Fulltime with 2 mornings, 2 afternoons and 1 night and part time with 1 morning and 1 night. Cycles ensure employees can have lifestyle balance. We have considered circadian cycles and homeostatic pressure. Employees remain alert whilst on duty. There are long enough periods for restorative sleep. The cycles allow employees to be most alert in peak times. Employees have no more than 2 night duties in a row, no more than two early starts in a cycle with no consecutive early starts. There are no more than 5 consecutive early starts. We formulated the weekly roster by using a binary integer program, maximising the total number of hours worked whilst minimising the total number of hours between shifts. The program set a maximum of 50 hours worked in a cycle and a minimum 12 hours between shifts as constraints. We calculated the time between any 2 shifts in MATLAB and the total time between shifts using VBA, inputting the values into our rostering program. See appendices D and G for reference.

Financial Analysis

I estimated the cost savings of covering delays with the excess staff. Full time ATCs are paid on an annual basis an estimated $170,000. I assumed part time employees earn half (Airways, 2017). I also accounted for kiwi saver schemes and additional benefits. I took the Auckland Airport's 157754 annual air traffic movements (Auckland Airport, 2016) and applied our probabilities of flight delay to calculate the number of flights delayed within different 10-minute windows. I assumed the cost of delay per minute is $88.10 NZD, equivalent to the $62.55 USD per minute (Airlines for America, 2017). I estimated the total cost of delay per interval for the start of the interval to the end. I assumed understaffed ATC tower attributes to 10% of total delays (Bureau of Transport Statistics, 2017) and the airline will charge airports for these costs, similar to Virgin Blue (Sydney Morning Herald, 2008). I compared the summation of ATCs' salaries, kiwi saver schemes and additional benefits to the maximum and minimum cost savings. Based on our research and assumptions, Auckland Airport will cover most delays and save between $11.06m and $18.47m. See appendix H for in depth analysis.

Conclusions

Results

After modelling and simulation, our roster has 12 different shifts with a requirement for 20 staff weekly, 16 full time and 4-part time. 99.854% to 99.856% of flights on time are covered every day. Mismanagement will only cause one flight per day to be delayed. The model took approximately one hour to solve.

Shift	Start	End	Shift length (hours)	Type of shift
1	0000	0730	7.5	Night
2	0630	1200	5.5	Morning
3	0630	1530	9	Morning
4	0700	1600	9	Morning
5	0730	1700	9.5	Morning
6	0730	1630	9	Morning
7	1300	2200	9	Afternoon
8	1330	2300	9.5	Afternoon
9	1500	0030	9.5	Afternoon
10	1700	0030	7.5	Afternoon
11	2230	0600	7.5	Night
12	2330	0700	7.5	Night

```
> t.test(experiment$Served)

        One Sample t-test

data:  experiment$Served
t = 203360, df = 99, p-value < 2.2e-16
alternative hypothesis: true mean is not equal to 0
95 percent confidence interval:
 99.85489 99.85684
sample estimates:
mean of x
 99.85586
```

Figure 9 (Left): Daily Roster   Figure 10 (Right): Confidence Interval of Served Flights

Delay costs justified our decision to prevent delays caused by air traffic controller delays. The estimated cost savings for Auckland Airport are between $11.06m to $18.47m NZD annually. Auckland Airport will maintain and continue to build goodwill as covering delays makes Auckland Airport reliable in the eyes of the consumer.

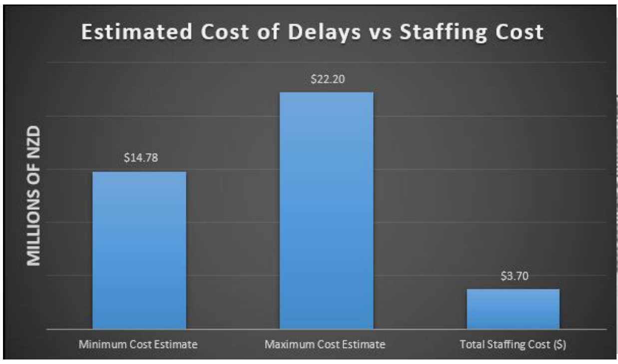

Figure 11 (Left): Cost of Delays   Figure 12 (Right): Cost Savings

Cycle	Shift pattern	Average hours worked in a week	Hours worked in one cycle	Total hours off during work cycle	Cycle length (hours)	Break after each cycle (hours)
F1	4-5-9-10-11-Break	37.6	43	76	119	73
F2	3-6-7-8-12-Break	38.5	44	76.5	120.5	71.5
P1	2-1-Break	22.8	13	12	25	71

Example roster for a particular week:

Employee	Cycle	Shift number							Hours worked
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	
A	F1	4	5	9	10	11	-	-	43
B	F1	5	9	10	11	-	-	-	34
C	F1	9	10	11	-	-	-	4	33.5
D	F1	10	11	-	-	-	4	5	33.5
E	F1	11	-	-	-	4	5	9	35.5
F	F1	-	-	-	4	5	9	10	35.5
G	F1	-	-	4	5	9	10	11	43
H	F1	-	4	5	9	10	11	-	43
I	F2	3	6	7	8	12	-	-	44
J	F2	6	7	8	12	-	-	-	35
K	F2	7	8	12	-	-	-	3	35
L	F2	8	12	-	-	-	3	6	35
M	F2	12	-	-	-	3	6	7	34.5
N	F2	-	-	-	3	6	7	8	36.5
O	F2	-	-	3	6	7	8	12	44
P	F2	-	3	6	7	8	12	-	44
Q	P1	2	1	-	-	2	1	-	26
R	P1	1	-	-	2	1	-	-	20.5
S	P1	-	-	2	1	-	-	2	18.5
T	P1	-	2	1	-	-	2	1	26

(number represents the shift number and the '–' represent a break for that day)

Figure 13: Final Weekly Shift Roster

Recommendations

The number of air traffic movements at Auckland Airport is projected to grow at a rate of 4.5% annually (Auckland Airport, 2016). Auckland Airport must keep up with the increase in number of flights by employing more ATCs or altering shifts. An efficient rostering will minimise the risk of delay, therefore, the exorbitant cost per minute associated. Our model will continue to help update rostering schedules due to the model's robust nature.

We built our model under many assumptions. Auckland Airport should try to expand on our model by removing assumptions with relevant, historical and future data. We used 11 consecutive days flight data, from the 21st of April to the 1st of May, to form a daily roster. We created a weekly roster by replicating the 'typical' daily roster. This assumption will need to be addressed as flight patterns do change daily, weekly and monthly. Peak periods are not considered in the data we gathered, thus increased air traffic movements around these times are inaccurately represented in our model. Weekends most likely have less flights as business flights are mostly during the week. Our current model will be over staffing on the weekend. To address these issues, a comprehensive dataset, collated through an airports historical records will help. Potentially model each day individually using the historical and predictive data from that day only. Many days may be modelled in a day as the model only takes approximately one hour to solve. The new data would help build a more realistic model, creating a roster to effectively cover air traffic movements.

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Appendix A: Personal Contribution

We split our project into three main parts: Data extraction and processing. Model development/Simulation. Research, Rostering and Financial Analysis.

Jin did the majority of the data extraction and processing. She wrote the MABLAB scripts to extract the data from flightradar24.com. She was crucial creating a weekly roster from our daily roster. She researched shift regulations. Jin was a pleasure to work with, a great team player.

Nik was incredible during the project. He formulated our model and implemented the various simulations. He produced various models and iterations, improving the model incrementally the entire semester. He wrote all VBA code to perform iterative simulations. He conducted research regarding the model and the assumptions we had to make to form the model. Nik was a pleasure to work with, incredibly helpful and was instrumental in completing the project.

Josh was great to work with. He conducted the majority of our Air Traffic Controller research. He researched the FAA(US) and CAA (UK). Josh was instrumental in formulating many of our assumptions.

I did the legislative research, using the information to help formulate our assumptions. I visualised the daily roster after the simulation process. I supported the other team members with subsidiary research whilst also conducting the financial analysis with our findings. I compiled the appendices.

Our team performed well together. We each honed a particular aspect of the project, with all our parts meshing together seamlessly. I enjoyed working on this project with my team and would love to work with them in the future.

Appendix B: Assumptions

Below is a list of assumptions we based our model on. Research was conducted and decisions were made as we went.

- There are minimum disruptions of shifts from Union representatives in the workplace.
- Do not account for 2 union meetings, max 2 hours each calendar year. A one-off event. Treated on a case by case basis.
- Union entry must comply with health and safety regulations, disrupting operations. Will consider on a case by case basis. Excluded from model formulation.
- No disruptions registering unions.
- No delays in bargaining for Collective Agreements.
- Negotiations and Strikes will be handled on a case by case basis.
- Strikes assumed to avoid as would disrupt social, environmental and economic interests.
- No delays due to remedy periods or negotiations.
- No delays caused by collective agreement ratifications.
- Employees can agree to additional terms and conditions if mutually agreed upon.
- No delays in employees seeking independent advice for contracts.
- Employees have passed probationary periods.
- Employees have agreed to the hours worked.
- Number of guaranteed hours of work, day of the week worked, start and finishing times are stated.
- No disruptions from employees refusing to working hours assigned.
- No retirements mid shift.
- Shifts are not reassigned or cancelled.
- Employees work in multiple monitoring stations. Not specialised to one particular section.
- Employees may request flexible working arrangements. Does not match nature of the job.
- We deny flexible working as ATC have an inability to reorganise work and the specialised nature of the job.
- There are no plans to restructure the company/ATC structure in the near future.
- No new employer is trying to employee current Auckland Airport ATC's.
- No concern for bargaining fee negotiations/restructuring.
- Breastfeeding breaks are organised to be taken during normal breaks (Organised).
- Break times are reasonable and have been negotiated.
- Employees are not pursuing other avenues. No need to educational leave.
- Consider employees require no further training. Employees train at smaller airport before working at Auckland Airport.
- ATC conduct an essential service. Necessary in the arrival, berthing, loading, unloading and departure of ships at a port. No strikes or lockouts due to nature of the role.
- Staff on call to cover sick leave etc.
- Leave given for the mourning of family and friends will be given on a case by case basis.

- Auckland Airport does not give employees any excuse reason to suspect personal grievances or disputes.
- No: discrimination, sexual harassment, racial harassment, subjection to duress, disadvantages.
- Wages are recorded
- No breaches in employment agreements.
- No disruptions due to labour inspections.
- Employees are not banned.
- ATC's have up to date qualifications.
- All employees abide by confidentiality agreements.
- No delays due to the employment court.
- Persons conducting business units follow health and safety obligations.
- Health and safety obligations kept up to date.
- Workers comply with health and safety regulations. No disruptions due to employees not following health and safety procedures.
- No reckless behaviour leading to disruptions.
- Health and Safety representative does not disrupt operations.
- No unsafe conditions resulting in employees refusing to work.
- Alternative, Improvement, prohibition and remedial notices are not issued.
- Health and Safety Practitioners do not need to disrupt work.
- All staff are physically and mentally able to perform in their duties.
- All employees have the necessary documentation to work in the industry.
- All employees have necessary documentation.

<u>Financial Model Assumptions</u>

- The Domestic and International movements are accurate as per Auckland Airport's Financial Report.
- The total delay cost per unit ($62.55 US) for New Zealand is the same as the one stated by the Airlines for America. $62.55 US = $88.10 NZD at 0.71 USD to 1 NZD.
- A total of 10% of delays is assumed to be attributable to Air Traffic Controllers (Bureau of Transport Statistics, 2017)
- The delays attributable to air traffic control are passed on to the airport, a similar situation to the Virgin Blue article (Sydney Morning Herald, 2008).
- The interval flight probabilities are valid for anticipating the overall delays for a year.
- Cost range is an estimate.
- The delay time when calculating the delay cost for the time interval is capped at 60 minutes.
- Part time employees are paid half the annual sum of full time employees.
- All employees are paid $170,000 NZD annually (Airways, 2017), (CareersNZ, 2017)
- Employees select kiwi saver scheme of 8%. Auckland Airport must make 8% contribution.
- Auckland Airport provide additional benefits for employees. These may include health and life Insurance, meal allowances and transport allowances.
- Domestic movements include domestic cargo and small planes.

- International movements include international cargo flights.
- Movement expected to continue to increase

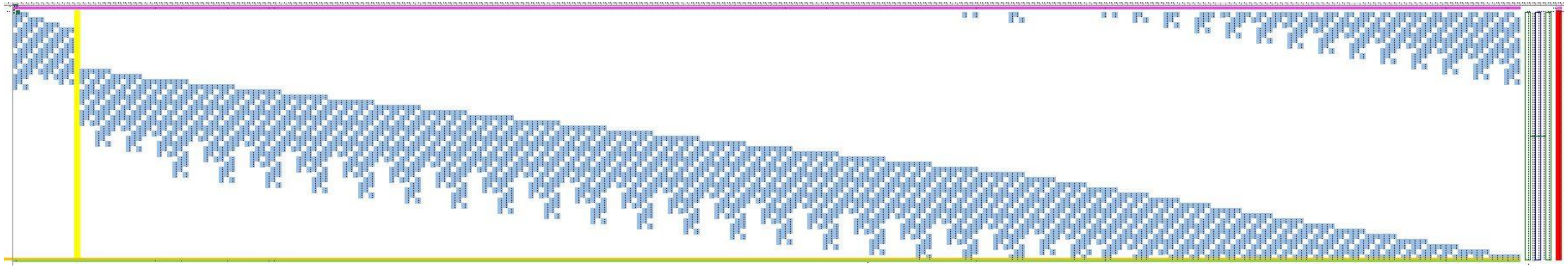
Shift Roster Assumptions

- When making model: assumed that the flights would be similar for everyday of the week (flight times are independent of the day of the week) – made model using data which was average the flight times for a week (any day of the week)
- When making roster: same assumption continued- shifts (obtained from our model) would be the same every day. The same shift structure was repeated for all the days but different shifts assigned to different employees.

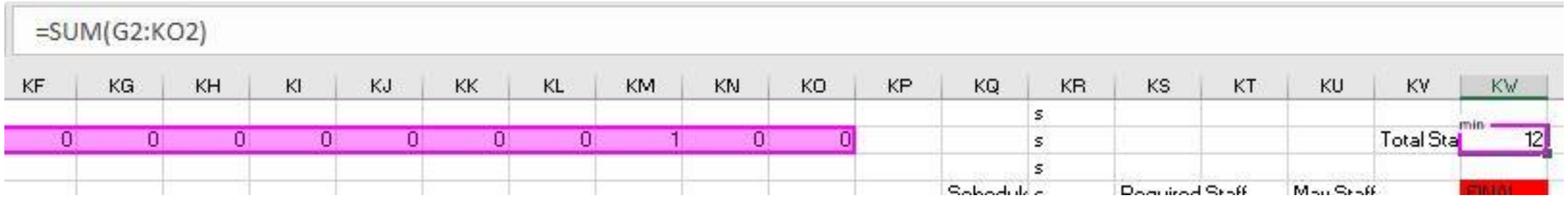
Model Assumptions

- One ATC worker can deal with as many as 3 flights at any one time.
- The most number of flights that can be dealt with during a 10-minute period is 10, (due to solo runway time and airflow disturbance).
- Flights classified as "unknown" on flightradar24 were presumed to be on time and still included in the number of flights per day.
- "Cancelled" flights on flightradar24 were assumed not to be dealt with at all by ATC workers.
- No morning shift can begin later than 5:30am.
- Morning shifts can be no longer than 8 hours.
- Night shifts can be no longer than 9.5 hours long.
- Afternoon shifts can be no longer than 10 hours long.
- Workers work in 2 hour blocks in which a 30-minute break has to be taken.
- There must be no less than 2 ATC workers on duty at any one time.
- Flights arriving between 0 – 10 minutes are effectively on time. Flight arriving/departing between 10 minutes to 20 minutes behind schedule are deemed to be 0 – 10 minutes delayed.
- We can model delays due to binomial inverse distribution.

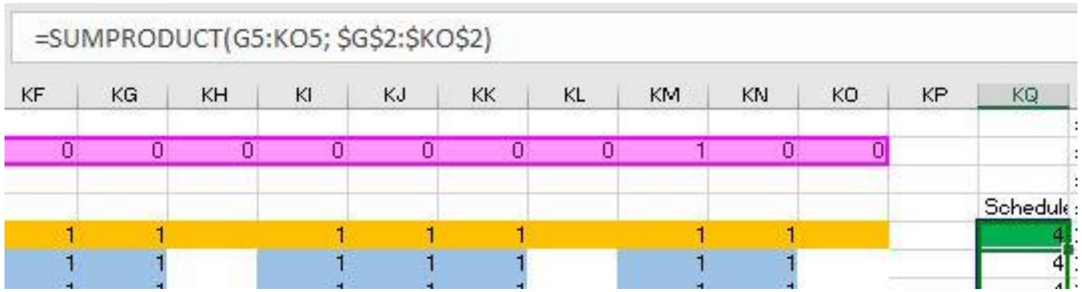
Appendix C: Model Screenshots



View of our Integer Linear Program, showing all possible shift combinations



Our Objective function is the Sum (above) of all SUM PRODUCTS (Below) from KQ5 to KQ147



		21-Apr	23-Apr	24-Apr	25-Apr	26-Apr	27-Apr	28-Apr	29-Apr	30-Apr			
Arrivals	-30	0.024096	0.026432	0.021552	0.021459	0.033613	0.012195	0.023346	0.00495	0.018182	0.185826		
	-20	0.012048	0.030837	0.030172	0.055794	0.058824	0.03252	0.027237	0.039604	0.022727	0.309764		
	-10	0.200803	0.237885	0.241379	0.253219	0.247899	0.247967	0.101167	0.069307	0.081818	1.681446		
	0	0.385542	0.361233	0.331897	0.407725	0.281513	0.264228	0.29572	0.222772	0.25	2.80063		
	10	0.228916	0.202643	0.228448	0.175966	0.231092	0.264228	0.319066	0.455446	0.3	2.405805		
	20	0.096386	0.044053	0.038793	0.038627	0.054622	0.04878	0.120623	0.089109	0.145455	0.676446		
	30	0.008032	0.048458	0.034483	0.017167	0.016807	0.028455	0.035019	0.029703	0.086364	0.304488		
	40	0.012048	0.013216	0.017241	0.012876	0.008403	0.03252	0.023346	0.019802	0.018182	0.157635	0.185826	0.010324
	50	0.012048	0.017621	0.00431	0.008584	0.008403	0.01626	0.015564	0.009901	0.018182	0.110874	0.309764	0.017209
	60	0.02008	0.017621	0.051724	0.008584	0.058824	0.052846	0.038911	0.059406	0.059091	0.367086	1.743109	0.096839
												5.783045	0.32128
												5.716626	0.31759
												2.066006	0.114778
Departure	-30	0	0	0	0	0	0	0	0	0	0	0.807923	0.044885
	-20	0	0	0	0	0	0	0	0	0	0	0.391939	0.021774
	-10	0.007968	0.013393	0	0.004425	0.004184	0.004098	0.003953	0.010309	0.013333	0.061663	0.628676	0.034926
	0	0.322709	0.334821	0.406926	0.442478	0.389121	0.311475	0.288538	0.304124	0.182222	2.982415	0.367086	0.020394
	10	0.438247	0.40625	0.363636	0.389381	0.34728	0.303279	0.395257	0.360825	0.306667	3.310821		1
	20	0.151394	0.133929	0.125541	0.106195	0.117155	0.204918	0.158103	0.170103	0.222222	1.38956		
	30	0.051793	0.049107	0.047619	0.017699	0.066946	0.04918	0.079051	0.030928	0.111111	0.503434		
	40	0.003984	0.026786	0.004329	0.017699	0.016736	0.036885	0.023715	0.046392	0.057778	0.234304		
	50	0.023904	0.035714	0.051948	0.022124	0.058577	0.090164	0.051383	0.07732	0.106667	0.517802		
	60	0	0	0	0	0	0	0	0	0	0		

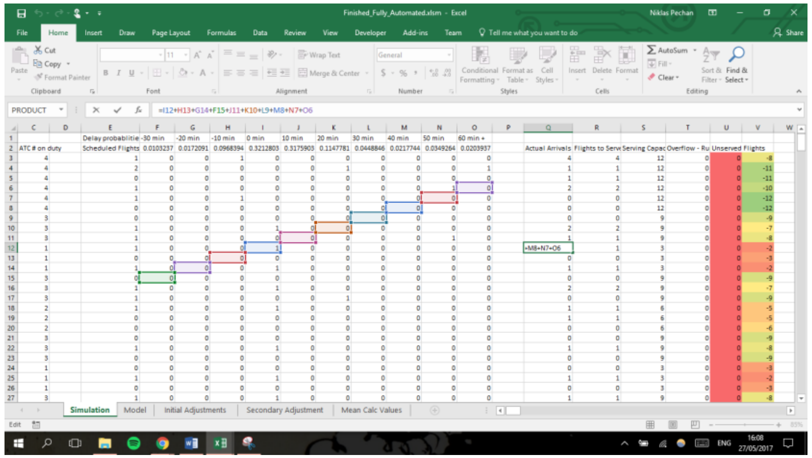
Probability of a Flight being delayed by a specified time from April 21st to April 30th

Flights to Serve	Serving Capacity	Overflow - Runway Constraint	Unserved Flights	Excess Capacity	Excess ATC's	Extra ATCs Required	Net ATC Change	Actual flights by now	Supposed flights by now
1	12	0	0	-11	-3.666666667	0	3.666666667	1	1
3	12	0	0	-9	-3	0	3	3	4
0	12	0	0	-12	-4	0	4	3	4
1	9	0	0	-8	-2.666666667	0	2.666666667	4	5
2	9	0	0	-7	-2.333333333	0	2.333333333	5	7
0	9	0	0	-9	-3	0	3	5	7
0	6	0	0	-6	-2	0	2	5	7
0	6	0	0	-6	-2	0	2	6	7
2	6	0	0	-4	-1.333333333	0	1.333333333	7	9
1	6	0	0	-5	-1.666666667	0	1.666666667	8	10
0	6	0	0	-6	-2	0	2	8	10
0	6	0	0	-6	-2	0	2	9	10
1	6	0	0	-5	-1.666666667	0	1.666666667	9	11
0	6	0	0	-6	-2	0	2	10	11
1	6	0	0	-5	-1.666666667	0	1.666666667	11	12
0	9	0	0	-9	-3	0	3	12	12
1	9	0	0	-8	-2.666666667	0	2.666666667	12	13
0	9	0	0	-9	-3	0	3	12	13
0	6	0	0	-6	-2	0	2	12	13
0	6	0	0	-6	-2	0	2	13	13
3	6	0	0	-3	-1	0	1	13	16
0	6	0	0	-6	-2	0	2	13	16
0	6	0	0	-6	-2	0	2	14	16
0	6	0	0	-6	-2	0	2	14	16
1	6	0	0	-5	-1.666666667	0	1.666666667	15	17
0	6	0	0	-6	-2	0	2	16	17
1	6	0	0	-5	-1.666666667	0	1.666666667	16	18
0	9	0	0	-9	-3	0	3	16	18
1	9	0	0	-8	-2.666666667	0	2.666666667	17	19
0	9	0	0	-9	-3	0	3	18	19
0	6	0	0	-6	-2	0	2	20	19
2	6	0	0	-4	-1.333333333	0	1.333333333	22	21
3	6	0	0	-3	-1	0	1	23	24
2	6	0	0	-4	-1.333333333	0	1.333333333	25	26
1	6	0	0	-5	-1.666666667	0	1.666666667	26	27
2	6	0	0	-4	-1.333333333	0	1.333333333	27	29
2	6	0	0	-4	-1.333333333	0	1.333333333	31	31
4	6	0	0	-2	-0.666666667	0	0.666666667	33	35
1	6	0	0	-5	-1.666666667	0	1.666666667	35	36
4	12	0	0	-8	-2.666666667	0	2.666666667	39	40
5	12	0	0	-7	-2.333333333	0	2.333333333	44	45
2	12	0	0	-10	-3.333333333	0	3.333333333	47	47
3	9	0	0	-6	-2	0	2	54	50
6	9	0	0	-3	-1	0	1	58	56
6	9	0	0	-3	-1	0	1	63	62
4	12	0	0	-8	-2.666666667	0	2.666666667	73	66
3	12	0	0	-9	-3	0	3	76	69
10	12	0	0	-2	-0.666666667	0	0.666666667	82	79
9	12	0	0	-3	-1	0	1	92	88
6	12	0	0	-6	-2	0	2	98	94
5	12	0	0	-7	-2.333333333	0	2.333333333	104	99
6	12	0	0	-6	-2	0	2	112	105
5	12	0	0	-7	-2.333333333	0	2.333333333	114	110
5	12	0	0	-7	-2.333333333	0	2.333333333	120	115
5	9	0	0	-4	-1.333333333	0	1.333333333	126	120
5	9	0	0	-4	-1.333333333	0	1.333333333	128	125
4	9	0	0	-5	-1.666666667	0	1.666666667	132	129
3	12	0	0	-9	-3	0	3	138	132
6	12	0	0	-6	-2	0	2	142	138
4	12	0	0	-8	-2.666666667	0	2.666666667	146	142
2	12	0	0	-10	-3.333333333	0	3.333333333	150	144
7	12	0	0	-5	-1.666666667	0	1.666666667	153	151
5	12	0	0	-7	-2.333333333	0	2.333333333	158	156
5	12	0	0	-7	-2.333333333	0	2.333333333	162	161
2	12	0	0	-10	-3.333333333	0	3.333333333	165	163
4	12	0	0	-8	-2.666666667	0	2.666666667	170	167
6	9	0	0	-3	-1	0	1	176	173
4	9	0	0	-5	-1.666666667	0	1.666666667	181	177

Excerpt of a simulation in progress

Time	Interation																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
9:00	0.4	0.3333	0.3667	0.3333	0.3667	0.3	0.2833	0.45	0.4333	0.45	0.2667	0.4167	0.3833	0.3333	0.3333	0.4333	0.5167	0.5	0.4333	0.4167	0.2667	0.3167	0.5167	0.3333	0.25
9:10	0.35	0.05	0.25	0.05	0.35	0.3	0.1	0.2	0.3	0.4	0.25	0.1	0.25	0.45	0.35	0.4	0.2	0.3	0.3	0.35	0.15	0.15	0.35	0.25	0.15
9:20	0.1	0.025	0.075	0.025	0.075	0.175	0.15	0.1	0.125	0.125	0.175	0.175	0.075	0.075	0.075	0.075	0.125	0	0.05	0.125	0.05	0.05	0.075	0.1	0.125
9:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9:40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9:50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0.2333	0.15	0.2667	0.25	0.25	0.2	0.1333	0.1667	0.1833	0.1667	0.4	0.15	0.2333	0.2	0.2	0.2	0.1833	0.25	0.2833	0.2167	0.2167	0.2333	0.25	0.2167	0.2167
11:10	0.28	0.4	0.38	0.46	0.3	0.28	0.26	0.3	0.22	0.4	0.28	0.32	0.28	0.34	0.34	0.36	0.32	0.42	0.3	0.32	0.28	0.22	0.24	0.32	0.26
11:20	0.35	0.25	0.125	0.325	0.375	0.25	0.275	0.325	0.275	0.35	0.25	0.325	0.275	0.475	0.225	0.1	0.325	0.425	0.225	0.325	0.25	0.25	0.225	0.2	0.325
11:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11:40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11:50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12:00	0.7667	0.7667	0.6	0.6	0.6667	0.3167	0.5667	0.45	0.6167	0.5833	0.55	0.55	0.6833	0.6167	0.5667	0.5833	0.8667	0.6667	0.6833	0.5833	0.5333	0.5667	0.4667	0.65	0.7333
12:10	0.72	0.6	0.52	0.6	0.72	0.6	0.54	0.72	0.48	0.46	0.52	0.54	0.58	0.74	0.56	0.64	0.64	0.68	0.48	0.38	0.36	0.56	0.44	0.58	0.58
12:20	0.42	0.4	0.38	0.52	0.42	0.44	0.48	0.62	0.48	0.5	0.34	0.32	0.44	0.42	0.5	0.34	0.36	0.46	0.48	0.38	0.44	0.62	0.46	0.48	0.68
12:30	0.4333	0.3333	0.2833	0.4833	0.4833	0.4167	0.4833	0.5833	0.4833	0.4167	0.6333	0.4833	0.3833	0.5333	0.4167	0.4167	0.3667	0.4833	0.3333	0.5833	0.5	0.5333	0.4333	0.4167	0.3667
12:40	0.325	0.425	0.4	0.45	0.75	0.525	0.5	0.6	0.4	0.675	0.575	0.55	0.55	0.375	0.325	0.7	0.375	0.6	0.55	0.45	0.675	0.5	0.575	0.575	0.525

Iterations used to calculate the Mean Probability of Delay for Time Intervals



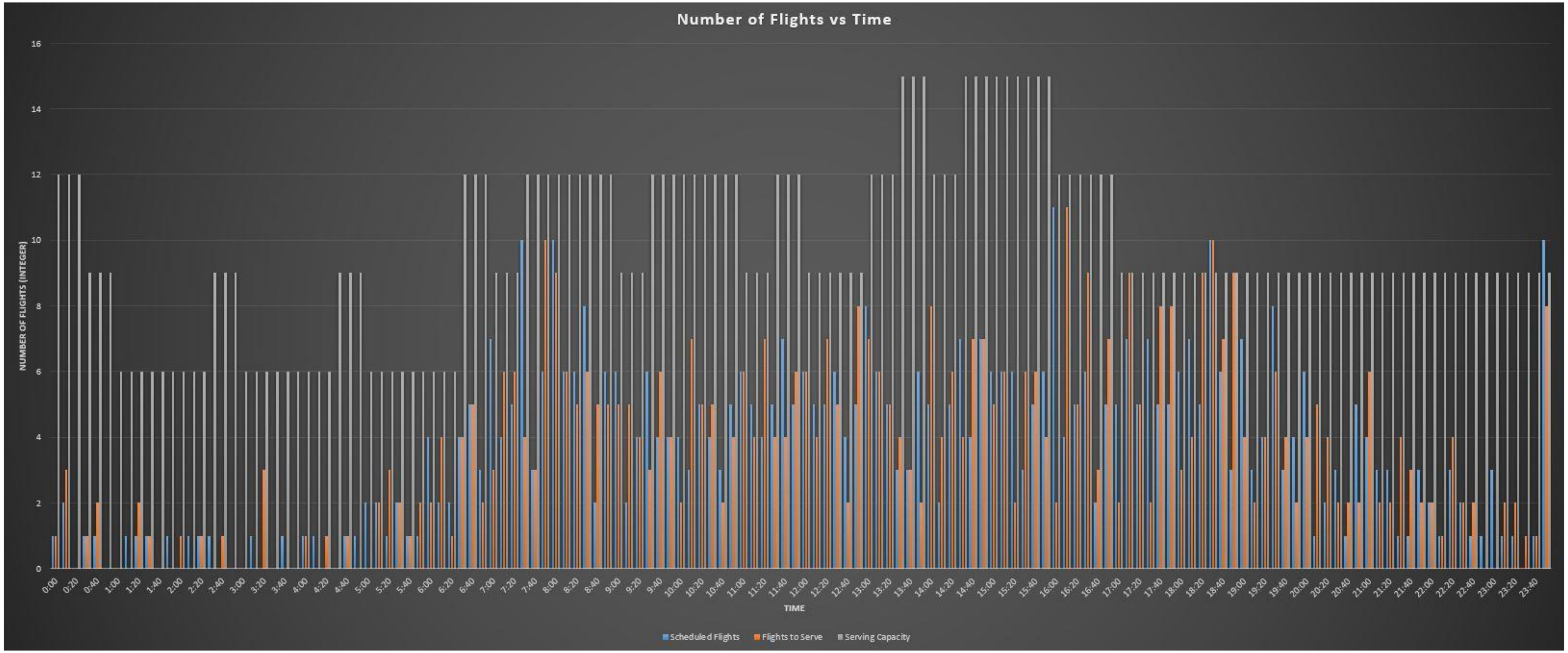
Excerpt of Calculating Actual Number of Flights Served in a time interval

	Iteration 1						Iteration 2								
Raw Flight Data	Initial ATC Require	Simulation Adjustment		Adjusted ATC Requirements		ATC Roster	Input ATC Require	Simulation Adjustment			Adjusted ATC Requirements			ATC Roster	
1	1	-1	1	1	1	3	1	1	0	0	2	2	1	2	1
2	1	-1	1	1	1	3	1	-1	1	0	1	1	0	2	1
0	0	0	1	0	0	3	0	0	1	1	0	0	0	2	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
0	0	0	1	0	0	2	0	0	1	1	0	0	0	2	0
0	0	0	1	0	0	2	0	0	1	1	0	0	0	1	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	2	1
0	0	0	1	0	0	1	0	0	1	1	0	0	0	2	1
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	2	1
0	0	0	1	0	0	2	0	0	1	1	0	0	0	2	0
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	1	0
0	0	0	1	0	0	1	0	0	1	1	0	0	0	1	0
0	0	0	1	0	0	1	0	0	1	1	0	0	0	1	0
0	0	0	1	0	0	2	0	0	1	1	0	0	0	1	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
0	0	0	1	0	0	2	0	0	1	1	0	0	0	1	1
0	0	0	1	0	0	1	0	0	1	1	0	0	0	2	1
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	2	1
0	0	0	1	0	0	1	0	0	1	1	0	0	0	2	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	2	0
0	0	0	1	0	0	2	0	0	1	1	0	0	0	2	0
0	0	0	1	0	0	1	0	0	1	1	0	0	0	1	0
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	1	0
1	1	-1	1	1	1	1	1	-1	1	0	1	1	0	1	0
2	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
2	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
1	1	-1	1	1	1	2	1	-1	1	0	1	1	0	1	1
2	1	-1	1	1	1	1	1	-1	1	0	1	1	0	3	2
1	1	1	1	2	2	1	2	-1	1	1	1	1	1	3	2
1	1	1	1	2	2	1	2	-1	1	1	1	1	1	3	2
4	2	-1	1	1	1	3	1	-1	1	0	1	1	0	2	1
2	1	-1	1	1	1	3	1	-1	1	0	1	1	0	2	1
2	1	-1	1	1	1	3	1	-1	1	0	1	1	0	2	1
4	2	-1	1	1	1	2	1	1	0	0	2	2	1	1	1
5	2	-1	1	1	1	2	1	2	0	0	3	3	2	1	1
3	1	0	1	1	1	2	1	3	0	0	4	4	3	1	1
7	3	-1	1	2	2	5	2	2	0	0	4	4	2	2	3
4	2	-1	1	1	1	5	1	2	0	0	3	3	2	2	3
5	2	-1	1	1	1	5	1	2	0	0	3	3	2	2	3
10	4	-1	1	3	3	4	3	-1	1	0	2	2	1	3	1
3	1	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
6	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
10	4	-1	1	3	3	4	3	-1	1	0	2	2	1	3	1
6	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
6	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
8	3	-1	1	2	2	3	2	2	0	0	4	4	2	2	1
2	1	-1	1	1	1	3	1	2	0	0	3	3	2	2	1
6	2	-1	1	1	1	3	1	1	0	0	2	2	1	2	1
6	2	-1	1	1	1	4	1	4	0	0	5	4	3	1	3
2	1	-1	1	1	1	4	1	5	0	0	6	4	3	1	3
4	2	-1	1	1	1	4	1	6	0	0	7	4	3	1	3
6	2	-1	1	1	1	4	1	1	0	0	2	2	1	3	1
4	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
4	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1
4	2	-1	1	1	1	4	1	-1	1	0	1	1	0	3	1

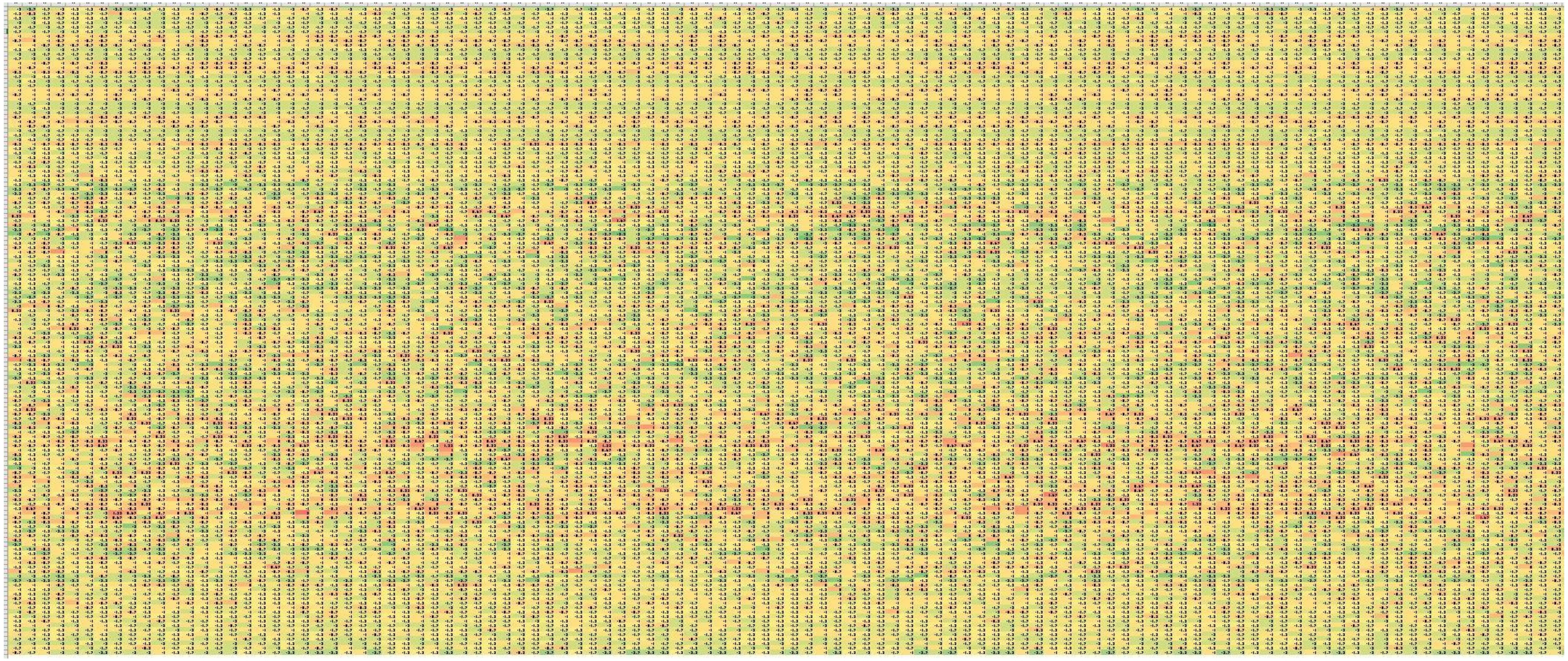
Different Iterations taking place

ATC Roster	Overstaffing Adjustment	New Roster	
4	-1	3	1
4	-1	3	1
4	-1	3	1
3	-1	2	1
3	-1	2	1
3	-1	2	1
1	0	1	0
1	0	1	0
1	0	1	0
2	0	2	0
2	0	2	0
2	0	2	0
1	0	1	0
1	0	1	0
1	0	1	0
2	0	2	0
2	0	2	0
2	0	2	0
1	0	1	0
1	0	1	0
1	0	1	0
2	0	2	0
2	0	2	0
2	0	2	0
1	0	1	0
1	0	1	0

Roster Adjustment to resolve Overstaffing



Comparisons between Scheduled Flights, Flights to Serve and Serving Capacity for all Time Intervals in a Day



Excerpt of Performing simulation on Excess ATCs' calculations

```
% This script calculates the time interval between two shifts (time between
% the end of one shift to the start of another shift). This information
% will be used in an integer program to produce a shift roster, where the
% total time between two shifts in a cycle will be minimised.
% The output is an array with the time intervals between all the combinations
% of any two shifts.
% Author: Jin Lee

% Tidy up
clear
clc

% Input the number of shifts
shiftNum = 12;

% open file containing the shift start and finish times
fid = fopen('shifts.txt','r');

% Record the start and finish times for each shift
line = fgetl(fid);
for i = 1:shiftNum
    start(i) = datetime(line,'Format','HHmm');
    line = fgetl(fid);
end

for i = 1:shiftNum
    finish(i) = datetime(line,'Format','HHmm');
    line = fgetl(fid);
end
fclose(fid);

% initialise arrays
interval = zeros(shiftNum,shiftNum);

% Calculate time interval between all the possible combinations of 2 shifts
% (rows represent 'from', columns represent 'to')
for i = 1:shiftNum
    for j = 1:shiftNum
        interval(i,j) = hours(start(j)-finish(i));
        % Minimum of 12 hour intervals between shifts
        % If less than 12 hours then go to the next day
        if interval(i,j) < 12
            interval(i,j) = interval(i,j) + 24;
            if interval(i,j) < 12
                interval(i,j) = interval(i,j) + 24;
            end
         end

    end
end
```

```
Module1 - 1

Sub Time_Find()
' this script analyses each potential shift cycle and sums
' the time between shifts within the cycle so that we can
' use a linear program to find a cycle with the least amount
' of time in the cycle that is not spent at work
' Author: Niklas Pechan
' Date: 27/05/2017


Sheets("Final").Select

With ThisWorkbook.Worksheets("Final")

'for every potential cycle
For k = 4 To 203

    'initialise a count variable
    Total_time = 0

    'for every potential shift in the cycle
    For i = 7 To 19
        Test_value = .Cells(i, k)
        Next_value = 0
        If Test_value = 1 Then 'once a shift is found, store which shift it is
            Dummy1 = .Cells(i, 1)
            switch_bool = 0
            j = i + 1 'initialise a search variable
            Do While switch_bool = 0 'search for the next shift
                If j = 20 Then
                    j = 7
                End If
                Next_value = .Cells(j, k)
                'once the next shift is found, calculate the time between them
                If Next_value = 1 Then
                    Dummy2 = .Cells(j, 1)
                    'do this by accessing a table of stored times in the sheet
                    temp = .Cells(22 + Dummy1, 4 + Dummy2)
                    Total_time = Total_time + temp
                    switch_bool = 1
                End If
                j = j + 1
            Loop
        End If

    Next i

    'store the total time between shifts in the labelled cell
    .Cells(4, k) = Total_time

Next k

End With

End Sub
```

```matlab
% This script extracts the scheduled and actual flight times from a text
% document with data from flightradar24.com. It then calculates the delay
% for each flight and the probability of a delay occurring for different
% lengths of time.
% Author: Jin Lee

% Tidy up
clear
clc

% Open text document containing the data
fid = fopen('25AprArr.txt','r');

% Initialising
flights = zeros(144,2);
j=0;

% Set up a column in FLIGHTS which represents time (every 10 minutes in 24 hours)
for i = 1:144
    flights(i)=j;
    j=j+(1/6); % 10 min interval
end

% Loop through the lines to extract scheduled times and delays
delay = duration(0,0,0);
x = 1;
line = fgetl(fid);
while ischar(line)
    flightTime(x) = textscan(line,'%{HH:mm}D%*s'); % scheduled time
    [~] = fgetl(fid);
    [~] = fgetl(fid);
    line = fgetl(fid);

    if (~isempty(strfind(line, 'Landed')))||(~isempty(strfind(line, 'Departed')))
        temp = textscan(line,'%*s%{HH:mm}D');
        delay(x) = temp{1} - flightTime{x}; % calculate delay

        % adjust for the special case when times are near 12am
        if delay(x) > duration(22,00,00)
            delay(x) = delay(x) - hours(24);
        elseif delay(x) < duration(-22,00,00)
            delay(x) = delay(x) + hours(24);
        end
    elseif (~isempty(strfind(line, 'Canceled')))||(~isempty(strfind(line, 'Unknown')))
        delay(x) = NaN; % ignore canceled and unknown flights in delay calculation
    end
    x = x+1;
    line = fgetl(fid);
end

% Counts the number of flights in each 10 minute time period
for i = 1:length(flightTime)
    hr = hour(flightTime{i});
    min = minute(flightTime{i});

    if min<10
        flights(hr*6+1,2)=flights(hr*6+1,2)+1;
    elseif min<20
        flights(hr*6+2,2)=flights(hr*6+2,2)+1;
    elseif min<30
```

```
        flights(hr*6+3,2)=flights(hr*6+3,2)+1;
    elseif min<40
        flights(hr*6+4,2)=flights(hr*6+4,2)+1;
    elseif min<50
        flights(hr*6+5,2)=flights(hr*6+5,2)+1;
    else
        flights(hr*6+6,2)=flights(hr*6+6,2)+1;
    end
end

fclose(fid);

% Convert the delays to minutes
delayMins(:) = minutes(delay(:));

% Exclude Unknown and Canceled flights
delayMins = delayMins(~isnan(delayMins));

% initialise delays
% (1st col: duration of delay, 2nd col: number of flights, 3rd col: probability)
delayTime = zeros(10,3);
for i = 1:10
    delayTime(i,1) = -30+10*(i-1); % from -30 to 60 in 10 minute intervals
end

% count the number of flights with different delay times
for i = 1:length(delayMins)
    if delayMins(i)<-30
        delayTime(1,2)=delayTime(1,2)+1;
    elseif delayMins(i)<-20
        delayTime(2,2)=delayTime(2,2)+1;
    elseif delayMins(i)<-10
        delayTime(3,2)=delayTime(3,2)+1;
    elseif delayMins(i)<0
        delayTime(4,2)=delayTime(4,2)+1;
    elseif delayMins(i)<10
        delayTime(5,2)=delayTime(5,2)+1;
    elseif delayMins(i)<20
        delayTime(6,2)=delayTime(6,2)+1;
    elseif delayMins(i)<30
        delayTime(7,2)=delayTime(7,2)+1;
    elseif delayMins(i)<40
        delayTime(8,2)=delayTime(8,2)+1;
    elseif delayMins(i)<50
        delayTime(9,2)=delayTime(9,2)+1;
    else
        delayTime(10,2)=delayTime(10,2)+1;
    end
end

% calculate the probabilities of each amount of delay occuring
delayTime(:,3)= delayTime(:,2)/sum(delayTime(:,2));
```

Connor McDowall 530913386

```
Sub FullExecution()
' This script solves our staffing linear program from scratch, including running
' 100,000 simulations at the end with the final roster to find enough mean values
' to construct a 95% confidence interval of delay coverage
' Author: Niklas Pechan
' Date: 29/05/2017
' Input: Flight schedule broken into 10 minute periods
' Output: ATC Roster for a single day

Application.ScreenUpdating = False 'prevent screen updating so the code runs faster

'take the initial staff requirements estimated from the flight data (estimated that
'1 ATC can serve 3 flights in a 10 minute period)
Sheets("Model").Select
Range("LC4:LC147").Select
Selection.Copy
Range("E5").Select 'place the initial requirements in one of the constraint cells for the IP
Selection.PasteSpecial Paste:=xlPasteValues

'initialise a count variable and give Sum_Change any non-zero value
Sum_Change = 1
i = 0

'solve the IP and use the roster to run simulations, which will adjust the roster in
'order to produce a roster that covers at least 95% of delays in every time interval.
Do While Sum_Change <> 0 'runs until a roster solution is converged upon (stops changing)
    RunOpenSolver
    Range("KQ5:KQ148").Copy 'copies produced ATC roster to a template
    With ThisWorkbook.Worksheets("Model")
        .Range(.Cells(4, 325 + i * 13), .Cells(147, 325 + i * 13)).Select
        Selection.PasteSpecial Paste:=xlPasteValues
    End With

    Sheets("Simulation").Select 'and to the simulation sheet
    Range("C3").Select
    Selection.PasteSpecial Paste:=xlPasteValues

    'run the simulation to find average unserved flight % in eaech 10 minute interval
        For j = 1 To 1000
            Worksheets("Simulation").Range("U3:U149").Copy
            Worksheets("Initial Adjustments").Cells(1, j).PasteSpecial Paste:=xlPasteValues
        Next j

    'take alterations produced by the simulation sheet and place them back into the model
    'sheet template
    Sheets("Initial Adjustments").Select
    Range("ALU1:ALV144").Copy
    Sheets("Model").Select
    With ThisWorkbook.Worksheets("Model")
        .Range(.Cells(4, 317 + i * 13), .Cells(147, 317 + i * 13)).Select
        Selection.PasteSpecial Paste:=xlPasteValues

        'take altered roster and place it in the next part of the template
        .Range(.Cells(4, 322 + i * 13), .Cells(147, 322 + i * 13)).Select
        Selection.Copy
        .Range(.Cells(4, 328 + i * 13), .Cells(147, 328 + i * 13)).Select
        Selection.PasteSpecial Paste:=xlPasteValues
        .Range("E5").Select
        Selection.PasteSpecial Paste:=xlPasteValues
    End With

    'once it has solved twice, start to check if the rosters are converging to a
    'steady state solution. Once it has the loop will stop
    If i > 0 Then
        With ThisWorkbook.Worksheets("Model")
            Sum_Change = .Cells(148, 336 + 13 * (i - 1))
            If Sum_Change = 0 Then 'once a solution is reached, save the preliminary roster
                .Range(.Cells(4, 325 + i * 13), .Cells(147, 325 + i * 13)).Select
                Selection.Copy
                .Range(.Cells(155, 313), .Cells(298, 313)).Select
                Selection.PasteSpecial Paste:=xlPasteValues
            End If
        End With
    End If

    'overflow prevention
    If i > 200 Then
```

```
        Exit Sub
    End If

    'increment each loop
    i = i + 1

Loop

'copy the preliminary roster into a second template for reducing overstaffing
Sum_Change = 1
j = 0
Range("LA155:LA298").Copy
Range("LD153:LD296").Select
Selection.PasteSpecial Paste:=xlPasteValues

'loop through, reducing overstaffing until a steady state roster is reached
Do While Sum_Change <> 0
    'take the current roster and copy it to the simulations sheet for testing
    Sheets("Model").Select
    With ThisWorkbook.Worksheets("Model")
        .Range(.Cells(153, 316 + j * 5), .Cells(296, 316 + j * 5)).Select
        Selection.Copy
    End With
    Sheets("Simulation").Select
    Range("C3:C146").Select
    Selection.PasteSpecial Paste:=xlPasteValues

    For i = 1 To 1000
        Worksheets("Simulation").Range("X3:X146").Copy
        Worksheets("Secondary Adjustment").Cells(1, i).PasteSpecial Paste:=xlPasteValues
    Next i

    'take the adjustment output of the simulation
    Sheets("Secondary Adjustment").Select
    Range("ALR1:ALR144").Copy
    Sheets("Model").Select
    'paste it into the template in the model sheet to adjust accordingly
    With ThisWorkbook.Worksheets("Model")
        .Range(.Cells(153, 317 + j * 5), .Cells(296, 317 + j * 5)).Select
        Selection.PasteSpecial Paste:=xlPasteValues
        'copy the adjusted roster to the next iteration template
        .Range(.Cells(153, 318 + j * 5), .Cells(296, 318 + j * 5)).Select
        Selection.Copy
        .Range(.Cells(153, 316 + (j + 1) * 5), .Cells(296, 316 + (j + 1) * 5)).Select
        Selection.PasteSpecial Paste:=xlPasteValues
        'update
        Sum_Change = .Cells(297, 319 + j * 5)
        'if a steady solution is reached, save it and stop the loop
        If Sum_Change = 0 Then
            .Range(.Cells(153, 318 + j * 5), .Cells(296, 318 + j * 5)).Select
            Selection.Copy
            .Range("E5:E148").Select
            Selection.PasteSpecial Paste:=xlPasteValues
        End If
    End With

    'maximum iteration limit
    If j > 200 Then
        Exit Sub
    End If

    'increment j
    j = j + 1
Loop

'with the final roster, run 100,000 simulations to compile enough data for creating a
'confidence interval

'take the final roster (by re-solving from the adjusted roster) and paste it into the
'simulations sheet
RunOpenSolver
Sheets("Model").Select
Range("KQ5:KQ148").Select
Selection.Copy
Sheets("Simulation").Select
Range("C3").Select
Selection.PasteSpecial Paste:=xlPasteValues
```

Module2 - 3

```
'repeat 1000 simulations 100 times and save the summary stats of each 1000 simulations in
'a final sheet, which we can then take the data off, place it in a .csv file and use R to
'construct confidence intervals for
For i = 1 To 100
    For j = 1 To 1000
         Worksheets("Simulation").Range("U3:U149").Copy
         Worksheets("Initial Adjustments").Cells(1, j).PasteSpecial Paste:=xlPasteValues
    Next j
    Worksheets("Initial Adjustments").Range("ALQ1:ALQ146").Copy
    Worksheets("Mean Calc Values").Cells(2, i + 2).PasteSpecial Paste:=xlPasteValues
Next i

End Sub
```

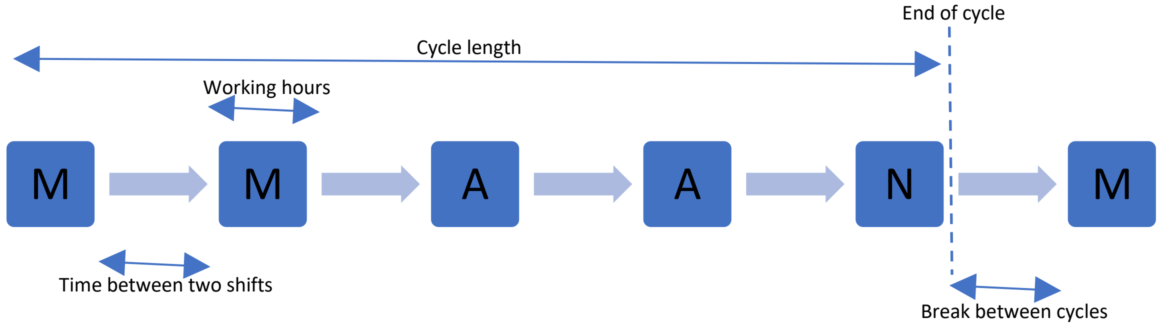
Shift Roster

Define types of shifts:
- Night (wholly or partly between 1:30 - 5:30am) = max 9.5 hours, end by 7:30am
- Early (starts between 5:30 – 6:29am) = max 8 hours
- Morning (starts between 6:30 – 7:59am)
- For simplicity, all the rest are defined as afternoon shifts

(Name each shift with a number for easy reference)

Shift	Start	End	Shift length (hours)	Type of shift
1	0000	0730	7.5	Night
2	0630	1200	5.5	Morning
3	0630	1530	9	Morning
4	0700	1600	9	Morning
5	0730	1700	9.5	Morning
6	0730	1630	9	Morning
7	1300	2200	9	Afternoon
8	1330	2300	9.5	Afternoon
9	1500	0030	9.5	Afternoon
10	1700	0030	7.5	Afternoon
11	2230	0600	7.5	Night
12	2330	0700	7.5	Night

Proposed "cycles"
Full time: Morning(M) – Morning(M) – Afternoon(A) – Afternoon(A) – Night(N) (5 days on, 3 days off)
Part time: Morning(M) – Night(N) (2 days on, 2 days off)



Cycle	Shift pattern	Average hours worked in a week	Hours worked in one cycle	Total hours off during work cycle	Cycle length (hours)	Break after each cycle (hours)
F1	4-5-9-10-11-Break	37.6	43	76	119	73
F2	3-6-7-8-12-Break	38.5	44	76.5	120.5	71.5
P1	2-1-Break	22.8	13	12	25	71

Example roster for a particular week:

Employee	Cycle	Shift number							Hours worked
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	
A	F1	4	5	9	10	11	-	-	43
B	F1	5	9	10	11	-	-	-	34
C	F1	9	10	11	-	-	-	4	33.5
D	F1	10	11	-	-	-	4	5	33.5
E	F1	11	-	-	-	4	5	9	35.5
F	F1	-	-	-	4	5	9	10	35.5
G	F1	-	-	4	5	9	10	11	43
H	F1	-	4	5	9	10	11	-	43
I	F2	3	6	7	8	12	-	-	44
J	F2	6	7	8	12	-	-	-	35
K	F2	7	8	12	-	-	-	3	35
L	F2	8	12	-	-	-	3	6	35
M	F2	12	-	-	-	3	6	7	34.5
N	F2	-	-	-	3	6	7	8	36.5
O	F2	-	-	3	6	7	8	12	44
P	F2	-	3	6	7	8	12	-	44
Q	P1	2	1	-	-	2	1	-	26
R	P1	1	-	-	2	1	-	-	20.5
S	P1	-	-	2	1	-	-	2	18.5
T	P1	-	2	1	-	-	2	1	26

(number represents the shift number and the '–' represent a break for that day)

Appendix H: Financial Analysis

	Cost of Employees			
Type	Number	Salary	Cost per Year	
Part Time	4	$ 85,000.00	$ 340,000.00	
Full Time	16	$ 170,000.00	$ 2,720,000.00	
Kiwisaver	Number	Contribution	Cost per Year	
Part Time	4	$ 6,800.00	$ 27,200.00	
Full Time	16	$ 13,600.00	$ 217,600.00	
Additional Benefits	Number	Cost	Cost Per year	
Part Time	4	$ 80,000.00	$ 80,000.00	
Full Time	16	$ 320,000.00	$ 320,000.00	
Annual Cost			Total	
Part Time			$ 447,200.00	
Full Time			$ 3,257,600.00	
Total			$ 3,704,800.00	
Estimate Costs Saved		Min	Max	
Net Gain		$ 11,077,011.98	$ 18,498,493.37	
Probabilty of Flight Delay	Time Interval	Number of flights delayed by interval	Cost	Cost
			Min	Max
0.3176	10 to 20	50103	$ 44,139,746.95	$ 88,279,493.90
0.1148	20 to 30	18110	$ 31,909,590.37	$ 47,864,385.55
0.0449	30 to 40	7083	$ 18,720,478.32	$ 24,960,637.76
0.0218	40 to 50	3439	$ 12,118,973.34	$ 15,148,716.68
0.0349	50 to 60	5506	$ 24,251,844.59	$ 29,102,213.51
0.02	60+	3155	$ 16,677,486.25	$ 16,677,486.25
			Total Min Cost	Total Max Cost
			$ 147,818,119.83	$ 222,032,933.66
Cost per Unit	$ 88.10			
International Movements (N)	107929		Total Min Cost ($)	Total Max Cost ($)
Domestic Movements (N)	49825		$ 14,781,811.98	$ 22,203,293.37
Overall Movement Growth Rat	4.30%			
Max Savings				
Min Savings				
Min Delay	$ 14.76			
Max Delay	$ 22.17			
Cost of ATCs	$ 3.70			
Maximum Delays	$ 11.06			
Minimum Delays	$ 18.47			

Appendix I: Project Timeline

Group 3
Connor McDowall
Niklas Pechan
Jin Lee
Josh Leaning

Primary Team meetings are held Fridays, 11:00am – 12:00pm. Secondary meetings are organised on a need by need basis.

Team Leader duties include co-ordinating team members, monitoring process, assigning tasks to other team members.

Tasks assigned to team members

Connor McDowall	Niklas Pechan	Jin Lee	Josh Leaning
Legislative Research	Model Construction	Script Creation	ATC Research
Daily Roster Visualisation	Simulation	Data Extraction and Processing	ATC Regulation Investigation
Financial Analysis	Model Research	Weekly Rostering Research and Implementation	

Timeline of Project:

Week	Date Intervals	Tasks to be completed/started
Mid-Semester Break – Week 7	11:00am 14th April – 12:00pm 5th May	Initial Model Construction, Script Creation and Data Extraction, Legislative and Assumption Research, ATC Research, Discussion on project approach, factors to consider and the direction we are going to take. Allocate report sections. Individual Progress Sheet Due
Week 7 – Week 8	11:00am 5th May – 12:00pm 12th May	Refine Model, Continue Research and building model. Begin Report Writing
Week 8 - Week 9	11:00am 12th May – 12:00pm 19th May	Refine Model, Continue Research and building model. Continue Report Writing
Week 9 – Week 10	11:00am 19th May – 12:00pm 26th May	Finish Modelling, Assumptions. Continue Report Writing
Week 10 – Week 11	11:00am 26th May – 12:00pm 2nd June	Finish report, Start preparation and practise. Modelling Summary and Problem Analysis due 12:00pm Friday 2nd June
Week 11 – Week 12	11:00pm 2nd June – 12:00pm 9th June	Finalise and Practise presentation. Presentation, Presentation due 12:00pm Friday 9th June