Optimized Decision Making

Prescriptive Analytics

A Case of X Airlines in India

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1. **Executive Summary:**

What is an important quality that the airline industry ought to possess? A response to this question has been put in the following manner:

"Measuring customer satisfaction in the airline industry is becoming ever more frequent and relevant due to the fact that the delivery of high-quality service is essential for airlines' survival and crucial to the competitiveness of the airline industry" (Park, 2005).

This paper has been inspired by the above statement. It focuses on optimal scheduling of flight crew of an airline company in India in order to avoid flight delays - to ensure "high quality" - and excessive costs. It is important to note that the airline company has not been disclosed due to data confidentiality. The company will be titled as "X Airlines." Moreover, a succinct version of the problem the company faced serves the purpose of this project; therefore, it has been reduced to a smaller scale as follows:

- The number of cities that the company serves has been reduced to 3.
- The total number of flights has been reduced to 12.
- The flight timings have been altered pertaining to confidentiality reasons.
- The different costs of flight crew members have also been altered pertaining to confidentiality reasons.

Elaborating more on this paper, it is noteworthy that in an age of economic upheaval in 2007, X Airlines, a medium sized airline company, was struggling for its market share. The company was ranked at the bottom of the industry as far as revenue, service-quality, number of flights, and crew members are concerned. Notwithstanding the presence of industry giants like Air India and Spice Jet in the market, the CEO decided to alter the company's operations: improve the quality of service and cut costs at the same time. These two major changes are addressed in this paper by refining crew scheduling for various flights and suggesting the total number of crew for a given budget.

Objective Function: This includes minimizing total costs as an objective function. The model is a Linear Programming model.

Decision Variables: The number of crew members in crew rotations for different flights as decision variables.

Business Constraints: A major constraint in the airline industry is that every flight, be it small or big, needs to have at least one flight crew member available at all times. Another major constraint that has been incorporated in the model is the requirement set forth by Airports Authority of India. Depending on its medium size, X Airlines required at least 1 crew member available as substitutes in case of absences of the working crew members. Catering to past experiences of crew absences, X Airlines takes a minimum of 2 extra members as substitutes.

Optimal Decision: In the end, after running solver table, a suggestion has been made to X Airlines' CEO regarding the best decision for how to alter the business's operations.

Sensitivity Analyses: The paper also includes one-way and two-way sensitivity analyses by comparing total costs against various variables and constraints.

Solver Table Analyses: The paper also includes both one-way and two-way solver table analyses.

Binary Model: The paper also includes a binary version of this model when there is no constraint of substitute crew members by Airports Authority of India.

The above-mentioned aspects of the project have been included in this paper with numeric, tabular and graphical displays.

2. <u>Introduction:</u>

X Airlines was launched in India in 2000. Headquartered in Mumbai, the company serves many local and international cities. The Indian airline industry is highly competitive. Moreover, a major barrier to entry faced by small players is the presence of local giants like Air India, Spice, Jet Airways and many other; and international giants like Emirates, Air Asia and many others. Nonetheless, X Airlines launched its operations with availability of huge investments from Indian industrialists and managed to overcome the mentioned obstacles. It started as a low-cost airline serving the local market initially.

2.1 Expansion:

It expanded to the international market by end of 2004. Today, X Airlines operates about 250 daily flights to 35 destinations. These destinations include 25 Indian cities and 10 international cities. The originating cities are Bangalore, New Delhi and Mumbai. Primarily, the company uses Boeing 737 for its flights. It acquired 32 of these airplanes worth USD 3.1 billion in 2000. It is also planning to expand its supplier base for its fleet. It is in talks with Airbus and Bombardier Aerospace.

2.2 Services:

X Airlines' low-cost model does not provide any kind of meal services and business class seats for its local flights. However, the international flights which also do not include business class have a basic meal package. In 2015 X Airlines introduced its premium services by acquiring 4 planes (Boeing 737). These premium services included the business class, extra legroom, highly qualified and well-trained air hostesses, priority baggage handling and many other such additional services. The management saw an additional inflow of revenue from this premium service. Thus, they planned to expand more into this market segment in 2018.

3. Main Issue:

X Airlines offers both international and domestic services. The CEO decided to make changes in the crew scheduling in their domestic network first as it contributes most to the revenue since domestic operations are characterized with frequent number of arrivals and departure. International operations, in contrast, tend to be sparse as X Airlines operates only in 10 cities internationally.

As of current schedule, X Airlines operates two flights daily between Bangalore, New Delhi and Mumbai. Total of 6 flights operate between these cities, and the earliest departure of any flight is 5:00 AM while as the latest arrival in any of the cities is 5:00 PM. Each flight is accompanied with a crew that includes the hospitality staff for quality service and sound customer experience. As per the company policy, a crew that leaves a city in the morning should return by night. The return of the crew does not necessarily have to be with X Airlines as the airlines have services with other low-cost carriers in which the return of the crew can be scheduled. Based on the historical data of flights between these cities, noticeably, the average delayed time frame of all the latest arrival flights was 20 – 35 mins. Since the latest flight arrival is 5:00 PM, company decided to fly back the crew on a 6:00 PM flight.

Crew is a cost to the company that varies depending on whether the crew is flying a plane or not. The entire crew is paid $170 per hour when the crew is flying in X Airline. For simplicity reasons, it has been assumed that the entire Crew is paid the same amount when the crew is flying back with any other airlines. When the crew is waiting between the X Airline flights or for other airlines to have them flown back, the crew costs X Airlines $80 per hour. Given below is the flight schedule.

Flight Schedule					
From	**To**	**Departure**	**Arrival**	**Departure**	**Arrival**
Bangalore	New Delhi	6:00 AM	9:00 AM	11:00 AM	2:00 PM
Bangalore	Mumbai	7:00 AM	11:00 AM	12:00 PM	4:00 PM
New Delhi	Bangalore	5:00 AM	8:00 AM	1:00 PM	4:00 PM
New Delhi	Mumbai	6:00 AM	8:00 AM	2:00 PM	4:00 PM
Mumbai	Bangalore	5:00 AM	9:00 AM	1:00 PM	5:00 PM
Mumbai	New Delhi	7:00 AM	9:00 AM	3:00 PM	5:00 PM

Table 3.1 Flight Scheduling

As per the fundamental requirements, each flight between any of the cities should have at least one crew member always. Without meeting this fundamental requirement, flight will not take off in any circumstances. Recently, there were instances wherein the crew members failed to board the returning flights at 6:00 PM hence they could not return to their respective cities on the same day. This resulted in lack of crew members for the next flight hence X Airlines had to deviate from their normal scheduling. Although these instances were very rare yet these situations lead to a strong public disapproval. X Airlines was not the only one to face the music as some other low-carrier airlines such as Vistara Airlines had faced the same situation. Given the ordeal that public had to face, Airport Authority of India regulated a law which forced Airline companies to have back up crews depending on the overall operations of the company. With the introduction if this law, X Airlines wanted to have minimum of 8 crew members. X Airlines have already determined all the possible crew rotations. Now, the decision that the CEO had to make is how many crew members should be present in any single crew rotation to minimize the total daily cost.

3.1 Crew Scheduling:

IP(Binary) and Simplex Linear programming was employed to determine the optimal number of crews for any possible crew rotation. This programming yielded the minimum total monthly cost taking in flight and waiting cost per hour into consideration. Based on the requirements and constraints, there are 14 different shifts. Based on these crew rotations we have set our decision variables.

4. <u>Decision Variables:</u>

The following table lists our decision variables:

B - ND + ND - B	# of crew(s) required for this possible crew rotation – Departing flight from Bangalore to New Delhi and returning flight from New Delhi to Bangalore, both flights are X Airlines. **(In-flight hours 6 – other hours 6).**
B - ND + (ND - B)	# of crew(s) required for this possible crew rotation – Departing flight from Bangalore to New Delhi is X Airlines. Returning flight from New Delhi to Bangalore is other airlines. **(In-flight hours 3 – other hours 12).**
B -ND + ND - M + (M - B)	# of crew(s) required for this possible crew rotation – Departing flight from Bangalore to New Delhi, then from New Delhi to Mumbai are X Airlines. Returning flight from Mumbai to Bangalore is other airlines. **(In-flight hours 5 – other hours 11).**
B - M + (M - B)	# of crew(s) required for this possible crew rotation – Departing flight from Bangalore to Mumbai is X Airlines. Returning flight from Mumbai to Bangalore is other Airlines. **(In-flight hours 4 – other hours 11).**
B - M + M - ND + (ND - B)	# of crew(s) required for this possible crew rotation – Departing flight from Bangalore to Mumbai, then Mumbai to New Delhi are X Airlines. Returning flight from New Delhi to Bangalore is other Airlines. **(In-flight hours 6 – other hours 10).**
ND - B + B - ND	# of crew(s) required for this possible crew rotation – Departing

	flight from New Delhi to Bangalore and returning flight from Mumbai to Bangalore, both flights are X Airlines. **(In-flight hours 6 – other hours 3).**
ND - B + (B - ND)	# of crew(s) required for this possible crew rotation – Departing flight from New Delhi to Bangalore is X Airlines. Returning flight from Bangalore to New Delhi is other Airlines. **(In-flight hours 3 – other hours 13).**
ND - B + B - M + (M - ND)	# of crew(s) required for this possible crew rotation – Departing flight New Delhi to Bangalore, then Bangalore to Mumbai are X Airlines. Returning flight from Mumbai to Bangalore is other Airlines. **(In-flight hours 7 – other hours 8).**
ND - M + M - B + (B - ND)	# of crew(s) required for this possible crew rotation – Departing flight from New Delhi to Mumbai, then Mumbai to Bangalore are X Airlines. Returning flight from Bangalore to New Delhi is other Airlines. **(In-flight hours 6 – other hours 9).**
ND - M + M - ND	# of crew(s) required for this possible crew rotation – Departing flight from New Delhi to Mumbai and returning flight both are X Airlines. **(In-flight hours 4 – other hours 7).**
M - B + B - ND + (ND - M)	# of crew(s) required for this possible crew rotation – Departing flight from Mumbai to Bangalore, then Bangalore to New Delhi are X Airlines. Returning flight from New Delhi to Mumbai is other Airlines. **(In-flight hours 7 – other hours 8).**
M - B + B - M	# of crew(s) required for this possible crew rotation – Departing

	flight from Mumbai to Bangalore and returning flight both are X Airlines. **(In-flight hours 8 – other hours 3).**
M - ND + ND - M	# of crew(s) required for this possible crew rotation – Departing flight from Mumbai to New Delhi and returning flight both are X Airlines. **(In-flight hours 4 – other hours 5).**
M - ND + ND - B + (B - M)	# of crew(s) required for this possible crew rotation – Departing flight from Mumbai to New Delhi, then from New Delhi to Bangalore are X Airlines. Returning flight from Bangalore to Mumbai is other Airlines. **(In-flight hours 5 – other hours 10).**

Table 4.1 Decision Variables

5. **Objective Function**:

The objective function of this crew scheduling is to minimize the total daily cost of X Airlines while satisfying all the constraints.

MINIMIZE

[B - ND + ND – B] *1500 + [B - ND + (ND - B)] * $1,470 +

[B -ND + ND - M + (M - B)] * $1,730 + [B - M + (M - B)] * $1,560 +

[B - M + M - ND + (ND - B)] * $1,820 + [ND - B + B – ND] * $1,260 +

[ND - B + (B –ND)] * $1,550 + [ND - B + B - M + (M - ND)] * $1,830 +

[ND - M + M - B + (B - ND)] * $1,740 + [ND - M + M – ND] * $1,240 +

[M - B + B - ND + (ND - M)] *$1,830 + [M - B + B - M] * $1,600 +

[M - ND + ND – M]* $1,080 + [M - ND + ND - B + (B - M)] * $1,650.

6. Constraints:

Following are the constraints that must be satisfied:

- **B - ND 1:** The first flight of the day from Bangalore to New Delhi should have at least one crew member.
- **B - ND 2:** The second flight of the day from Bangalore to New Delhi should have at least one crew member.
- **B - M 1:** The first flight of the day from Bangalore to Mumbai should have at least one crew member.
- **B - M 2:** The second flight of the day from Bangalore to Mumbai should have at least one crew member.
- **ND - B 1:** The first flight of the day from New Delhi to Bangalore should have at least one crew member.
- **ND - B 2:** The second flight of the day from New Delhi to Bangalore should have at least one crew member.
- **ND - M 1:** The first flight of the day from New Delhi to Mumbai should have at least one crew member.
- **ND - M 2:** The second flight of the day from New Delhi to Mumbai should have at least one crew member.
- **M - B 1:** The first flight of the day from Mumbai to Bangalore should have at least one crew member.
- **M - B 2:** The second flight of the day from Mumbai to Bangalore should have at least one crew member.

- **M - ND 1:** The first flight of the day from Mumbai to New Delhi should have at least one crew member.
- **M - ND 2:** The second flight of the day from Mumbai to New Delhi should have at least one crew member.
- **TC:** Minimum number of total crew members should be 8 as per X Airlines to abide by the Airport Authority of India regulated law.
- **NN:** The total number of crews at any time should be equal or greater than zero (Non-negativity)

7. Binary (IP) Model Solution

The model is solved using Excel Solver with Simplex Algorithm using binary constraints. We can see that the optimal solution shown in the table below suggests that X Airlines should schedule its crew rotation as follows:

- 1 crew member for flight from Bangalore to New Delhi leaving at 6am. The same member will also assist in a flight from New Delhi to Bangalore with departure time as 1pm.
- 1 crew member for flight from Bangalore to Mumbai leaving at 7am. The same member will assist in a flight leaving Mumbai at 3pm for New Delhi. After this, this crew member will return to Bangalore in another airline's flight.
- 1 crew member for flight from New Delhi to Bangalore leaving at 5am. The same member will assist in a flight leaving Bangalore at 11am for New Delhi.
- 1 crew member for flight from New Delhi to Mumbai leaving at 6am. The same member will also assist in a flight leaving Mumbai at 1pm for Bangalore and the crew will return back to New Delhi in another airline's flight.
- 1 crew member for flight from Mumbai to Bangalore leaving at 5am. The same crew will assist in a flight leaving Bangalore 12pm for Mumbai.
- 1 crew member for flight from Mumbai to New Delhi leaving at 7am. The same crew will also assist in a flight leaving New Delhi at 2pm for Mumbai, with a total daily cost of $9000.

This shows that exactly one crew is on each flight, which is our constraint and from each airport, there are two flights for two different airports.

Possible Crew Rotations					
B = Bangalore, ND = New Delhi, M = Mumbai, ( )=Back with other company					**1=selected 0=rejected**
Flight	**In-Flight Hours**	**Other Hours**	**Cost**		**Decision**
B - ND + ND - B	6	6	**$1,500**		**1**
B - ND + (ND - B)	3	12	**$1,470**		**0**
B -ND + ND - M + (M - B)	5	11	**$1,730**		**0**
B - M + (M - B)	4	11	**$1,560**		**0**
B - M + M - ND + (ND - B)	6	10	**$1,820**		**1**
ND - B + B - ND	6	3	**$1,260**		**1**
ND - B + (B - ND)	3	13	**$1,550**		**0**
ND - B + B - M + (M - ND)	7	8	**$1,830**		**0**
ND - M + M - B + (B - ND)	6	9	**$1,740**		**1**
ND - M + M - ND	4	7	**$1,240**		**0**
M - B + B - ND + (ND - M)	7	8	**$1,830**		**0**
M - B + B - M	8	3	**$1,600**		**1**
M - ND + ND - M	4	5	**$1,080**		**1**
M - ND + ND - B + (B - M)	5	10	**$1,650**		**0**

Objective Function		**Minimize Total Cost**	**$9,000**

Table 7.1 Binary IP Model Solution

8. LIP Model Solution:

The model is solved using Excel Solver with Simplex Algorithm. The optimal solution shown in the table below suggests that X Airlines should schedule as follows:

- 1 crew member for flight from Bangalore to New Delhi leaving at 6am. The same crew member will assist in a flight leaving New Delhi at 1pm for Bangalore.
- 1 crew member for flight from Bangalore to Mumbai leaving at 7am. The same crew member will fly back to Bangalore with another airline's flight.
- 1 crew member for flight from New Delhi to Bangalore leaving at 5am. The same crew will fly back to New Delhi in a flight leaving at 11am.
- 1 crew member for flight from New Delhi to Mumbai leaving at 6am. The same crew member will also assist in a flight leaving Mumbai at 1pm for Bangalore. This crew member will then return to New Delhi in another airline's flight,
- 1 crew member for flight from New Delhi to Mumbai leaving at 6am. The same crew member will also assist in a flight leaving Mumbai at 4pm for New Delhi
- 1 crew member for flight from Mumbai to Bangalore leaving at 5am. The same crew will assist in a flight leaving Bangalore at 12pm for Mumbai.
- 2 crew members for the flight from Mumbai to New Delhi leaving at 7am. The same crew members will assist in a flight leaving New Delhi at 2pm for Mumbai, with a total daily cost of $11060.

Possible Crew Rotations					
B = Bangalore, ND = New Delhi, M = Mumbai, ( )=Back with other company					**1=selected 0=rejected**
Flight	**In-Flight Hours**	**Other Hours**	**Cost**		**Decision**
B - ND + ND - B	6	6	**$1,500**		**1**
B - ND + (ND - B)	3	12	**$1,470**		**0**
B -ND + ND - M + (M - B)	5	11	**$1,730**		**0**
B - M + (M - B)	4	11	**$1,560**		**1**
B - M + M - ND + (ND - B)	6	10	**$1,820**		**0**
ND - B + B - ND	6	3	**$1,260**		**1**
ND - B + (B - ND)	3	13	**$1,550**		**0**
ND - B + B - M + (M - ND)	7	8	**$1,830**		**0**
ND - M + M - B + (B - ND)	6	9	**$1,740**		**1**
ND - M + M - ND	4	7	**$1,240**		**1**
M - B + B - ND + (ND - M)	7	8	**$1,830**		**0**
M - B + B - M	8	3	**$1,600**		**1**
M - ND + ND - M	4	5	**$1,080**		**2**
M - ND + ND - B + (B - M)	5	10	**$1,650**		**0**

Objective Function		**Minimize Total Cost**	**$11,060**

Table 8.1 Linear IP Model Solution

9. Sensitivity Analysis

Part 1: Sensitivity Analysis for Decision variables

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
F15	B - ND + ND - B Decision	1	0	1500	540	30
F16	B - ND + (ND - B) Decision	0	0	1470	30	390
F17	B -ND + ND - M + (M - B) Decision	0	260	1730	1E+30	260
F18	B - M + (M - B) Decision	1	0	1560	100	480
F19	B - M + M - ND + (ND - B) Decision	0	100	1820	1E+30	100
F20	ND - B + B - ND Decision	1	0	1260	50	180
F21	ND - B + (B - ND) Decision	0	290	1550	1E+30	290
F22	ND - B + B - M + (M - ND) Decision	0	50	1830	1E+30	50
F23	ND - M + M - B + (B - ND) Decision	1	0	1740	1E+30	660
F24	ND - M + M - ND Decision	1	0	1240	100	160
F25	M - B + B - ND + (ND - M) Decision	0	750	1830	1E+30	750
F26	M - B + B - M Decision	1	0	1600	50	520
F27	M - ND + ND - M Decision	2	0	1080	160	50
F28	M - ND + ND - B + (B - M) Decision	0	540	1650	1E+30	540

Some crew rotations are not included in our optimal decision due to the high cost associated with operating them. For these crew rotations to become a part of the optimal mix, the cost of operating these crew rotations should reduce by their respective reduced costs. Below table gives details of each crew rotation which is not in the optimal mix and its reduced cost:

B -ND + ND - M + (M - B)	For number of crew rotation going from Bangalore to New Delhi, and then to Mumbai with X Airlines and returning from Mumbai to Bangalore with other airline to become a part of the optimal mix, it’s crew operating cost should reduce by 260.
B - M + M - ND + (ND - B)	For number of crew rotation going from Bangalore to Mumbai and then to New Delhi with X Airlines and returning from New Delhi to Bangalore with other airline to become a part of the optimal mix,

	it's crew operating cost should reduce by 100.
ND - B + (B - ND)	For number of crew rotation departing from New Delhi to Bangalore with X Airlines and returning from Bangalore to New Delhi with other airline to become a part of the optimal mix, it's crew operating cost should reduce by 290.
ND - B + B - M + (M - ND)	For number of crew rotation going from New Delhi to Bangalore and then to Mumbai with X Airlines and returning from Mumbai to New Delhi with other airline to become a part of the optimal mix, it's crew operating cost should reduce by 50.
M - B + B - ND + (ND - M)	For number of crew rotation going from Mumbai to Bangalore and then to New Delhi with X Airlines and returning from New Delhi to Mumbai with other airline to become a part of the optimal mix, it's crew operating cost should reduce by 750.
M - ND + ND - B + (B - M)	For number of crew rotation going from Mumbai to New Delhi and then to Bangalore with X Airlines and returning from Bangalore to Mumbai with other airline to become a part of the optimal mix, it's crew operating cost should reduce by 540.

Table 9.1. Sensitivity Analysis of Decision Variables not included in Optimal Solution

Part 2: Sensitivity Analysis for Constraints

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
C34	B - ND 1 LHS	1	390	1	1	0
C35	B - ND 2 LHS	1	0	1	0	1E+30
C36	B - M 1 LHS	1	480	1	1	1
C37	B - M 2 LHS	1	520	1	1	0
C38	ND - B 1 LHS	1	180	1	1	0
C39	ND - B 2 LHS	1	30	1	0	1
C40	ND - M 1 LHS	2	0	1	1	1E+30
C41	ND - M 2 LHS	2	0	1	1	1E+30
C42	M - B 1 LHS	1	0	1	0	1E+30
C43	M - B 2 LHS	1	660	1	1	1
C44	M - ND 1 LHS	2	0	1	1	1E+30
C45	M - ND 2 LHS	1	160	1	1	1
C46	TC LHS	8	1080	8	1E+30	1

The shadow price helps us understand the change in optimal solution value by changing the RHS value of the constraints within the range of their respective allowable increase and decrease so that all the constraints are still satisfied.

If we wish to change the RHS value of the constraint outside the allowable range, we will have to re-run the solver and sensitivity analysis report again to get our new optimal solution and shadow prices.

Based on this report, we see that we can further minimize our operation costs by reducing the following number of crew rotations:

B -M1	If the minimum number of crew rotation of first flights of the day going from Bangalore to Mumbai decreases by 1 (i.e. becomes zero), the total cost of crew operation reduces by $480.
ND-B2	If the minimum number of crew rotation of second flights of the day going from New Delhi to Bangalore decreases by 1 (i.e. becomes zero), the total cost of crew operation reduces by $30.
M-B2	If the minimum number of crew rotation of second flights of the day going from Mumbai to Bangalore decreases by 1 (i.e. becomes zero), the total cost of crew operation reduces by $660.
M-ND2	If the minimum number of crew rotation of second flights of the day going from Mumbai to New Delhi decreases by 1 (i.e. becomes zero), the total cost of crew operation reduces by $160.
TC	If the mandatory minimum number of crew members reduces by 1 (i.e. becomes 7), $1080. Although this would give us the maximum reduction in crew operation cost, this is not feasible to the regulatory laws.

Table 9.2. Sensitivity Analysis of Constraints w.r.t. allowable decrease

Thus, operation cost can be minimized the most by reducing the number of crew rotation for flights travelling from Mumbai to Bangalore at 1:00 pm from1 to 0. In other words, if we cancel the 1:00 pm flight from Mumbai to Bangalore, we can reduce the operation cost by $660.

The second crew rotation that will prove most profitable in terms of reducing operation costs is the first flight from Bangalore to Mumbai. Cancelling this crew rotation (reducing number of flights from 1 to 0) will reduce the cost of operation by $480.

Similarly, we can increase the frequency/ number of crew rotation within the allowable range. The corresponding increase in cost of operating the crew for the additional flight is given by its shadow price.

B -ND1	If the minimum number of crew rotation of first flights of the day going from Bangalore to New Delhi increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $390.
B-M1	If the minimum number of crew rotation of first flights of the day going from Bangalore to Mumbai increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $480.
B-M2	If the minimum number of crew rotation of second flights of the day going from Bangalore to Mumbai increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $520.
ND-B1	If the minimum number of crew rotation of first flights of the day going from New Delhi to Bangalore increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $180.
ND-M1	If the minimum number of crew rotation of first flights of the day going from New Delhi to Mumbai increases by 1 (i.e. becomes 3), the total cost of crew operation increases by $0 (there is no increase).

ND-M2	If the minimum number of crew rotation of second flights of the day going from New Delhi to Mumbai increases by 1 (i.e. becomes 3), the total cost of crew operation increases by $0 (there is no increase).
M-B2	If the minimum number of second flights of the day going from Mumbai to Bangalore increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $660.
M-ND1	If the minimum number of crew rotation with first flights of the day going from Mumbai to New Delhi increases by 1 (i.e. becomes 3), the total cost of crew operation increases by $0 (there is no increase).
M-ND2	If the minimum number of crew rotation with second flights of the day going from Mumbai to New Delhi increases by 1 (i.e. becomes 2), the total cost of crew operation increases by $160.

Table 9.3 Sensitivity Analysis of Constraints w.r.t. allowable increase

Thus, we can increase the number of crew travelling from New Delhi to Mumbai departing at 6 am and 2 pm and the crew travelling from Mumbai to New Delhi departing at 7am without any increase in total cost of crew operation.

The results provided by the sensitivity report are merely suggestive. Before taking any administrative decision, we need to conduct further analyses for factors like:

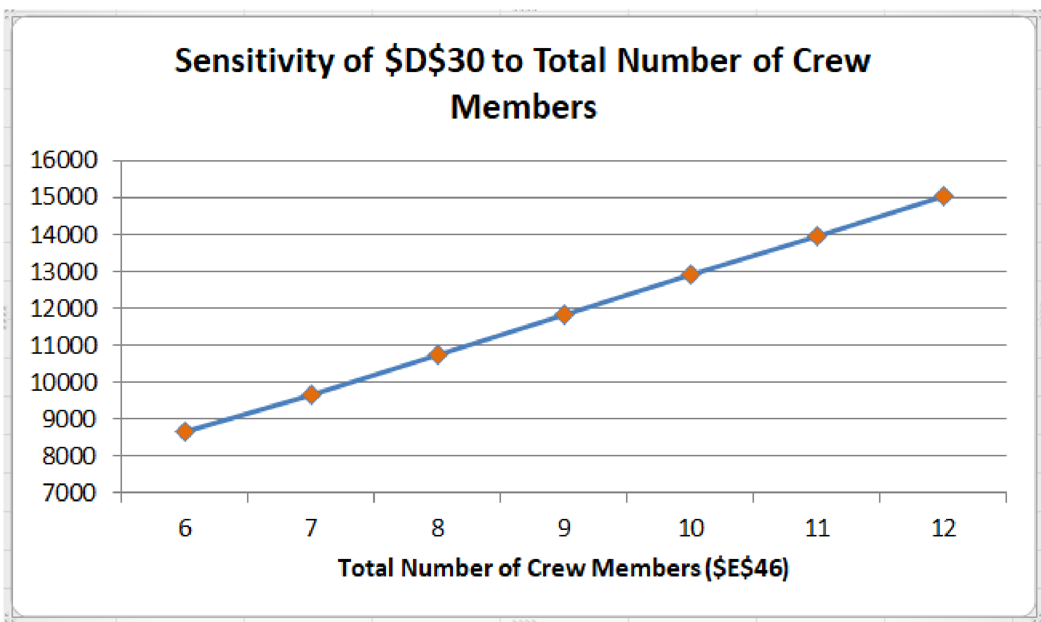
- Cost of operating each flight (fuel price, distance covered)
- Profit earned from each flight (profit margin for tickets, average number of customers)

10. Solver Table Analyses

10.1 One-Way Sensitivity:

We ran the solver table for one-way sensitivity analyses by increasing the number of crew members by 1 starting with 6 and ending with 12 total number of crew members. We found out that X Airlines total cost keeps on increasing. This makes sense because cost is directly related to the number of crew members.

Interestingly, it can be noted that for the first increase in number of crew members from 6 to 7 the increase in total cost is $980. Furthermore, each incremental crew member from 7 to 12 increases the total cost of X Airlines by $1,080. This can be seen in the graph below. The y-axis shows total cost and the x-axis shows total number of crew members. Therefore, it can be said that, given the objective function of cost minimization, X-Airlines should be wary of the incremental costs for each additional crew member.



10.2 Two-Way Sensitivity

- Two-way sensitivity analysis is performed to illustrate how the total cost is affected by changing the cost/flight hour and cost/waiting hour. It is observed that total cost increases by $840 for every $20 increase in cost/flight hour and the total cost increases by $480 for every $10 increase in cost/waiting hour.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Bangalore to New Delhi and New Delhi to Bangalore is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Bangalore to New Delhi and flying back to Bangalore with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Bangalore to New Delhi and New Delhi to Mumbai & flying back to Bangalore with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Bangalore to Mumbai and flying back to with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change in cost/flight hour and it decreases

as the cost/waiting hour increases & becomes constant as the cost/waiting hour reaches $70.

- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Bangalore to Mumbai and Mumbai to New Delhi & flying back to Bangalore with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from New Delhi to Bangalore and flying back to New Delhi is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change in cost/flight hours and it stays constant till the value of cost/waiting hour reaches $90 & then, it increases as the cost/waiting hour increases.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from New Delhi to Bangalore and flying back to New Delhi with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from New Delhi to Bangalore and Bangalore to Mumbai and flying back to New Delhi with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.

- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from New Delhi to Mumbai and Mumbai to Bangalore and flying back to New Delhi with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
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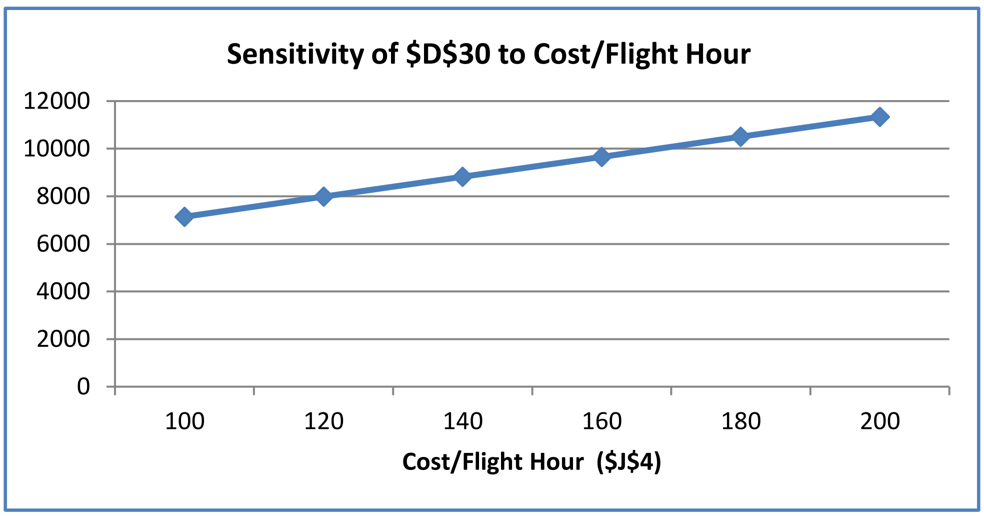
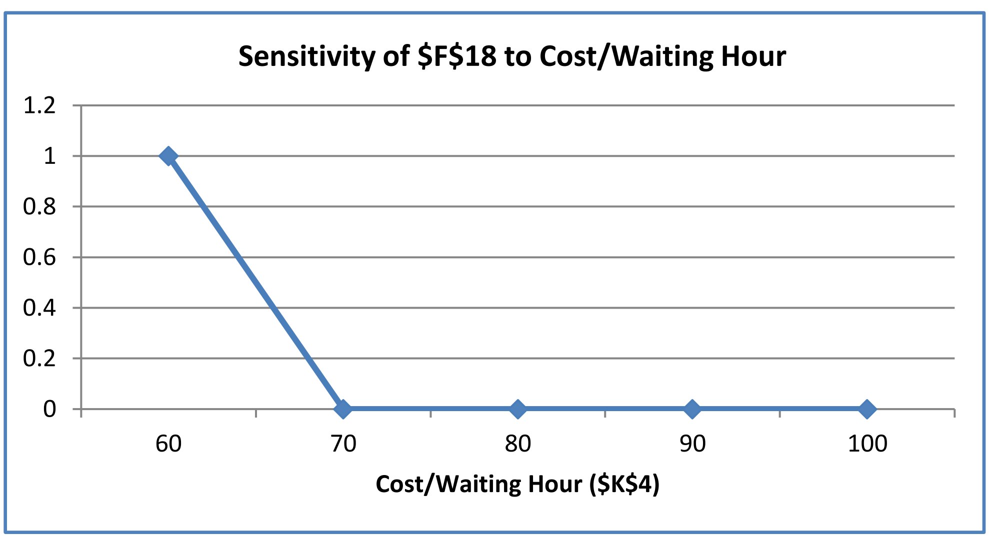
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Mumbai to Bangalore and Bangalore to New Delhi flying back to Mumbai with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Mumbai to Bangalore and flying back to Mumbai is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.
- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Mumbai to New Delhi and flying back to Mumbai is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change in cost/flight hour and it increases when the

cost/waiting hour increases from $60 to $70 and it stays constant until the cost reaches $90 and it then decreases until the cost reaches $100.

- Two-way sensitivity analysis is performed to illustrate how the number of crew members on the flight from Mumbai to New Delhi and New Delhi to Bangalore & flying back to Mumbai with other airline's flight is affected by changing the cost/flight hour and the cost/waiting hour. It is observed that the number of crew members is insensitive to the change.

This paper includes two graphs from the two-way analyses for references. All of the graphs can be found in the excel file.





11. Conclusion

Based on our optimization, we conclude that in order to spend minimum possible amount on daily domestic crew operation, Airline X should select following crew rotations:

Crew Rotation	Description	Cost	# crew following rotation
B - ND + ND - B	Departing flight from Bangalore to New Delhi and returning flight from New Delhi to Bangalore, both flights are X Airlines. **(In-flight hours 6 – other hours 6).**	$1,500	1
B - ND + (ND - B)	Departing flight from Bangalore to New Delhi is X Airlines. Returning flight from New Delhi to Bangalore is other airlines. **(In-flight hours 3 – other hours 12).**	$1,470	0
B -ND + ND - M + (M - B)	Departing flight from Bangalore to New Delhi, then from New Delhi to Mumbai are X Airlines. Returning flight from Mumbai to Bangalore is other airlines. **(In-flight hours 5 – other hours 11).**	$1,730	0
B - M + (M - B)	Departing flight from Bangalore to Mumbai is X Airlines. Returning flight from Mumbai to Bangalore is other Airlines. **(In-flight hours 4 – other hours 11).**	$1,560	1
B - M + M - ND +	Departing flight from Bangalore to Mumbai, then	$1,820	0

(ND - B)	Mumbai to New Delhi are X Airlines. Returning flight from New Delhi to Bangalore is other Airlines. **(In-flight hours 6 – other hours 10).**		
ND - B + B - ND	– Departing flight from New Delhi to Bangalore and returning flight from Mumbai to Bangalore, both flights are X Airlines. **(In-flight hours 6 – other hours 3).**	**$1,260**	**1**
ND - B + (B - ND)	Departing flight from New Delhi to Bangalore is X Airlines. Returning flight from Bangalore to New Delhi is other Airlines. **(In-flight hours 3 – other hours 13).**	**$1,550**	**0**
ND - B + B - M + (M - ND)	Departing flight New Delhi to Bangalore, then Bangalore to Mumbai are X Airlines. Returning flight from Mumbai to Bangalore is other Airlines. **(In-flight hours 7 – other hours 8).**	**$1,830**	**0**
ND - M + M - B + (B - ND)	Departing flight from New Delhi to Mumbai, then Mumbai to Bangalore are X Airlines. Returning flight from Bangalore to New Delhi is other Airlines. **(In-flight hours 6 – other hours 9).**	**$1,740**	**1**
ND - M + M - ND	Departing flight from New Delhi to Mumbai and returning flight both are X Airlines. **(In-flight hours 4 – other hours 7).**	**$1,240**	**1**
M - B + B - ND +	Departing flight from Mumbai to Bangalore, then	**$1,830**	**0**

(ND - M)	Bangalore to New Delhi are X Airlines. Returning flight from New Delhi to Mumbai is other Airlines. **(In-flight hours 7 – other hours 8).**		
M - B + B - M	Departing flight from Mumbai to Bangalore and returning flight both are X Airlines. **(In-flight hours 8 – other hours 3).**	**$1,600**	**1**
M - ND + ND - M	Departing flight from Mumbai to New Delhi and returning flight both are X Airlines. **(In-flight hours 4 – other hours 5).**	**$1,080**	**2**
M - ND + ND - B + (B - M)	Departing flight from Mumbai to New Delhi, then from New Delhi to Bangalore are X Airlines. Returning flight from Bangalore to Mumbai is other Airlines. **(In-flight hours 5 – other hours 10).**	**$1,650**	**0**

Table 4.1 Decision Variables

For crew rotations which are not selected to become a part of the optimal mix, the cost of operating these crew rotations should reduce by their respective reduced costs as explained in the sensitivity analysis section.

The operation cost can be further minimized significantly by reducing the number of crew rotations for flights travelling from Mumbai to Bangalore at 1:00 pm from1 to 0. In other words, if we cancel the 1:00 pm flight from Mumbai to Bangalore, we can reduce the operation cost by $660.

The second crew rotation that will prove most profitable in terms of reducing operation costs is the first flight from Bangalore to Mumbai. Cancelling this crew rotation (reducing number of flights from 1 to 0) will reduce the cost of operation by $480.

We can increase the number of crew travelling from New Delhi to Mumbai departing at 6 am and 2 pm and the crew travelling from Mumbai to New Delhi departing at 7am without any increase in total cost of crew operation.

These conclusions are merely suggestive. Before taking any administrative decision, we need to conduct further analyses for factors like:

- Cost of operating each flight (fuel price, distance covered)
- Profit earned from each flight (profit margin for tickets, average number of customers)

12. **Bibliography**:

https://pdfs.semanticscholar.org/cede/5829392008ed89cfc182ae47091e6ea6c131.pdf

13. APPENDIX:

Appendix 1 *Calculation of total cost per crew rotation:*

POSSIBLE CREW ROTATIONS	In Flight Cost/hr	Waiting Cost/ hr	In Flight hours	Waiting Hours	Total Cost
(B = Bangalore, ND = New Delhi, M = Mumbai, ( )=Back with other company)					
B - ND + ND - B	170	80	6	6	1500
B - ND + (ND - B)	170	80	3	12	1470
B -ND + ND - M + (M - B)	170	80	5	11	1730
B - M + (M - B)	170	80	4	11	1560
B - M + M - ND + (ND - B)	170	80	6	10	1820
ND - B + B - ND	170	80	6	3	1260
ND - B + (B - ND)	170	80	3	13	1550
ND - B + B - M + (M - ND)	170	80	7	8	1830
ND - M + M - B + (B - ND)	170	80	6	9	1740
ND - M + M - ND	170	80	4	7	1240
M - B + B - ND + (ND - M)	170	80	7	8	1830
M - B + B - M	170	80	8	3	1600
M - ND + ND - M	170	80	4	5	1080
M - ND + ND - B + (B - M)	170	80	5	10	1650

Appendix 2: *One-way sensitivity analysis of total cost vs number of crews*

Total number of crew members (cell E46) values along side, output cell(s) along top

	D30	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28
6	$9,000	1	0	0	0	1	1	0	0	1	0	0	1	1	0
7	$9,980	1	0	0	1	0	1	0	0	1	1	0	1	1	0
8	$11,060	1	0	0	1	0	1	0	0	1	1	0	1	2	0
9	$12,140	1	0	0	1	0	1	0	0	1	1	0	1	3	0
10	$13,220	1	0	0	1	0	1	0	0	1	1	0	1	4	0
11	$14,300	1	0	0	1	0	1	0	0	1	1	0	1	5	0
12	$15,380	1	0	0	1	0	1	0	0	1	1	0	1	6	0

Appendix 3: *Two-way sensitivity analysis of total cost vs cost/waiting hour and cost/flight hour*

Cost/Flight Hour (cell J4) values along side, Cost/Waiting Hour (cell K4) values along top, outp

D30	60	70	80	90	100
100	$7,140	$7,620	$8,080	$8,540	$9,000
120	$7,980	$8,470	$8,960	$9,420	$9,880
140	$8,820	$9,310	$9,800	$10,290	$10,760
160	$9,660	$10,150	$10,640	$11,130	$11,620
180	$10,500	$10,990	$11,480	$11,970	$12,460
200	$11,340	$11,830	$12,320	$12,810	$13,300

Output	Cost/Flight Hour value
D30	100
7140	
7620	
8080	
8540	
9000	

Output	Cost/Waiting Hour value
D30	60
7140	
7980	
8820	
9660	
10500	
11340	