Problem Chosen	2022	Team Control Number
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Aboard! Boarding and Disembarking a Plane

Abstract

Nowadays, with the advancement of technology, airline companies can greatly control their flight times. However, delay in flights still occurs, surprisingly, on a relatively large scale. A big part of this delay is due to boarding and disembarking. Airlines developed multiple methods to predict the time needed for boarding accurately and disembarking, while debates are still on which of them is the best. Time is money for airline travel, and thus, it is necessary to suggest an optimal method mathematically.

We first built a model to calculate the boarding and disembarking time to solve this problem. **The Boarding and Disembarking Time Calculation (BDTC) Algorithm** will simulate the actions of every person in the queue with a time interval of 1 second and eventually give out the overall time usage for every seat on the plane to be occupied (for boarding) and cleared (for disembarking), which means when the whole process is finished. Different circumstances that affect the times were considered in the algorithm, and with and varying input of the sequence of passengers with their seats indicated, the algorithm can be applied to any aircraft with different methods, even considering the circumstance of people disobeying the methods.

Then, we applied this model to find the optimal boarding and disembarking strategy. 1) *Firstly, we analyzed the probability of when different boarding times occur.* Based on our analysis, the different boarding times are even likely events, and therefore, by finding the maximum and minimum time, we can find the average time, practical maximum time, and practical minimum time. This significantly reduced the complexity since we do not need to simulate all the circumstances to get all these three values. 2) *Secondly, we applied this to three different aircraft, the Narrow-Body Aircraft, Flying Wing Aircraft, and Two Entrance, Two Aisle Aircraft, with five different boarding and disembarking methods including by random, by section, by seat, by section by seat, and by optimal.* For a different aircraft and method, we generated input data of the sequence of passengers that should be the relatively fastest and slowest arrangement. Each passenger is assigned a seat based on these relative optimal and worst arrangements. Then we calculated the time based on our **BDTC Algorithm**. The shortest time is the minimum time for the method, while the biggest time is the maximum. Then we calculated the average, practical maximum, and practical minimum based on these two data.

However, these three data cannot be used to find the optimal strategy. The sensitivity of the methods to changes in different parameters is important. We first carried out the sensitivity analysis on changes in carryons. These include the change in the number of carryons that are put into the overhead bin, that are not put into the carryons, and when all the carryons are put into the overhead bin. These were accomplished by adjusting the parameters in our algorithms. Secondly, we performed the sensitivity analysis on the percentage of people disobeying the method. This is accomplished by generating the input data for our **BDTC Algorithm** by randomly shuffling people's orders.

Lastly, we found the optimal method by carrying out a **Multi-Criteria Decision Making Model**. We used a **Criteria Importance Through Intercriteria Correlation based Technique for Order of Preference by Similarity of Ideal Solution (C-TOPSIS)**. With the criteria including average boarding time, practical maximum boarding time, practical minimum boarding time, and the three slopes of the linear sensitivity analysis on changes in carryons, we determined the optimal strategy for the three aircraft. The result came out as that *for the Narrow-Body aircraft, the optimal method is by random*; *for the Flying Wing Aircraft, the optimal method is to board and disembark by seat*; *for the Two Entrance, Two Aisle Aircraft, the optimal method is to board and disembark by section*.

Finally, we accounted for pandemic situations when the capacity is limited to 70%, 50%, and 30% of the full capacity. The exact process for different capacities was carried out, assuming evenly distributed passengers for pandemic prevention measures. With the same process, we suggested the optimal method of the 9 different circumstances.

Keywords: Boarding and Disembarking Time Calculation(BDTC) Algorithm, Criteria Importance Through Intercriteria Correlation Based Technique for Order of Preference by Similarity of Ideal Solution(C-TOPSIS)

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1 Introduction

1.1 Background

With the promotion of globalization and the enhanced technology in air travel, more and more people travel by plane for either business or traveling purposes. Before the COVID-19 pandemic, the annual number of flights globally increased from 23.8 million to 40.3 million from 2004 to 2020 [1]. This increases the competition in the airline industry. For airline companies, time is money. This is especially the case when planning the boarding and disembarking time, as this can significantly influence if the flight can be on time [2]. Currently, there are many different boarding and disembarking methods deployed by different airline companies, while debates are still fierce on which is the most optimal strategy. Therefore, there is a need to evaluate these strategies mathematically to help improve the airline industry.

1.2 Problem Restatement

1. Develop a model to calculate the total boarding and disembarking time of a plane. The model needs to be applicable to different prescribed methods, plane interiors, and any passengers breaking the given method.
2. Find the optimal boarding and disembarking method for a narrow-body aircraft, flying wing aircraft, and two-entrance, two aisle aircraft by
   a. first calculating the total boarding and disembarking time with the following methods and comparing the average, 95th percentile, and 5th percentile. (Reversing the sequence when disembarking)
      I Random boarding
      II Boarding by section: In the order of aft section, middle section, and bow section, each 1/3 of the rows in the aircraft.
      III Boarding by seat: In the order of window seats, middle seats, and aisle seats.
      IV Boarding by section by seat: First obeying boarding by section and secondly in the order of by seat.
      V Boarding by lining up with the least time method: By lining before boarding in the order of the fastest method in the above methods.
   b. Carrying out sensitivity analysis on the percentage of passengers not following the prescribed method, average number of carry-on bags, average number of overhead carry-ons, and when all carry-ons are put in the overhead bin.
3. Identify the optimal method of the three planes when the number of passengers is limited to 70%, 50%, and 30% of the full capacity due to pandemic prevention measures.
4. Write a letter to an airline executive describing and explaining the results.

1.3 Summary of References

There is plentiful research done on similar topics. Bachmat et al. developed a model for calculating the boarding time with a random method in their paper *Analysis of Airplane*

Boarding Times[3]. Willamowski and Tillmann developed a model for minimum boarding time by constructing a mathematical function on the random boarding method[4]. Other research also constructed similar models, but they all attempted only one boarding method. There is little work on one general model to solve for the boarding time for every boarding method. Furthermore, little is done on the disembarking time calculation. Therefore, there is a need to combine boarding and disembarking time together and develop a generalized model.

In addition, to evaluate the optimal method with the average, practical maximum, practical minimum, and sensitivity analysis of the different methods, we used the Criteria Importance Through Intercriteria Correlation CRITIC method. It is a multiple-criteria decision-making (MCDM) model that considers contrast intensity and conflict of the different criteria.[5] This can help us calculate the weight of each of the indexes that we consider. Then, we would use the Technique of Order of Preference by Similarity of Ideal Solution (TOPSIS), another commonly used MCDM model, developed by Hwang et al. in 1981[6], and modified twice in 1987 and 1993, respectively[7][8]. It is now widely used to find the optimal solution in an MCDM problem,[9] which can also be used in our evaluation model for the modification plan.

2 Assumptions and Variables

2.1 Variables and Descriptions

The symbols and their descriptions used in the paper are shown in the following Table 1. Additional symbols used in the calculation process is attached in Appendix A.

Table 1: Variables and Descriptions

Variables	Descriptions
$\bar{T}$	Average Boarding/Disembarking Time of A Given Method, in minutes
T_{pmax}	Pratical Maximum Time for Boardin/Disembarking Time of a Given Method, in minutes
T_{pmin}	Pratical Minimum Time for Boarding/Disembarking Time of a Given Method, in minutes
T_{max}	Maximum Time for Boarding/Disembarking Time of a Given Method, in minutes
T_{min}	Minimum Time for Boarding/Disembarking Time of a Given Method, in minutes
S_o	Slope of the Linear Sensitivity Analysis (SA) of the change in the carryon that are put at overhead bins
S_c	Slope of the Linear SA of the change in the carryon that are not put at overhead bins
S_a	Slope of the Linear SA of the circumstance that all the carryon are put into the overhead bins
s_b	The maximum minimum time value when a percentage of breaks the method

2.2 Assumptions

Here are the assumptions necessary for the development of our models.

1. Aircraft operate at full capacity.
   If aircraft do not operate at full capacity, the sensitivity analysis on a limited percentage of passengers will be biased as it is compared to circumstances that are not the full capacity.
2. Every controlled variable including but not limited to walking speed, sitting time, luggage storing time, luggage stowing time, luggage numbers, are stable and evenly distributed, meaning that it will be the average for all passengers.
   These are the controlled variables that need to be constant. Therefore, an estimation of the average number is necessary.
3. Priorities and disabilities are not considered.
   To simplify and generalise the model, not to consider these special cases is necessary.
4. Passengers arrive on time, there will be no delays.
   For simplicity, delays are not considered as delays will be breaking the boarding and disembarking methods.
5. On aircraft 3, people at the first half can only board and disembark at the first entrance, while people with seats at the second half can only board and disembark at the second entrance.
   Otherwise, two passengers will meet in the middle of the aisle in opposite directions, complicating the problem.
6. At pandemic situations, capacity is limited to 70%, 50%, and 30%. These passengers will be evenly distributed in the plane, as far from each other as possible.
   Otherwise, if they all gather at a section of the plane, the pandemic prevention measure will not find its goal.
7. People walk directly to their seats.
   For simplicity, circumstances such as taking selfies in the middle of the aisle and walking too far.

2.3 Parameters

Here are some parameters used in our model with their value given.

1. Walking speed: 1ms^{-1} [10]
2. Pitch: 0.8128m [11]
3. Sitting time: 1s
4. Time of putting a carryon to the overhead bin: 5s
5. Additional sitting time when there is a carryon not put into the overhead bin: 1s
6. Time for one people to give way: 2s
7. Time for two people to give way: 5s

3 Boarding and Disembarking Time Calculation Algorithm

3.1 Introduction to Model

To calculate the boarding and disembarking time, we need to develop an algorithm to achieve this purpose. All circumstances need to be considered, and the algorithm needs to be adaptable to any aircraft interiors, any methods, as well as the people not obeying the methods. We developed the **Boarding and Disembarking Time Calculation (BDTC) Algorithm** to solve this problem. The algorithm is built in the train of thought of boarding, but disembarking is just the opposite of it as it is symmetrical to boarding. Therefore, by reversing the sequence, we can get the disembarking time.

3.2 Development of Model

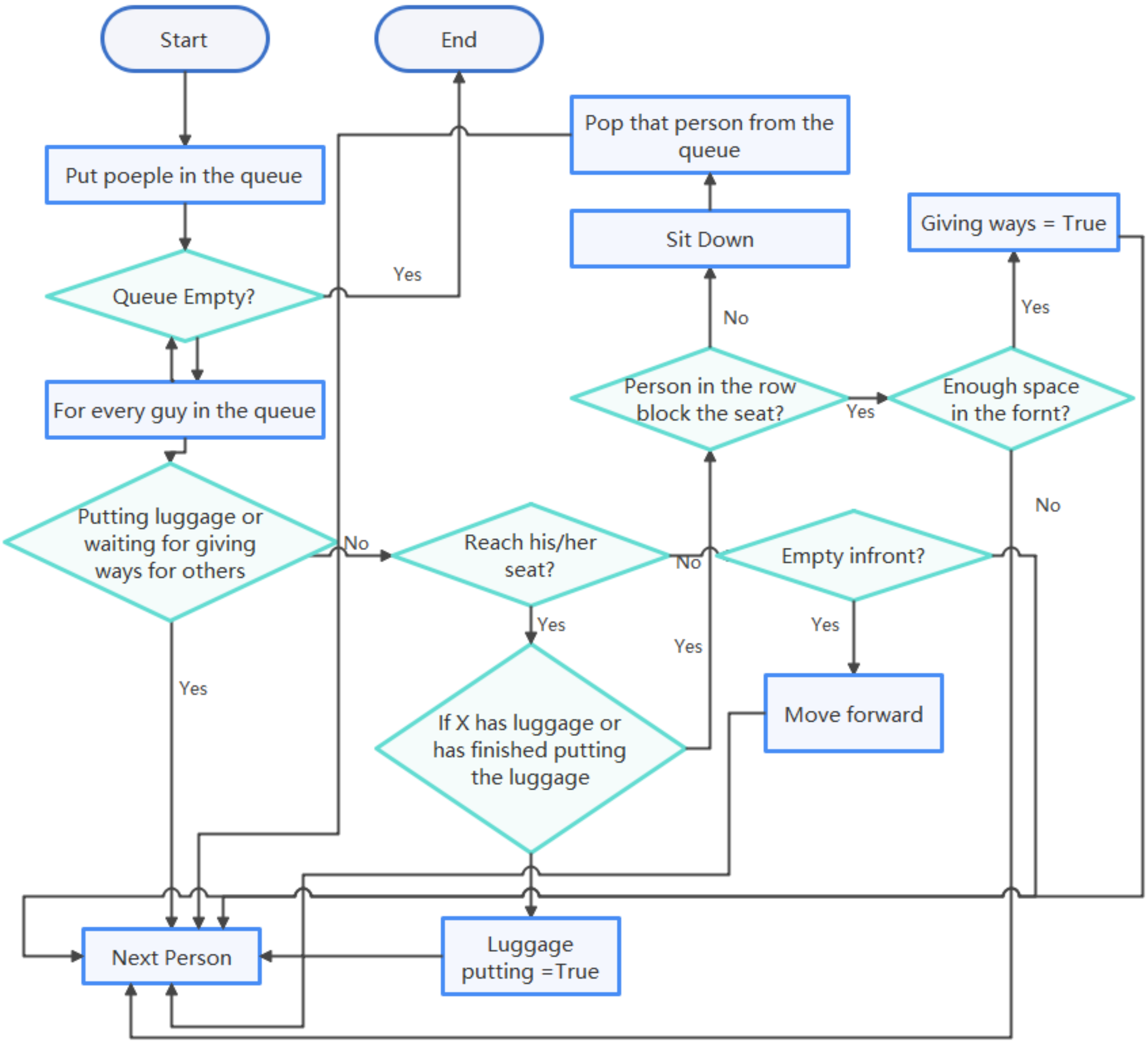

Figure 1: Flow Chart of BDTC Algorithm

We discussed and listed out several factors we should take into consideration when building up our calculation algorithm: the peoples walking speed, time taken for them to stow their luggage into the overhead bins, the time needed for giving ways to others. There are also some other constants such as the lengths of the aisle, the pitch (the sum of the length of the seat and the legroom in front of the seat), and the number of rows and columns. The main idea of our model is to simulate the circumstances inside the plane with a 1-second interval. Every second, the people in the queue would do different actions such as advancing toward their seats and leaving their seats through the aisle, putting luggage, taking luggage, giving ways, or just being stuck and remaining stationary. These actions would also take different times to finish. When every seat on the plane is occupied or cleared, the program will stop, and the accumulated overall time would be the time used for the boarding or disembarking process. The specific steps and processes of the algorithm of the boarding process are shown in the flowchart (Figure 1) above. With an input of the sequence of passengers with their seats identified, the boarding and disembarking time can be calculated. This helps to make for the changes of different methods, since we can generate the input data which obeys the method. People disobeying the method can also be accounted for just by generating the data with people not in the right place. The python code of the BDTC Algorithm is attahced in Appendix B.

3.2.1 Different Circumstances Under Consideration

Moving Forward When one person has space in front of him (Figure2), he will move forward, and the people behind him will follow on and also move unless they reach their seats, which forces them and the people behind them to stop.

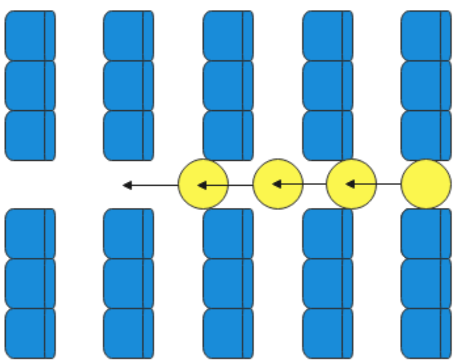

Figure 2: Moving Forward

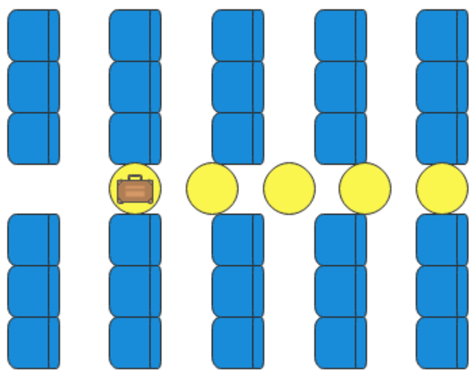

Figure 3: Putting Luggage

Putting Luggage When a person reaches his seat and has luggage with him (Figure 3), he will have to stop and spend some time putting his luggage in the overhead bins. On this occasion, the people behind them will stop and wait until the person finishes putting his luggage, enters the row, and create the space for the following pass his row and advance.

Giving Ways

Blocking When another person blocks a persons way to his seat, as shown in Figure 4, the person blocking the way will have to move outside the aisle to enable the other person to move into his seat. However, if there is no space in front of the person waiting, there will be no space to get out to the aisle to let the other go in the row. That means he has to wait until the person in front moves forward.

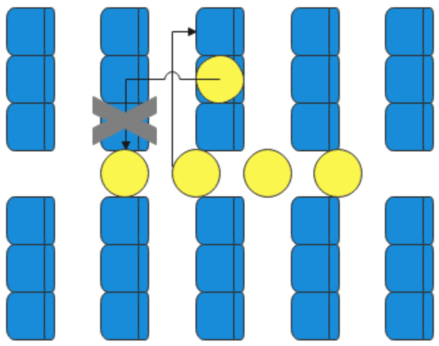

Figure 4: Blocking

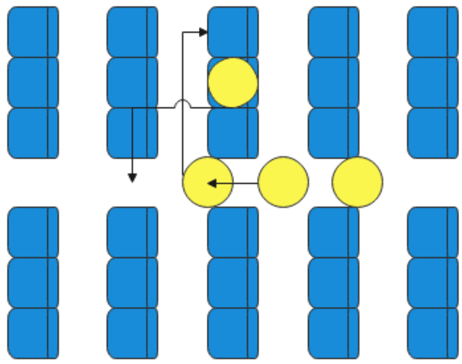

Figure 5: Empty

Empty When a persons way to his seat is blocked by another person while having space right in front of him (Figure 5), he still has to wait but only for the person blocking his way to move to the aisle area in front of him. Therefore, in this case, the time added will just be the time the person spends moving from his seat to the aisle and returning to the row area.

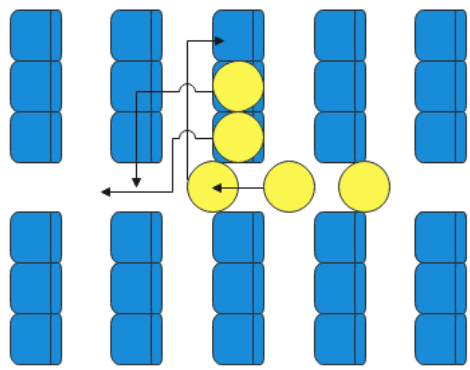

Figure 6: Two People

Two People The situation shown in Figure 6 is similar to the one in Figure 5. The difference is that this time, two people will block the way, so both will have to move to the aisle in order to let the third person pass. Since there will be overlap between the time the two-person spends, we only count the latest to return to the row area.

4 Optimal Boarding and Disembarking Method

4.1 Introduction to Model

In this model, we aimed to find the optimal boarding and disembarking method based on the **BDTC Algorithm**. We calculated the average, practical maximum, and practical minimum time for the three different aircraft, Narrow-Body Aircraft, Flying Wing Aircraft, and Two Entrance, Two Aisle Aircraft, with the different methods, by random, by section, by seat, by section by seat, and by optimal. Then, to ensure the optimal method is stable to any change, sensitivity analysis was carried out on the change in the number of carry-ons and the percentage of passengers disobeying the methods. With these data, we carried out a **Multi-Criteria Decision Making (MCDM)** model, the **Criteria Importance Through Intercriteria Correlation based Technique for Order of Preference by Similarity of Ideal Solution (C-TOPSIS)**, to evaluate the boarding method for different aircraft. Pandemic situations were considered when the full capacity was limited. Optimal methods were suggested using the same process for different aircraft at different capacity limitations.

For disembarking, we avoided overcomplicating the problem as it is a symmetrical process with boarding. By reversing the sequence, the optimal method is found. Furthermore, the time will be the same as boarding, as it is symmetrical with boarding.

4.2 Development of Model

To find the average, practical maximum, and practical minimum boarding time, there are two ways: first, to simulate all the circumstances and, second, to simplify the problem. As in the Narrow-Body Aircraft, there were 195 passengers. Therefore, there will be 195! types of different seat arrangements. It is too complicated to simulate all the possibilities. To simplify the problem, we think of probability. If we can prove that different boarding times are even likely events, we can find these three values by simple calculations.

Every different time event is based and dependent on only another even likely event, which is the probability of an onboard passenger having a given seat or the different arrangement of seats of the sequence of boarding passengers. This is because other factors, mostly the parameters listed in 2.3, is controlled. They would not change its value. The probability of an onboard passenger having a given seat is a completely random event as the onboard passenger can be on any seat. The probability is $P(p_i) = \frac{1}{[n-(i-1)]}$, where n is the total seats, i is the sequence of the onboard passenger, assuming full capacity. The probability of any arrangement is $\frac{1}{195!}$. Therefore, these are even likely events, which then the different boarding times are also even likely events.

After proving that every different time events are even likely events, we can calculate the average, practical maximum, and practical minimum boarding time with the following equations.

$$\bar{T} = \frac{T_{max} + T_{min}}{2} \tag{1}$$

$$T_{pmax} = T_{min} + 0.95 \times (T_{max} - T_{min}) \tag{2}$$

$$T_{pmin} = T_{min} + 0.05 \times (T_{max} - T_{min}) \tag{3}$$

With the BDTC Algorithm, the maximum and minimum time calculation needs to be based on given input data. Therefore, we need to generate the arrangement sequence for the quickest and slowest circumstances. However, we cannot ensure that the circumstance we generate is the fastest or the slowest one. Therefore, we need to generate three possible arrangements for the fastest and slowest circumstances and then calculate the time with the BDTC

Algorithm. The largest and the smallest value for an aircraft at a given method is recorded as the maximum and the minimum time, respectively.

As the prompt provided us with three methods only, we promoted other two methods, the Boarding by section by seat: First obeying boarding by section and secondly in the order of by seat and Boarding by lining up with the least time method: By lining before boarding in the order of the fastest method in the above methods. [12]

Finally, we can apply our model to the three aircraft and five methods.

4.2.1 Narrow-Body Aircraft

This is a very typical aircraft, as shown in Figure 1 in the prompt. Every maximum and minimum time value calculation of the other two aircraft is based on the arrangement in this aircraft. The fastest and slowest arrangements in the following different methods are all different.

By Section In this circumstance, the fastest situation will be when there is no time to give way to others, and the time of walking should be as overlapping as possible. On the other hand, the slowest situation should have the maximum time to give way to others, time to put the luggage to the overhead bins, and as minimum overlapping as possible.

By Seat In this circumstance, as there will be no time for giving way to the other passengers, the fastest situation will be when the time of putting the luggage, sitting, and walking has maximum overlap, while the slowest situation is when these times have minimum overlap.

By Section By Seat In this circumstance, as there will be no time for giving way to the other passengers, the fastest situation will be when the time of putting the luggage, sitting, and walking has maximum overlap, while the slowest situation is when these times have minimum overlap. However, the fastest situation will not be faster than by seat as the overlap of time is only within one section, not the whole aircraft.

By Random In this circumstance, the fastest situation is the fastest among all the above methods, while the slowest is the slowest among all.

By Optimal There is only one situation in this circumstance, which is the fastest among all the above methods.

The time results of the above methods are listed in the following table.

Table 2: Time Results for Narrow-Body Aircraft

	T_{pmax}	T_{pmin}	$\bar{T}$	T_{max}	T_{min}
By Random	4.379928	35.80637	20.09315	34.23504386	5.95125
By Section	6.719836	35.80637	21.2631	34.35203923	8.174162
By Seat	4.379928	35.37142	19.87567	33.82184687	5.929503
By Section by Seat	4.656574	17.2619	10.95924	16.63163518	5.286841
By optimal	4.379928	4.379928	4.379928	4.379928205	4.379928

4.2.2 Flying Wing Aircraft

In this aircraft, we need to split the plane into four, as shown in the following figure. Each part will be independent when calculating the time, also with the same arrangement as in the narrow-body aircraft. The only extra thing that needs to be accounted for is the time overlap between each part.

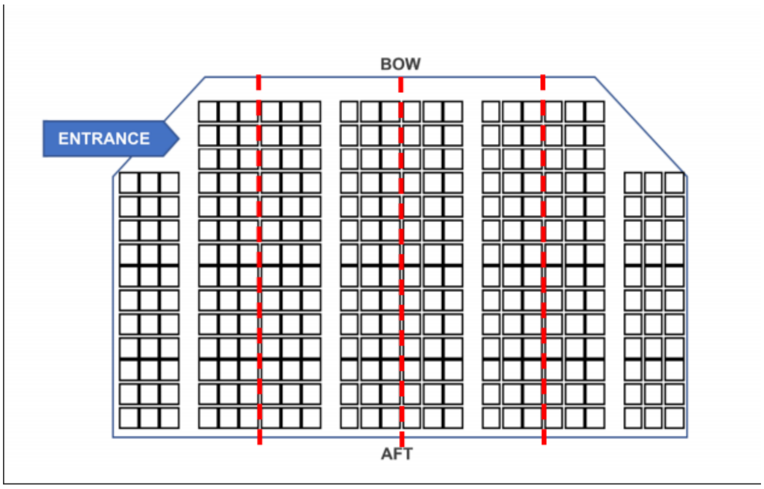

Figure 7: Seperation of the Flying Wing Aircraft

The time results of the five methods of this aircraft are listed in the following table.

Table 3: Time Results for Flying Wing Aircraft

	T_{pmax}	T_{pmin}	$\bar{T}$	T_{max}	T_{min}
By Random	8.14894359	188.6919538	98.42045	179.6648033	17.17609
By Section	14.58424505	188.6919538	101.6381	179.9865683	23.28963
By Seat	8.14894359	38.80054154	23.47474	37.26796164	9.681523
By Section by Seat	9.97454359	39.79976615	24.88715	38.30850503	11.4658
By optimal	8.14894359	8.14894359	8.148944	8.14894359	8.148944

4.2.3 Two-Entrance, Two-Aisle Aircraft

According to our fifth assumption, the aircraft will be split into half when calculating in this aircraft. This solves the problem of having two entrances. Then the problem of two aisles, or more specific, the problem of having three seats in the middle column, should be addressed. The aircraft will be split into half vertically, then horizontally. The horizontal separation will be based on whether or not the arrangement is for the maximum time or minimum time. When calculating the fastest circumstance, the middle column will be split in half, while the middle column will not be split when calculating the slowest circumstance. This is shown in the following figure.

The red line indicates the vertical separation, the blue line indicates the horizontal separation for the fastest circumstances, and the red line indicates the horizontal separation for the slowest circumstances. The time results of the five methods of this aircraft are listed in the following table.

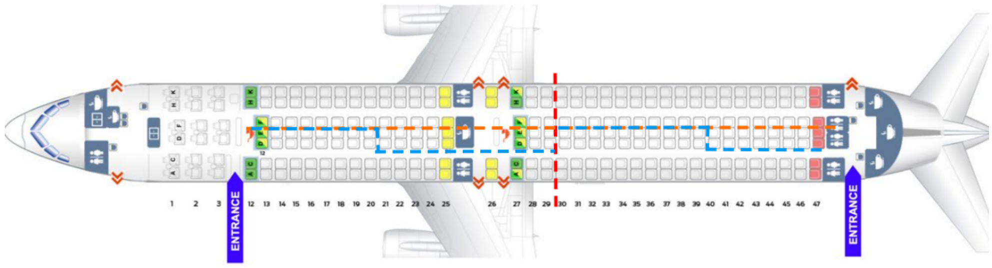

Figure 8: Seperation of the Two Entrance, Two Aisle Aircraft

Table 4: Time Results for Two Entrance, Two Aisle Aircraft

	T_{pmax}	T_{pmin}	$\bar{T}$	T_{max}	T_{min}
By Random	1.474082051	19.02960615	10.25184	18.15182995	2.351858
By Section	1.474082051	18.10588308	9.789983	17.27429303	2.305672
By Seat	2.005528205	18.97008	10.4878	18.12185241	2.853756
By Section by Seat	2.291825641	18.99203692	10.64193	18.15702636	3.126836
By optimal	1.474082051	1.474082051	1.474082	1.474082051	1.474082

4.3 Sensitivity Analysis

The sensitivity analysis tests the response of the different boarding methods to the change in different parameters. The parameters that change include the number of carryons put into the overhead bin, the number of carryons that are not put into the overhead bin, when all carryons are put into the overhead bin, and the percentage of people disobeying the rule. The sensitivity analysis is carried out separately.

4.3.1 Sensitivity Analysis on the Change of Number of Carryons that are Put into the Overhead Bin

During this circumstance, the time used on adjusting the carryons that are not put into the overhead bin and the sitting time is constant, which is 2 seconds in total. Each time a carryon that needs to be put into the overhead bin is added, 5 seconds are added. With this, we can plot the graph for the practical maximum, practical minimum, and the average boarding time regarding the change in the number of carryons that are put into the overhead bin.

The result for this sensitivity analysis of the narrow-body plane by seat method is shown in the following. For the other methods and in other aircraft, the results are shown in Appendix D.

Here, the vertical axis is in minutes. As we can see, it is a linear line. However, without comparison with other methods, no conclusions can be made. In the model to find the optimal method, the slope of the linear sensitivity analysis will be counted as a criterion, which a smaller slope will be better as an airline company would want their method to be stable so they can make more accurate predictions.

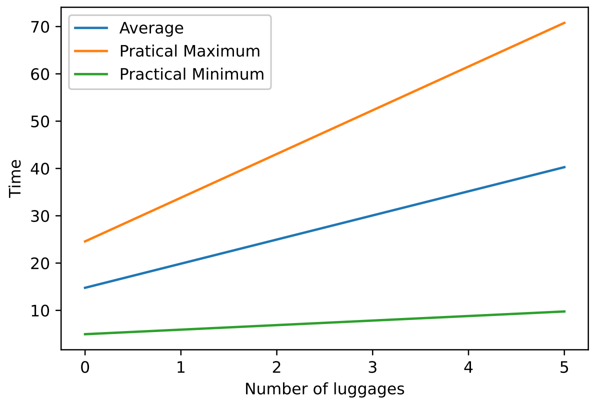

Figure 9: Sensitivity Analysis on the Change of Number of Carryons that are Put into the Overhead Bin of the By Seat Method in the Narrow-Body Aircraft

4.3.2 Sensitivity Analysis on the Change of Number of Carryons that are not Put into the Overhead Bin

During this circumstance, the time to put a carryon to the overhead bin and the sitting time is constant, which is 6 seconds in total. Each time a carryon that does not need to be put into the overhead bin is added, 1 second is added. With this, we can plot the graph for the practical maximum, practical minimum, and the average boarding time regarding the change in the number of carryons that are put into the overhead bin.

The result for this sensitivity analysis of the narrow-body plane by seat method is shown in the following. For the other methods and in other aircraft, the results are shown in Appendix D.

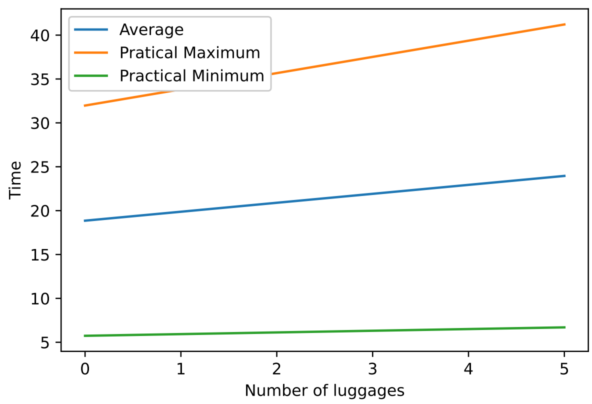

Figure 10: Sensitivity Analysis on the Change of Number of Carryons that are not Put into the Overhead Bin of the By Seat Method in the Narrow-Body Aircraft

Again, the results need to be compared with the result of other sensitivity analyses, which will be addressed in 4.4 Optimal Boarding and Disembarking Methods as the slope of the linear sensitivity analysis.

4.3.3 Sensitivity Analysis of the Circumstance that all the Carryons are Put into the Overhead Bins

Under this circumstance, only one time is kept constant, which is the sitting time. There is no additional time when a carryon is not put into the overhead bin as all the carryons are put into the overhead bin. The only fluctuating parameter is the number of carryon bags, which has an additional 5 seconds each bag added when all put into the overhead bin.

The result for this sensitivity analysis of the narrow-body plane by seat method is shown in the following. For the other methods and in other aircraft, the results are shown in Appendix D.

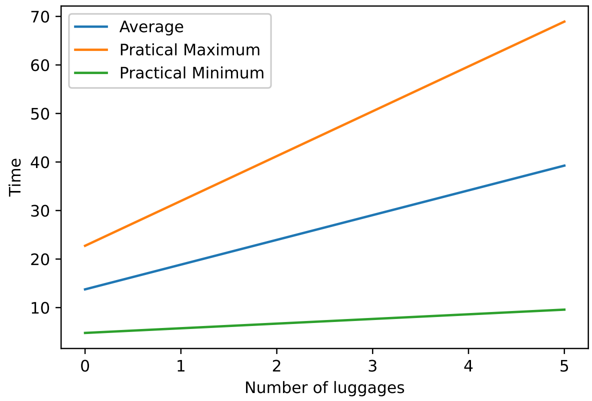

Figure 11: Sensitivity Analysis of the Circumstance that all the Carryons are Put into the Overhead Bins of the By Seat Method in the Narrow-Body Aircraft

These results will be compared in 4.4 Optimal Boarding and Disembarking Methods as the slope of the linear sensitivity analysis.

4.3.4 Senstivity Analysis with Percentage of People Disobeying the Method

This sensitivity analysis will be more complicated than the others. First of all, it cannot be done by simply adjusting some parameters. Secondly, only one time can be calculated, and thus there is a need to choose one time to be analyzed. Thirdly, two methods, the random method and the by optimal method, cannot undergo this sensitivity analysis as there is no such thing as breaking the rule in a random method, and by optimal method, pre-lining-up will avoid this issue. The time chosen to be analyzed is the minimum time, directly calculated by the BDCT Algorithm, which simplifies the problem.

To account for people disobeying the rule, the input data of the BDCT Algorithm needs to be changed. By shuffling a given number of people, from 1% to 60% of the full capacity, the new time can be found. As the shuffling is random, we shuffled multiple times to get the average.

The result of this SA for the three methods in the narrow-body aircraft is shown as the following, where the vertical axis is in seconds.

As we can see, the sensitivity varies greatly. This will be accounted for in 4.4 Optimal

Boarding and Disembarking Methods.

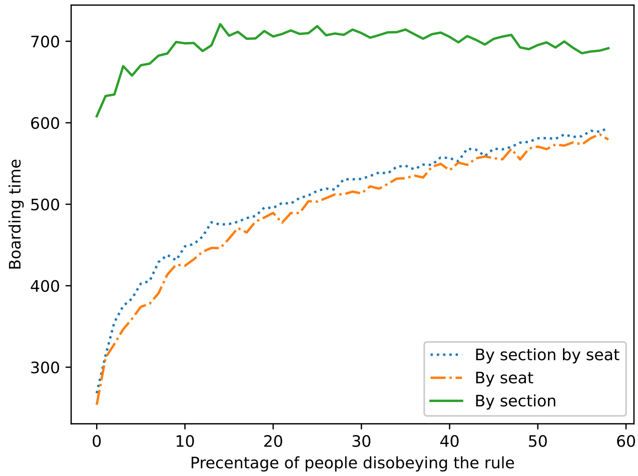

Figure 12: Sensitivity Analysis of Percentage of People Disobeying the Method in the Narrow-Body Aircraft

4.4 Optimal Boarding and Disembarking Methods

To find the optimal method for different aircraft, we carried out the MCDM model C-TOPSIS, a Critetrai Importance Through Intercriteria Correlation based Technique for Order of Preference by Similarity of Ideal Solution. The value for the different criteria, including average boarding time, practical maximum boarding time, practical minimum boarding time, the slope for sensitivity analysis of on the change of the number of carryons that not are put into the overhead bin, slope for sensitivity analysis of on the change of the number of carryons that are put into the overhead bin, slope for sensitivity analysis of the circumstance that all the carryons are put into the overhead bins, and the maximum minimum boarding time when a percentage of people disobeys the method, are used in the calculation. The same data group is first processed through CRITIC to calculate the weight and then through TOPSIS to determine the final score. The highest scoring method is the optimal method for the aircraft.

The method by optimal is not considered in the evaluation as it is not practical. Even though there is a short boarding time, it requires much time before boarding to line up.

4.4.1 Criteria Importance Through Intercriteria Correlation

First, we need to construct a decision matrix with the methods on each row and the value for each criterion in each column.

Normalization of data First of all, we need to normalize the data from the decision matrix. To normalize the data, any data $q_{ij}$is normalized using the following equation where q_j^{best} is the best value and q_j^{worst} is the worst value.

$$\bar{X}_{ij} = \frac{X_{ij} - X_j^{\text{worst}}}{X_j^{\text{best}} - X_j^{\text{worst}}} \tag{4}$$

Calculating the standard deviation Then, we need to calculate the standard deviation value of each of the criterion using the following equation.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{N} (q_i - \bar{q})^2}{n}} \tag{5}$$

Developing the symmetric matrix After that, the symmetric matrix of $n \times n$ is constructed where n is the number of criteria. A generic element, which is the linear correlation coefficient, is used in the calculation of the matrix.

Calculating the conflict between each criterion and the rest of the criteria The conflict between each criterion and the rest of the criteria is calculated by the following equation where $r_{jk}$is the linear correlation coefficient.

$$\sum_{k=1}^{m} \left(1 - r_{jk}\right) \tag{6}$$

Finding the objective weight The objective weight of the criteria is found by using the quantity of information in relation to each criterion. The calculation of the quantity of information is shown as the following.

$$\alpha_j = \sigma_j * \sum_{k=1}^{m} \left(1 - r_{jk}\right) \tag{7}$$

Then the objective weight $w_i$is calculated by the following equation.

$$w_j = \frac{\alpha_j}{\sum_{k=1}^{m} \alpha_j} \tag{8}$$

These are the general steps of carrying out a CRITIC model.

4.4.2 Technique for Order of Preference by Similarity of Ideal Solution

After we got the weight value for each criterion, we could apply them to the TOPSIS model to calculate the score of different methods. To create the evaluation matrix, we need to convert our plans and the corresponding indexes into an evaluation matrix using the following equation where gong from left to right, it is in the same method $\mathrm{P_m}$, and going from up to down, it is in the same criterion $\mathrm{C_n}$.

$$x = \begin{pmatrix} x_{11} & \dots & x_{1n} \\ \vdots & & \vdots \\ x_{m1} & \dots & x_{mn} \end{pmatrix} \tag{9}$$

Normalize the matrix The matrix shown above is then normalized using a linear normalization shown in the following.

$$h_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}^2}} \tag{10}$$

Constructing the weighted normalized decision matrix The weighted normalized decision matrix is constructed by multiplying the weight of each of the criteria to the normalized matrix, forming a new matrix, $T = (t_{ij})$, where w_i is the weight of the ith criterion, shown as the following.

$$T = \begin{pmatrix} w_1 r_{11} & \dots & w_n r_{1n} \\ \vdots & & \vdots \\ w_1 r_{m1} & \dots & w_n r_{mn} \end{pmatrix} \tag{11}$$

Determining the best and worst vector The best and worst vector of the methods is calculated as the following where P_b is the best vector and P_w is the worst vector.

$$\begin{aligned} P_b &= (t_{b1}, t_{b2}, \dots, t_{bn})^T, \\ P_w &= (t_{w1}, t_{w2}, \dots, t_{wn})^T. \end{aligned} \tag{12}$$

Calculating the Euclidean Distance Then, we need to calculate the Euclidean distance between each alternative to the best and worst alternative. The calculations is shown in the following where d_{ib} is the distance to the best alternative while d_{iw} is the distance to the worst alternative.

$$\begin{aligned} d_{ib} &= \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{bj}\right)^2} \\ d_{iw} &= \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj}\right)^2} \end{aligned} \tag{13}$$

Calculating the similarity of each of alternatives to the best and worst alternative Finally, the last step of the TOPSIS model is to calculate the similarity of each alternatives to the best and worst alternative. The calculation is defined as the following.

$$s_{iw} = \frac{d_{iw}}{d_{ib} + d_{iw}} \tag{14}$$

4.4.3 Results

The results of the C-TOPSIS model of the narrow-body aircraft is shown in the following. For the other two aircraft, the result is attached in Appendix E.

Table 5: Plane 1 Optimal Method

	Score	Rank
By Random	0.974742	1
By Seat	0.18899	2
By Section	0.023235	4
By Section by Seat	0.181327	3

As we can see from the results, the optimal method for the narrow-body aircraft is by random. The method ranks for the three aircraft are shown in the following.

- Narrow-Body Aircraft: By Random, By Seat, By Section By Seat, By Section
- Flying Wing Aircraft: By Seat, By Section By Seat, By Section, By Random
- Two Entrance, Two Aisle Aircraft: By Section, By Random, By Seat, By Section By Seat

4.5 Pandemic Situations

For the past few years, due to the COVID-19 pandemic, there have been prevention measures on the airline company, including wearing masks and, most importantly, limits on the full capacity. With respect to different countries, this figure can vary from 30% to 70%. In this part, we will consider 30%, 50%, and 70%, respectively.

Under the limitations, to prevent the spread of the disease, the passengers need to be evenly distributed, as far from each other as possible. Therefore, with this assumption, we can set how the passengers should be arranged, thus generating the input data for the BDTC Algorithm. Thus, the mentioned procedure can be carried out.

The result of the time values and the optimal method of the 30% circumstance of the narrow-body aircraft are shown below. The other results are attached in Appendix F.

As we can see from the results, the optimal methods for the Narrow-Body Aircraft with 30% limitation of the full capacity is the by random method. However, the second ranking method, by seat, only has a very small difference than the by random method. The other results are shown in Appendix F.

Table 6: 30% Limit of the Narrow-Body Aircraft Time Results

	T_{pmin}	T_{pmax}	$\bar{T}$	T_{max}	T_{min}
By Random	3.563262	35.42944	19.49635	33.8361336	5.156571
By Section	5.84163	35.27944	20.56054	33.80755205	7.313521
By Seat	3.238262	25.2545	14.24638	24.15368662	4.339073
By Section by Seat	3.778369	7.144978	5.461674	6.976648	3.9467
By optimal	3.238262	3.238262	3.238262	3.238261538	3.238262

Table 7: Slope of Linear Sensitivity Analysis for 30% Limit of the Narrow-Body Aircraft

	S_o	S_c	S_a
By Random	1.04	1.04	1.04
By Section	1.14	0.912	0.912
By Seat	0.725	0.725	0.725
By Section by Seat	0.83	0.83	0.83

4.6 Results and Analysis

The optimal method for the different circumstances are listed below.

- Narrow-Body Aircraft: **By Random**
- Flying Wing Aircraft: **By Seat**
- Two Entrance, Two Aisle Aircraft: **By Section**
- Narrow-Body Aircraft 30% Limitation: **By Section**
- Flying Wing Aircraft 30% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 30% Limitation: **By Section**
- Narrow-Body Aircraft 50% Limitation: **By Section By Seat**
- Flying Wing Aircraft 50% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 50% Limitation: **By Random**
- Narrow-Body Aircraft 70% Limitation: **By Section By Seat**
- Flying Wing Aircraft 70% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 70% Limitation: **By Random**

Table 8: Plane 1 30% Optimal Method

	Score	Rank
By Random	0.989464	1
By Seat	0.968835	2
By Section	0	4
By Section by Seat	0.069401	3

At first sight, these optimal boarding and disembarking methods seem to be randomly distributed. However, if we take a deeper look into it, there are still some patterns. By seat is the method that appears the most time. This may be because the by seat method excludes the time of giving way to other passengers. By section by seat is the method that appears for the least times. This may be because even though it inherent both the benefits of the by seat and section methods, it also inherent the disadvantages, such as high sensitivity to people breaking the rules.

Furthermore, patterns occur within different aircraft. For the Narrow-Body Aircraft, the method by section by seat appears two times, more significant than any other method. In the Flying Wing Aircraft, the optimal method is definitely by seat; it appears four times. There is no such sequence in the Two Entrance, Two Aisle Aircraft.

In the **C-TOPSIS** evaluation, four optimal methods show the perfect similarity with the ideal solution, scoring 1. They are the Flying Wing Aircraft By Seat Method, Two Entrance, Two Aisle Aircraft 70% Limitation By Random Method, Flying Wing Aircraft 50% Limitation By Seat Method, Flying Wing Aircraft 30% Limitation By Seat Method. This proves the high accuracy of our optimal methods.

There are definitely some methods that do not worth a try. They are the Flying Wing Aircraft 70% Limitation By Section Method, Two Entrance, Two Aisle Aircraft 50% By Section By Seat Method, and the Two Entrance, Two Aisle Aircraft 30% By Section By Seat Method. They have the perfect resemblance with the ideal worst method, scoring 0 in the **C-TOPSIS** model.

5 Strengths and Weaknesses

Our model has some strengths and weaknesses. Although some weaknesses and limitation occurs, the strengths still outweigh the weaknesses.

5.1 Strengths

In our model, there are som strengths, these include:

1. **Generalized**
   Our model is generalized. It can be applied to different aircraft, different methods, and even people disobeying the rules. This can be achieved just by adjusting the input data to the **BDTC Algorithm**. Therefore, our model can be applied not only to the air travel industry, but also to other similar industries such as the train industry.

2. **Accurate**
   Our model is accurate. As it is processed with simulation at every time interval, the time calculation is accurate. Therefore, our results are reliable. Furthermore, we compared three relatively fast and three relatively slow circumstances when generating the input data for the maximum and minimum time. Therefore, this makes sure our models accuracy. The C-TOPSIS model result of 1 occurs several time. This means that the method is the most optimal one, since it is the same as the ideal result. This further proves our accuracy.

3. **Stable**
   Our model is stable. Despite when people disobey the methods, the other three sensitivity analyses are all linear. This suggests that our model is very stable. Furthermore, when finding the optimal method, the one with the smallest slope is identified as the best value. This makes sure that the sensitivity is as small as possible. People do not want to have a highly sensitive boarding and disembarking method in the airline industry as it would complicate their planning.

4. **Objective**
   The finding of the optimal strategy with the **C-TOPSIS** model is all based on the calculated data. Therefore, there are no subjective factors in determining the optimal strategy, unlike many **MCDM models**. This reinforces an accurate model.

5.2 Weaknesses

However, there are still some problems and weaknesses in our model. These include:

1. **May not Reach Perfect Precision**
   In our **BDTC Algorithm**, the time interval cannot be smaller than the unit of a second. Therefore, the time calculation results will not be more precise than a second.

2. **May not Consider Real-life Problems Fully**
   Many real-life circumstances such as delaying boarding, priorities, getting too far, stopping in the aisle, and exchanging seats are not considered for simplicity. However, these cases will happen in real-life cases.

3. **May be Slightly Complicated**
   The input data generation for the **BDTC Algorithm** may be complicated when considering the relatively fast and slow circumstances with big aircraft carrying large amounts of people.

6 Conclusion

This paper developed an algorithm, the **Boarding and Disembarking Time Calculation (BDTC) Algorithm**, to calculate the boarding and disembarking time. This algorithm can be adaptable to any aircraft, method and even account for people disobeying the rules. We achieved this by simply adjusting the input data of the sequence of the boarding passengers with a given seat.

Based on this algorithm, we attempted to calculate the average, practical maximum, and practical minimum boarding and disembarking time of a given method on a given aircraft. To achieve this, we first proved that the different boarding times are even likely events with a uniform distribution. Therefore, we found these three required time values with the maximum and minimum values. In each method, we find three relatively fast and three relatively slow arrangements and thus calculated the time for boarding. The greatest value then becomes the maximum time, while the minimum value represents the minimum time.

The boarding and disembarking time is highly dependent on other multiple factors. We accounted for these factors in our sensitivity analysis. Then, we needed to develop a model to evaluate the optimal method. The **Criteria Importance Through Intercriteria Correlation Based Technique for Order of Preference by Similarity of Ideal Solution (C-TOPSIS)** model is used to carry out the multi-criteria decision making. Criteria taken into consideration includes the average time, practical maximum time, practical minimum time, slope of the linear sensitivity analysis on the change of the number of carryons that are put into the overhead bins, the slope of the linear sensitivity analysis on the change of the number of carryons that are not put into the overhead bins, the slope of the linear sensitivity analysis of the circumstance that all the carryons are put into the overhead bins, and the maximum minimum boarding time when a percentage of passengers disobeys the methods. The results of the optimal boarding and disembarking methods of the three aircraft are shown in the following:

- Narrow-Body Aircraft: **By Random**
- Flying Wing Aircraft: **By Seat**
- Two Entrance, Two Aisle Aircraft: **By Section**

We also accounted for pandemic situations where prevention measures limit the full capacity. For each aircraft and each maximum onboard passenger, we repeated the up-mentioned process. The results are shown in the following:

- Narrow-Body Aircraft 30% Limitation: **By Section**
- Flying Wing Aircraft 30% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 30% Limitation: **By Section**
- Narrow-Body Aircraft 50% Limitation: **By Section By Seat**
- Flying Wing Aircraft 50% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 50% Limitation: **By Random**
- Narrow-Body Aircraft 70% Limitation: **By Section By Seat**
- Flying Wing Aircraft 70% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 70% Limitation: **By Random**

Our model is highly accurate, as the time calculation is carried out with a simulation. The C-TOPSIS evaluation yielded several scores of 1, meaning perfect resemblance to the ideal solution. It is also generalized to different situations, as we can simply generate the sequence of passengers with their seats indicated. The optimal method results are also objective as the C-TOPSIS model is a completely objective MCDM model.

Our model solves the complicated boarding and disembarking problem, which is concerning for airline companies. This helped them save time and, most importantly, save money, as time is money for the air travel industry.

7 Letter

FROM: Team IMMC22155287, IM^{2}C

To: ABC Airline Executive

Date: March 14, 2022

Dear Sir or Madam:

It is our pleasure to help develop the optimal boarding and disembarking methods.

We evaluated the boarding and disembarking methods on different aircraft. The methods taken into consideration are by random, by section, by seat, by section by seat, and by optimal. The aircraft is a Narrow-Body Aircraft, a Flying Wing Aircraft, and a Two Entrance, Two Aisle Aircraft. The circumstances considered are operation under full capacity, 70% capacity, 50% capacity, and 30% capacity due to pandemic prevention measures.

The results of the optimal methods are shown in the following:

- Narrow-Body Aircraft: **By Random**
- Flying Wing Aircraft: **By Seat**
- Two Entrance, Two Aisle Aircraft: **By Section**
- Narrow-Body Aircraft 30% Limitation: **By Section**
- Flying Wing Aircraft 30% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 30% Limitation: **By Section**
- Narrow-Body Aircraft 50% Limitation: **By Section By Seat**
- Flying Wing Aircraft 50% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 50% Limitation: **By Random**
- Narrow-Body Aircraft 70% Limitation: **By Section By Seat**
- Flying Wing Aircraft 70% Limitation: **By Seat**
- Two Entrance, Two Aisle Aircraft 70% Limitation: **By Random**

Boarding by random is without any methods. Boarding by section is to board in the order of aft section, middle section, and bow section, each 1/3 of the aircraft. Boarding by seat is to board in the order of window seats, middle seats, and aisle seats. Boarding by section by seat is to board first obeying the by section method and secondly in the order of by seat. Boarding by optimal, however, is not considered. It cannot be used as it requires much time before boarding to line up at the optimal sequence, despite the very short boarding and disembarking time.

Our model is accurate and reliable as we took multiple situations into consideration. We carried out sensitivity analysis, which is used as a criterion in the evaluation model, which helped find a stabilized method. The methods will not fluctuate on a very great scale with the change in multiple parameters and people disobeying the given method.

For the full capacity situations, the average, practical maximum, and practical minimum boarding and disembarking time is shown as the following:

Table 9: Time Results for Optimal Methods of Three Aircrafts Under Full Capacity

Aircraft	Average	Practical Maximum	Practical Minimum
Narrow-Body	20.1	35.8	4.4
Flying Wing	23.5	38.8	8.1
Two Entrance, Two Aisle	9.8	18.1	1.5

We hope our information is helpful for your company. If you have any questions, please dont hesitate to contact us.

Sincerely yours,

IM^{2}C Team IMMC22155287

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Appendices

Appendix A Symbols and Descriptions

Here are the symbols used in the calculations in our model and their descriptions.

Table 10: Symbols and Descriptions

Symbols	Descriptions
p_i	The ith method in C-TOPSIS calculation
h_{ij}	Linear normalization in C-TOPSIS calculation
p^{best}	The best alternative vector in C-TOPSIS calculation
p^{worst}	The worst alternative vector in C-TOPSIS calculation
$d_{ib/iw}$	Euclidean distance in C-TOPSIS calculation
s_{iw}	Similarity to the worst alternative vector in CRITIC
σ_j	Standard deviation in CRITIC
α_j	Quantity of the information in relation to each criterion in CRITIC
q^{jworst}	The worst value of one criteria among the methods in CRITIC
q^{jbest}	The best value of one Criteria among the methods in CRITIC
q_{ij}	Corresponding value of normalization matrix in CRITIC
$\overline{q}_{ij}$	The mean value of the corresponding value of normalization matrix in CRITIC
w_i	Objective weight of criteria

Appendix B Python Code on Boarding and Disembarking Time Calculation Algorithm

Below is the python code used in the boarding and disembarking time calculation algorithm.

```
import numpy as np

people = 195
#0 action
#1 row
#2 column
#3 row_now
#4 lug


filepath = "bsbc/"
passenger_row = np.loadtxt("bsbc_row.txt")
passengers_column = np.loadtxt("bsbc_column.txt")
passengers_lug = np.loadtxt("luggage.txt")

item = []
seatd = [[0 for j in range(0,7)] for i in range(0,34)]



for i in range(0,people):
    temp = [0,passenger_row[i],passengers_column[i],-i,int((passengers_lug[
        i]+3)/0.6252307692),0,i+1]
    item.append(temp)

counttt=0

for i in range(0,people):
    item[i][6]=i+1

item.insert(0,([0,0,0,1000000,0,0,0]))#stackoverflow

time=0

while people:
    i=-1
    while i<people:
        i+=1
        if item[i][0] and item[i][4] >= 1: #putting action
            item[i][4]-= 1
            #print(i)
            continue;
        if item[i][4] < 1 and item[i][0]:#seated
            cnt = checkseat(int(item[i][1]),int(item[i][2]))
            #print(cnt)
            #print(seatd)
            #print(int(item[i][1]),int(item[i][2]))
            if cnt == 0:
                seatd[int(item[i][1])][int(item[i][2])]=item[i][6]

                del item[i]
                i-=1
```

```
                people -= 1
                continue;
            else:
                item[i][0]=0
                item[i][4] = int((3/0.6252307692)*cnt) #TODO rang zuo time
                item[i][5] = 1
                continue;
        if item[i][5] and item[i][4] >= 1:
            #item[i][6]+=1

            item[i][4]-= 1
            continue;
        if item[i][4] < 1 and item[i][5]:
            seatd[int(item[i][1])][int(item[i][2])]=item[i][6]
            del item[i]
            i-=1
            people -= 1
            #for ii in seatd:
                #print(ii)
            continue;
        if item[i][3] < item[i][1]:
            if item[i][3] < item[i-1][3]-1:
                item[i][3] += 1
                continue
        else:
            if item[i][3]==item[i][1] and not item[i][0] and not item[i
               ][5]:
                item[i][0] = 1
                item[i][4] -= 1
    time+=1
print(time)
```

Appendix C Boarding and Disembarking Time Calculation Algorithm Visualization

Below is the link of a visualization of the BDTC Algorithm. It includes each snapshots at time intervals. **We strongly recommend you to take a look.**
https://drive.google.com/drive/folders/1Zekey8P2doRvqKL2utLZL5oENbNUKfth
https://cloud.tiancesec.com/index.php/s/C4JtWxjWwwDkCpk
The visualisation is processed with the following python code.

```
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.ticker import MultipleLocator
import random
from visu import draw
import cv2


people = 195
printpicture=False
#0 action
#1 row
```

```
#2 column
#3 row_now
#4 lug

def visual(data_path,num):
    fps = 30          #
    size = (620, 480) #
    video = cv2.VideoWriter(data_path+"output.mp4", cv2.VideoWriter_fourcc(
       'F', 'M', 'P', '4'), fps, size)

    for i in range(1,618):
        image_path = data_path + str(i)+".jpg"
        #print(image_path)
        img = cv2.imread(image_path)
        video.write(img)

    video.release()
    cv2.destroyAllWindows()

def checkseat(row,column):
    cnt = 0
    if column < 3:
        for iii in range(column+1,3+1):
            if seatd[row][iii]:
                cnt+=1
    if column > 3+1:
        for iii in range(4,column):
            if seatd[row][iii]:
                cnt+=1
            #print(iii,row)
    if cnt == 0:
        return 0;
    else:
        return cnt;
    retur


filepath = "bsbc/"
passenger_row = np.loadtxt("bsbc_row.txt")
passengers_column = np.loadtxt("bsbc_column.txt")
passengers_lug = np.loadtxt("luggage.txt")

item = []
seatd = [[0 for j in range(0,7)] for i in range(0,34)]



for i in range(0,people):
    temp = [0,passenger_row[i],passengers_column[i],-i,int((passengers_lug[
       i]+3)/0.6252307692),0,i+1]
    item.append(temp)

counttt=0

#random.shuffle(item)
#for i in range(0,people):
#    item[i][3]=-i
```

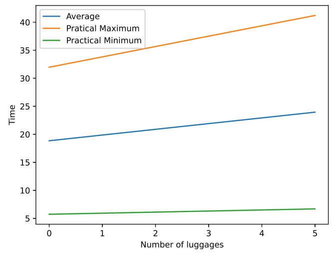
```
for i in range(0,people):
    item[i][6]=i+1

item.insert(0,([0,0,0,1000000,0,0,0]))#stackoverflow
#print(item)

time=0
index=0


while people:
    i=-1
    while i<people:
        i+=1
        if item[i][0] and item[i][4] >= 1: #putting action
            item[i][4]-= 1
            #print(i)
            continue;
        if item[i][4] < 1 and item[i][0]:#seated
            cnt = checkseat(int(item[i][1]),int(item[i][2]))
            #print(cnt)
            #print(seatd)
            #print(int(item[i][1]),int(item[i][2]))
            if cnt == 0:

                seatd[int(item[i][1])][int(item[i][2])]=item[i][6]
                #draw-----------------

                #index+=1
                #if printpicture:
                    #print(index)
                '''
                    if item[i][2]<=3:

                        ax.fill_between(np.linspace(item[i][1],item[i
                            ][1]+1),item[i][2]-1,item[i][2],facecolor='green
                            ')
                    else:
                        ax.fill_between(np.linspace(item[i][1],item[i
                            ][1]+1),item[i][2],item[i][2]+1,facecolor='green
                            ')

                    plt.savefig("bysection_visu/fig"+str(index)+".jpg")
                '''
                    #draw(seatd,index,item)
                    #plt.show()
                #print(index)
                #print(seatd)
                #print()
                #print(item)
                #print(item[i][6])
                del item[i]
                i-=1
                people -= 1
                continue;
            else:
                #if item[i][3]+2<item[i-1][3]:
                    #print("1111")
```

```
                    #print(item[i][1],item[i][2])
                    #print("\n\n\n\n\n\n\n\n\n\n\n\n\n")
                #print(cnt)
                item[i][0]=0
                item[i][4] = int((3/0.6252307692)*cnt) #TODO rang zuo time
                item[i][5] = 1
                continue;
        if item[i][5] and item[i][4] >= 1:
            #item[i][6]+=1

            item[i][4]-= 1
            continue;
        if item[i][4] < 1 and item[i][5]:
            seatd[int(item[i][1])][int(item[i][2])]=item[i][6]
            #draw-----------------

            #index+=1
            #if printpicture:
                #print(index)
            '''
            if item[i][2] <= 3:
                ax.fill_between(np.linspace(item[i][1],item[i][1]+1),item[i
                    ][2]-1,item[i][2],facecolor='green')
            else:
                ax.fill_between(np.linspace(item[i][1],item[i][1]+1),item[i
                    ][2],item[i][2]+1,facecolor='green')
            plt.savefig("bysection_visu/fig"+str(index)+".jpg")
            '''
                #draw(seatd,index,item)
            #plt.show()
            #print(index)
            #print(seatd)
            #print()
            del item[i]
            i-=1
            people -= 1
            #for ii in seatd:
                #print(ii)
            continue;
        if item[i][3] < item[i][1]:
            if item[i][3] < item[i-1][3]-1:
                item[i][3] += 1
                continue
        else:
            if item[i][3]==item[i][1] and not item[i][0] and not item[i
               ][5]:
                item[i][0] = 1
                item[i][4] -= 1
    index+=1
    draw(seatd,index,item,filepath)
    try:
        print(people,index,item[1][4])
    except:
        pass


    #for iiii in item[0:10]:
    #    print(iiii[3])
```

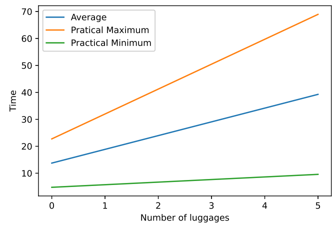
```
    #print()
    #print()
    #print()
    #print(seatd)
    #draw(seatd,indexx)
    time+=1
print(time)
visual(filepath,index)
```

Appendix D Sensitivity Analysis Visualization Results

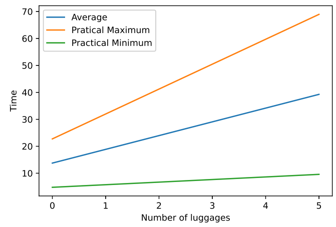
Below is the visualization results of the senstivity analysis in 4.3. Plane 1 refers the Narrow-Body Aircraft, plane 2 refers to the Flying Wing Aircraft, and plane 3 refers to the Two Entrance, Two Aisle Aircraft.



(a) S_o

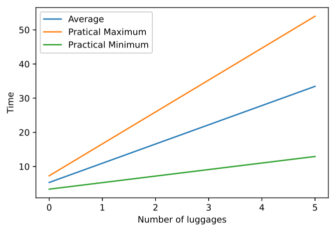


(b) S_c

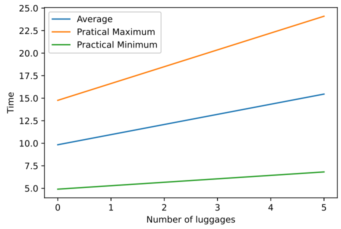


(c) S_a

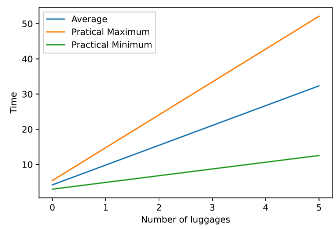
Figure 13: Plane 1 By Section



(a) S_o

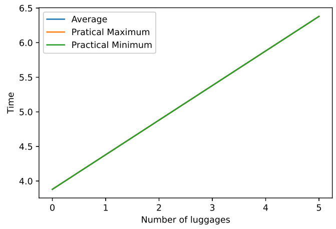


(b) S_c

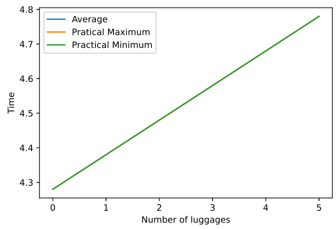


(c) S_a

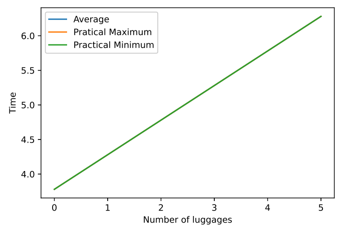
Figure 14: Plane 1 By Section by Seat



(a) S_o

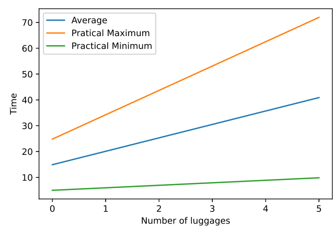


(b) S_c

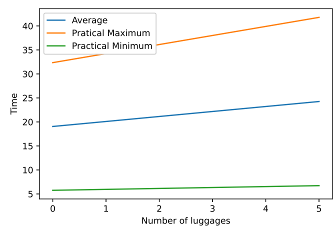


(c) S_a

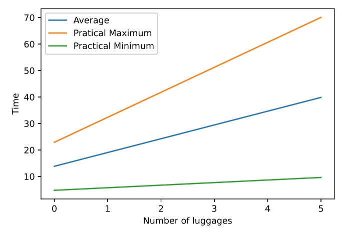
Figure 15: Plane 1 By Optimal



(a) S_o

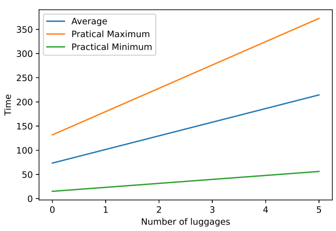


(b) S_c

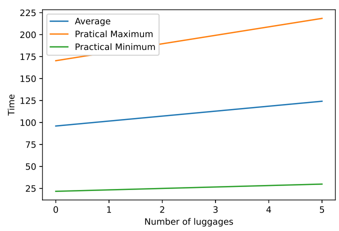


(c) S_a

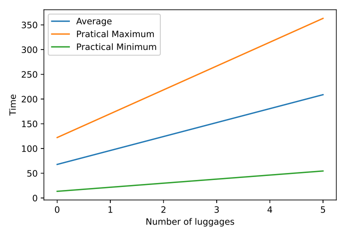
Figure 16: Plane 1 By Random



(a) S_o

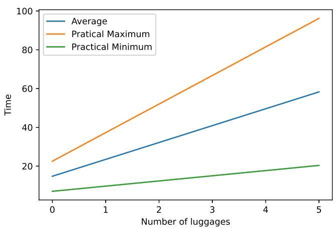


(b) S_c

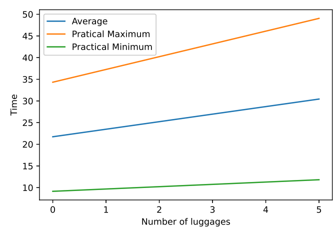


(c) S_a

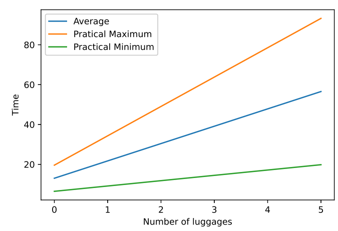
Figure 17: Plane 2 By Section



(a) S_o

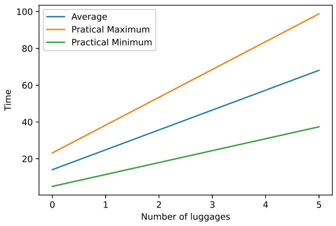


(b) S_c

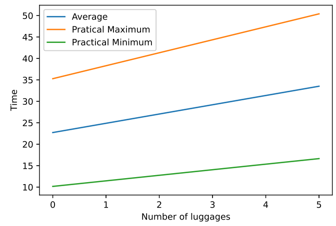


(c) S_a

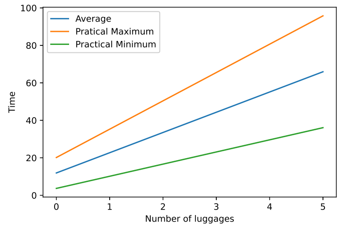
Figure 18: Plane 2 By Seat



(a) S_o

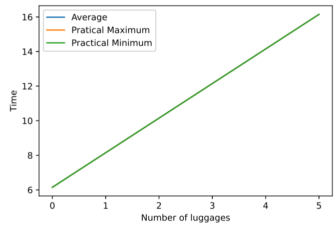


(b) S_c

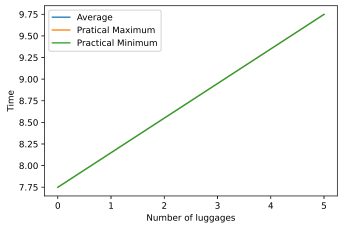


(c) S_a

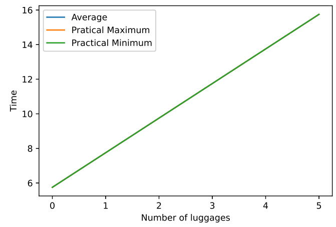
Figure 19: Plane 2 By Section By Seat



(a) S_o

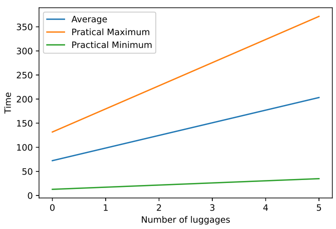


(b) S_c

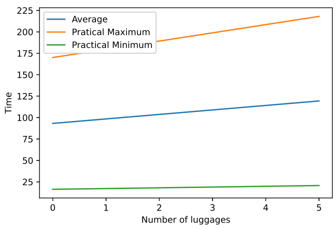


(c) S_a

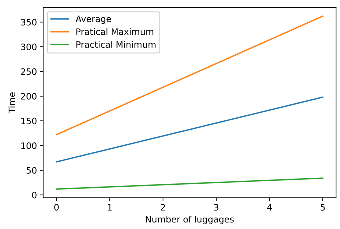
Figure 20: Plane 2 By Optimal



(a) S_o

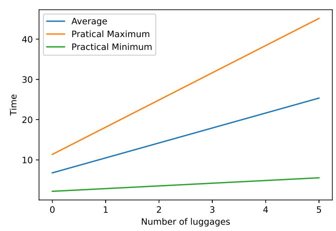


(b) S_c

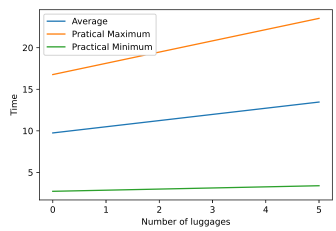


(c) S_a

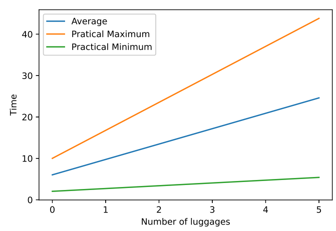
Figure 21: Plane 2 By Random



(a) S_o

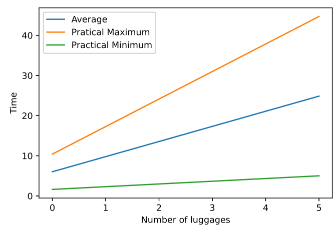


(b) S_c

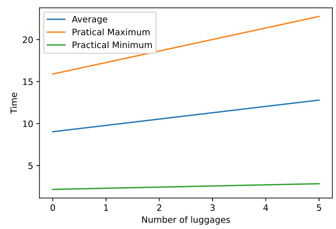


(c) S_a

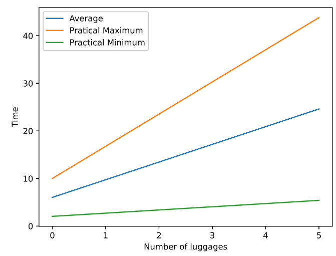
Figure 22: Plane 3 By Seat



(a) S_o

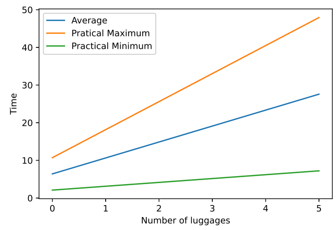


(b) S_c

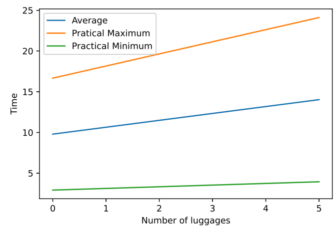


(c) S_a

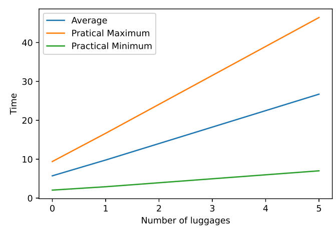
Figure 23: Plane 3 By Section



(a) S_o

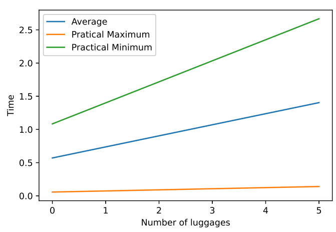


(b) S_c

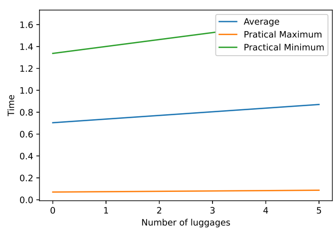


(c) S_a

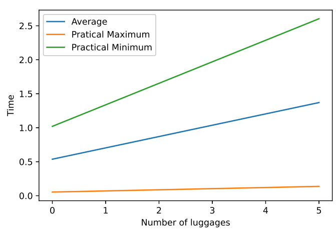
Figure 24: Plane 3 By Seat By Section



(a) S_o

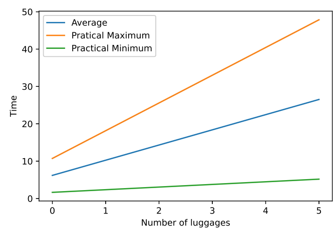


(b) S_c

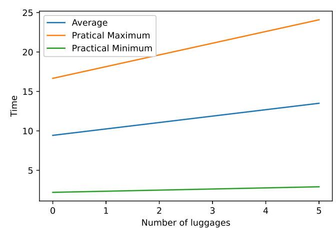


(c) S_a

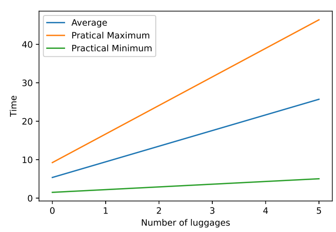
Figure 25: Plane 3 By Optimal



(a) S_o



(b) S_c



(c) S_a

Figure 26: Plane 3 By Random

Appendix E Optimal Method Results

Below are the results of the optimal method finding in 4.4.

Table 11: Plane 2 Optimal Method

	Score	Rank
By Random	0.349145	4
By Seat	1	1
By Section	0.435705	3
By Section by Seat	0.913789	2

Table 12: Plane 3 Optimal Method

	Score	Rank
By Random	0.003427	4
By Seat	0.808179	2
By Section	0.415759	3
By Section by Seat	0.971839	1

Appendix F Results on Capacity Limitations

Below are the results for the capacity limitation circumstances in 4.5. Plane 1 refers the Narrow-Body Aircraft, plane 2 refers to the Flying Wing Aircraft, and plane 3 refers to the Two Entrance, Two Aisle Aircraft.

Time Results

Table 13: 70% Limit of Plane 1 Time Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	3.888261538	35.57944	19.73385	33.9948836	5.472820594
By Section	6.341630492	35.57944	20.96054	34.11755205	7.803521101
By Seat	3.888261538	31.0145	17.45138	29.65818662	5.244573385
By Section by Seat	4.278369231	12.90498	8.591674	12.473648	4.709699692
By optimal	3.888261538	3.888262	3.888262	3.888261538	3.888261538

Table 14: 70% Limit of Plane 2 Time Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	7.34894359	188.5996	97.97429	179.537111	16.41147871
By Section	13.96886043	188.5996	101.2843	179.8681068	22.70039971
By Seat	7.34894359	31.71131	19.53013	30.49319241	8.567061949
By Section by Seat	9.359158974	32.71054	21.03485	31.54296656	10.52672779
By optimal	7.34894359	7.348944	7.348944	7.34894359	7.34894359

Table 15: 70% Limit of Plane 3 Time Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	1.33305641	12.90416	7.118608	12.32560385	1.911611538
By Section	1.33305641	15.02588	8.17947	14.34124174	2.017697744
By Seat	1.864502564	15.72085	8.792676	15.0280319	2.557319897
By Section by Seat	2.137979487	15.44742	8.792701	14.78194944	2.80345159
By optimal	1.33305641	1.333056	1.333056	1.33305641	1.33305641

Table 16: 50% Limit of Plane 1 Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	3.563262	35.42944	19.49635	33.8361336	5.156571
By Section	6.09163	35.42944	20.76054	33.96255205	7.558521
By Seat	3.563262	28.1345	15.84888	26.90593662	4.791823
By Section by Seat	4.028369	10.02498	7.026674	9.725148	4.3282
By optimal	3.563262	3.563262	3.563262	3.563261538	3.563262

Table 17: 50% Limit of Plane 2 Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	6.848944	188.542	97.69545	179.4573033	15.93359
By Section	13.58425	188.542	101.0631	179.7940683	22.33213
By Seat	6.848944	27.28054	17.06474	26.25896164	7.870523
By Section by Seat	8.974544	28.27977	18.62715	27.31450503	9.939805
By optimal	6.848944	6.848944	6.848944	6.84894359	6.848944

Table 18: 50% Limit of Plane 3 Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	1.243313	13.26961	6.150659	10.56727051	1.734047
By Section	1.243313	13.06588	7.154598	12.47475456	1.834441
By Seat	1.774759	13.65316	7.713958	13.05923703	2.368679
By Section by Seat	2.291826	18.99204	10.64193	18.15702636	3.126836
By optimal	1.243313	1.243313	1.243313	1.243312821	1.243313

Table 19: 30% Limit of Plane 1 Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	3.563262	35.42944	19.49635	33.8361336	5.156571
By Section	5.84163	35.27944	20.56054	33.80755205	7.313521
By Seat	3.238262	25.2545	14.24638	24.15368662	4.339073
By Section by Seat	3.778369	7.144978	5.461674	6.976648	3.9467
By optimal	3.238262	3.238262	3.238262	3.238261538	3.238262

Table 20: 30% Limit of Plane 2 Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	6.31561	188.4804	97.39801	179.3721751	15.42385
By Section	13.17399	188.4804	100.8272	179.715094	21.93931
By Seat	6.31561	22.55439	14.435	21.74244882	7.127549
By Section by Seat	8.564287	23.55361	16.05895	22.80414605	9.313753
By optimal	6.31561	6.31561	6.31561	6.315610256	6.31561

Table 21: 30 % Limit of Plane 3 Time Results

	T_{pmin}	T_{pmax}	T	T_{max}	T_{min}
By Random	1.147159	9.088774	5.117967	8.69169359	1.54424
By Section	1.147159	9.138236	5.142697	8.738682051	1.546713
By Seat	1.678605	9.531477	5.605041	9.138833333	2.071249
By Section by Seat	2.291826	15.8267	9.059262	15.14995385	2.968569
By optimal	1.147159	1.147159	1.147159	1.147158974	1.147159

Senstivity Analysis

Table 22: Slope of Linear Sensitivity Analysis for 70% Limit of Plane 1

	S_o	S_c	S_a
By Random	1.04	1.04	1.04
By Section	1.14	0.912	0.912
By Seat	0.725	0.725	0.725
By Section by Seat	0.83	0.83	0.83

Table 23: Slope of Linear Sensitivity Analysis for 70% Limit of Plane 2

	S_o	S_c	S_a
By Random	0.4	0.4	0.4
By Section	5.64	5.64	5.64
By Seat	1.26	1.26	1.26
By Section by Seat	1.68	1.68	1.68

Table 24: Slope of Linear Sensitivity Analysis for 70% Limit of Plane 3

	S_o	S_c	S_a
By Random	0.483333333	0.483333	0.483333
By Section	0.533333333	0.533333	0.533333
By Seat	0.523333333	0.523333	0.523333
By Section by Seat	0.606666667	0.606667	0.606667

Table 25: Slope of Linear Sensitivity Analysis for 50% Limit of Plane 1

	S_o	S_c	S_a
By Random	1.04	1.04	1.04
By Section	1.14	0.912	0.912
By Seat	0.53	0.53	0.53
By Section by Seat	0.635	0.635	0.635

Table 26: Slope of Linear Sensitivity Analysis for 50% Limit of Plane 2

	S_o	S_c	S_a
By Random	3.224	10.28	4.4336
By Section	5.64	5.64	5.64
By Seat	0.96	0.96	0.96
By Section by Seat	1.38	1.38	1.38

Table 27: Slope of Linear Sensitivity Analysis for 50% Limit of Plane 3

	S_o	S_c	S_a
By Random	0.358333	0.358333	0.358333
By Section	0.393333	0.393333	0.393333
By Seat	0.383333	0.383333	0.383333
By Section by Seat	0.846667	0.846667	0.846667

Table 28: Slope of Linear Sensitivity Analysis for 30% Limit of Plane 1

	S_o	S_c	S_a
By Random	1.04	1.04	1.04
By Section	1.14	0.912	0.912
By Seat	0.335	0.335	0.335
By Section by Seat	0.44	0.44	0.44

Table 29: Slope of Linear Sensitivity Analysis for 30% Limit of Plane 2

	S_o	S_c	S_a
By Random	3.224	10.28	4.4336
By Section	5.64	5.64	5.64
By Seat	0.64	0.64	0.64
By Section by Seat	1.06	1.06	1.06

Table 30: Slope of Linear Sensitivity Analysis for 30% Limit of Plane 3

	S_o	S_c	S_a
By Random	0.225	0.225	0.225
By Section	0.208333	0.208333	0.208333
By Seat	0.2	0.2	0.2
By Section by Seat	0.716667	0.716667	0.716667

Optimal Methods

Table 31: Plane 1 70% Limitation Optimal Method

	Score	Rank
By Random	0.415673	3
By Seat	0.117184	4
By Section	0.860942	1
By Section by Seat	0.552529	2

Table 32: Plane 2 70% Limitation Optimal Method

	Score	Rank
By Random	0.906629	1
By Seat	0.857435	2
By Section	0.438687	3
By Section by Seat	0.032511	4

Table 33: Plane 3 70% Limitation Optimal Method

	Score	Rank
By Random	1	1
By Seat	0.70836	2
By Section	0.350702	3
By Section by Seat	0.032511	4

Table 34: Plane 1 50% Limitation Optimal Method

	Score	Rank
By Random	0.641088	2
By Seat	0.860775	1
By Section	0.427535	3
By Section by Seat	0.09896	4

Table 35: Plane 2 50% Limitation Optimal Method

	Score	Rank
By Random	0.302891	4
By Seat	0.376204	3
By Section	1	1
By Section by Seat	0.852283	2

Table 36: Plane 3 50% Limitation Optimal Method

	Score	Rank
By Random	0	4
By Seat	0.653458	3
By Section	0.99514	1
By Section by Seat	0.930343	2

Table 37: Plane 2 30% Limitation Optimal Method

	Score	Rank
By Random	0.839557	2
By Seat	1	1
By Section	0.284592	4
By Section by Seat	0.393043	3

Table 38: Plane 3 30% Limitation Optimal Method

	Score	Rank
By Random	0.989464	1
By Seat	0.968835	2
By Section	0	4
By Section by Seat	0.069401	3