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Decision-Making Matrix to Enable Shorter Connections

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EMBRY-RIDDLE
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DECISION-MAKING MATRIX TO ENABLE SHORTER CONNECTIONS

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A Capstone Project Submitted to Embry-Riddle Aeronautical University in Partial Fulfillment of the Requirements for the Aviation Management Certificate Program

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This Capstone Project was prepared and approved under the direction of the Group's Capstone Project Chair, Dr. Leila Halawi
It was submitted to Embry-Riddle Aeronautical University in partial fulfillment of the requirements for the Aviation Management Certificate Program

Capstone Project Committee:

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Dr. Leila Halawi
Capstone Project Chair

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We experienced challenging moments during the course, mainly caused due to Corona Virus pandemic. Even with this scenario, all the parts mentioned above made it possible to conclude the high-quality course.

Abstract

Group: G. Fernanda, R. Talita, R Sérgio

Title: DECISION-MAKING MATRIX TO ENABLE SHORTER CONNECTIONS
Institution: Embry-Riddle Aeronautical University

Year: 2020

MCT is known as Minimum Connection Time. It refers to the time needed for a passenger to connect from a flight to another in a specific airport, varying according to the connection type. MCT is an essential tool for airlines. It is used as an input in constructing their network and daily, specifically by operational teams, to connect or disconnect a passenger from a flight, for example, during an IROPS scenario. However, the MCT is considered the worst scenario of the variables that composes it, which means that there are opportunities for airlines to reduce the connection time in daily operations to reduce the number of misconnections. The reduction of misconnected passengers would also provide companies' savings opportunities once, according to the 400 ANAC Resolution, companies must provide for misconnected passengers hotel, accommodation, and food.

This research is divided into two parts, and both aim to calculate the savings opportunities considering a Flexible Connection Time. In the first part of the research, the savings are calculated assuming the real displacement time between gates, obtaining a connection time lower or equal to the MCT. In the second part of the research, a Linear Programming Model tool was used to optimize the aircraft's parking position and minimize the number of misconnections, providing additional cost savings for the airlines.

Abstract

Grupo: G. Fernanda, R. Talita, R Sérgio

Título: MATRIZ DE DECISÃO PARA POSSIBILITAR CONEXÕES CURTAS
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Ano: 2020

MCT, conhecido como Mínimo Tempo de Conexão, refere-se ao tempo necessário para um passageiro realizar uma conexão em um aeroporto especifico, variando de acordo com o tipo de conexão. O MCT é uma importante ferramenta para a companhia aérea estruturar sua malha aérea e além disso, no dia-a-dia da operação, tomar a decisão em relação a conexão e a desconexão de passageiros de um voo, durante operações irregulares. Porém o MCT é calculado considerando somente o pior cenário de todas as variáveis que o compõe, fazendo com que haja oportunidades para a empresa aérea de diminuir o tempo de conexão e com isso diminuir o número de desconectados. Essa redução pode fazer com que a companhia aérea evite gastos de acordo com a Resolução 400 da ANAC, essa que indica que o passageiro deve receber hospedagem, transporte e alimentação em caso de um atraso.

Essa pesquisa é dividida em duas partes e ambas procuram calcular as oportunidades de ganho em relação a flexibilização aos tempos de conexão. Na primeira parte, o ganho é calculado considerando o tempo real de deslocamento entre os portões, obtendo a quantidade de passageiros que poderiam ter conectado em um tempo menor que o MCT. Na segunda parte, uma ferramenta de Programação Linear foi utilizada no intuito de otimizar a posição de parada das aeronaves, na busca de diminuir ainda mais a quantidade de desconectados, gerando um ganho ainda maior na economia da empresa aérea.

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Chapter I

Introduction

The utilization of the modality hub-spoke airport makes resources optimized in comparison to the point-to-point old pattern. Usually, the number of flights on a hub-spoke network is smaller than the point-to-point one (considering the same number of attended cities). Due to the connected system, these flights can still cover many regions. (Danesi, 2016)

From an airport point of view, the hub-spoke network creates the necessity to have arrivals and departures coordination to enable passengers to make a fast connection without losing time waiting at the airport. The Minimum Connection Time (MCT), a variable that determines the necessary time to attend passengers' connection during peak hours (Sang-Young Lee, 2014), is discussed along with this research.

Project Definition

An airline network design is a complex activity. Many factors affect the creation of flight, as market demand, number of aircraft, aircraft flying hours, and airport slots. Thinking about a continental country like Brazil, connection hubs are an essential and necessary part of the network strategy. There is a standardized MCT that was previously calculated for each airport and type of connection, considering the worst-case scenario of each of its variables.

In case of a connection between two domestic flights, for example, the MCT is calculated as follows:

$$MCT = Deboarding\ time + Transit\ time + Close\ door\ time$$

The deboarding time is calculated considering the last passenger. The transit time considers the displacement time between the two most distant gates. The closing door time is calculated based on all the company's procedures (considering the last passenger to arrive at the departure gate).

The MCT ends up being a standard time that the airline network team and revenue sector uses to plan the network, creating the possibilities of connections between flights and making all passengers available to make the connection without the airline employees' interference. However, in the daily routine, contingency situations directly impact the connection time, as an origin flight delay or short non-schedule maintenance in the aircraft before departure. In many IROP (Irregular Operation), the MCT cannot be reached, which means that the passengers are automatically disconnected according to the current airline processes.

Furthermore, the ANAC 400 Resolution sets many rules regarding passengers' compensation in case of lost connection, which means high costs to the airlines. Depending on the time that the passenger spends at the airport because of a lost connection flight, the ANAC 400 Resolution states that Airlines need to provide communication, food, or even accommodation. For example, in Guarulhos International Airport, the delay of 4 hours or more represents the company a total cost of R$322,00 per passenger.

Project Goals and Scope

Based on the previous discussion, this research aims to analyze MCT's conditions and provide a better solution to daily basis decisions to reduce the number of missed connections, which would bring relevant savings to the airlines. The estimated saving is close to

$953,800.00 per year with this project for GRU Airport, considering the cost reduction with the ANAC 400 Resolution.

The main research output is a tool - a decision matrix - based on this specific airport that enables connections in a period below the MCT but comparing the RCT (Real Connection Time) with the estimated connection time between the airport gates' areas. Moreover, the research also studies the possibility of optimizing aircraft parking positions with passengers to reduce their displacement.

As commented previously, the actual calculation considers static variables of MCT in the worst-case scenario. The idea of calculating the RCT (Real Connection Time) and comparing it with the specific connection time between areas (called FCT) enables the decision of go/no-go with the particular connections, decreasing the number of total disconnected passengers.

Many data regarding the chosen airport were collected from December of 2019 to March of 2020 and analyzed: number of departures and arrivals daily, number of gates and the distance between them, passenger flow for domestic and international flights, etc. After that, it was possible to design a new matrix considering:

- Park position for the flight arriving
- Park position for the flight departing
- Displacement time (between two gates, including any control that may have)
- Deboarding time
- Close door time
- Number of connected passengers on the flight arriving
- Belly aircraft load factor for the flight arriving

● Type of connection (domestic/international flights)

Once the airlines have a stated MTC, it is essential to highlight that this research does not pretend to change this number. Still, it discusses how this value's daily flexibilization can improve the airlines' service, always respecting the OTP (On Time Performance). The MTC is still an essential standard for network planning and sales, but the operational area must organize a shorter connection if the matrix is possible.

Finally, this research aims to contribute to the airlines, once the matrix would help them make better decisions regarding passengers' connections. By the end, it would make it possible for the airline to have a smaller number of passengers having problems with the connections. Training the operational team regarding this tool, they will be prepared to analyze all the connection variables better to connect passengers instead of disconnecting them. What could happen once the MCT is the single decision metric nowadays. The airlines would keep organizing their network based on the MCT, but they could better act in case of IROP, such as delaying the origin flight. Connecting more passengers, the company would avoid hotel and food costs, according to ANAC 400 Resolution.

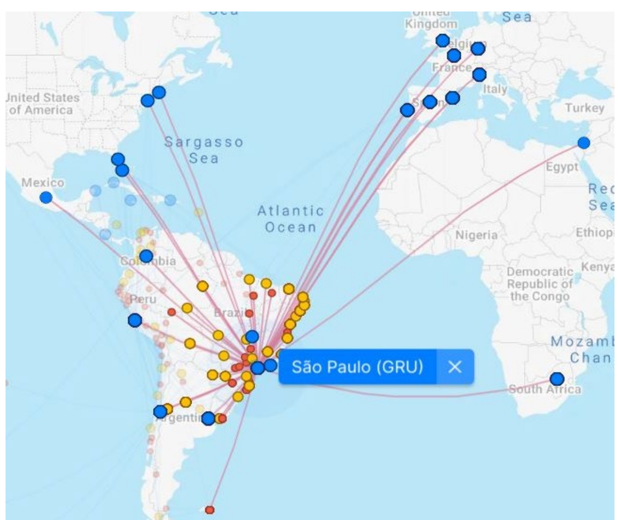

Figure 1: GRU Airport Network

This research's chosen airport is the Guarulhos International Airport, mainly because of its importance in the Latin American market. GRU Airport is responsible for a significant part of flights connecting South America to Europe and North America. Before the COVID-19 pandemic, it used to have more than 100 international departures and 322 domestic departures a day, transporting more than 120,000 passengers a day.

Definitions of Terms

List of Acronyms

ANAC	Agência Nacional de Aviação Civil
ATA	Actual Time of Arrival
FCT	Flexible Connection Time
GRU	Guarulhos International Airport
HCC	Hub Control Center
MCT	Minimum Connection Time
OTP	On-Time Performance
RCT	Real Connection Time
STD	Scheduled Time Departure

Chapter II

Review of the Relevant Literature

Brazilian Aviation Market

According to the Anuário do Transporte Aéreo of ANAC, in 2019, the Brazilian aviation market had a slight decrease (-1,7%) in total departures (domestic and international flights) compared to 2018. On the other hand, 2019 represented the third consecutive year with an increase in total paid passengers.

Figure 2 represents the departures' trend and paid passengers of the Brazilian market, including domestic and international flights. In 2019, 951 thousand flights operated, and 119,4 million passengers were transported (domestic and international flights).

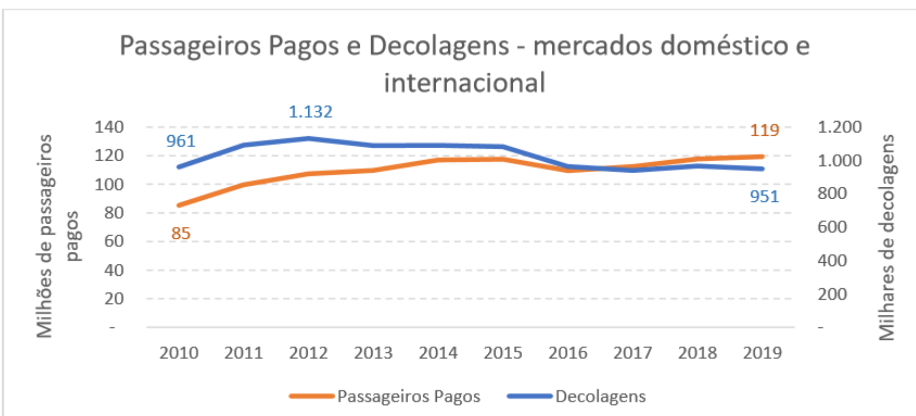

Figure 2: Brazil's Total Departures - Domestic and International Flights

The Brazilian domestic aviation market it's composed mainly of 3 airlines: Azul, Gol, and LATAM, which together represent more than 90% of the total number of paid passengers. 2019 was also the last year of operation of Avianca Airlines, the company transported in 2018 12% of domestic passengers and 3% of international passengers and stopped its process in May of 2019. Figure 3 below represents the share of each company regarding transported passengers since 2015.

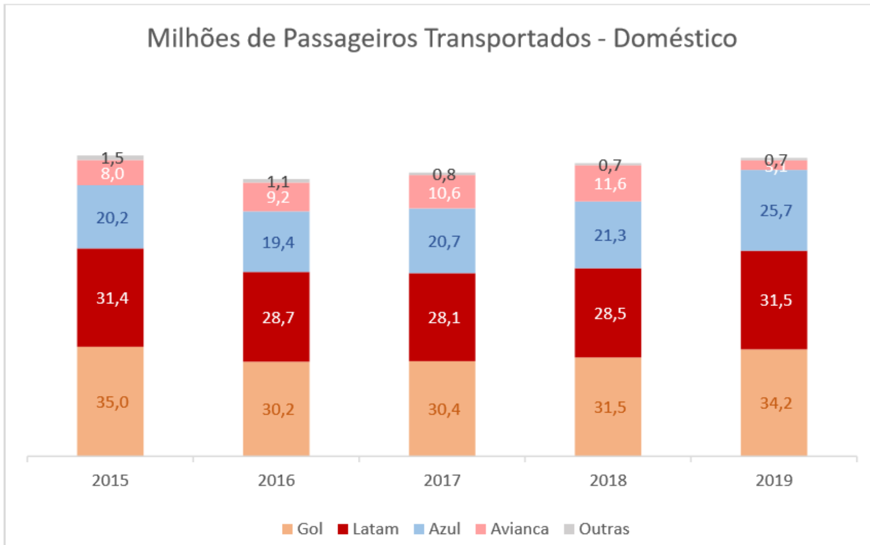

Figure 3: Share of Brazilian Airlines Regarding Passengers Transported – Domestic Flights

According to CNT (Confederação Nacional do Transporte), the airlines responsible for the air transport offer. Several factors affect their availability, including aircraft and input costs, specialized employees, and different transportation and technology available.

More than 50% of an airline's costs are fuel, leasing, and aircraft maintenance. Brazil's air sector is still small, mainly due to its price compared to other transportation types. According to ABEAR (Associação Brasileira das Empresas Aéreas), the average penetration of domestic air transport was 0.47 flights per capita in Brazil in 2015, and the industry revenue (direct impact) represented 0.4% of the national economy in the same year.

Guarulhos Airport Capacity and Connectivity

Guarulhos airport started to operate in January of 1985 and was built in a land that belongs to the Brazilian Air Force. The Urban Plan for the city of São Paulo planned that GRU Airport could receive domestic flights first, but in 1989 was constructed a second runway. The passengers' terminal was increased, allowing the airport to receive local and international flights (Infraero website). In 2014, Terminal 3 was built with 192,000m² to welcome many international flights. After 2014, Terminal 2 was designated to receive domestic and international flights (GRU Airport website). Currently, the airport began to manage connections for the international airlines and the Brazilian airlines as well.

GRU Airport's actual operation is divided into three terminals. As discussed above, the first domestic, the second one is mixed by international and domestic flights, and the third one is focused on international flights, as highlighted in Figures 4 through 6.

Terminal 1: Domestic Flights

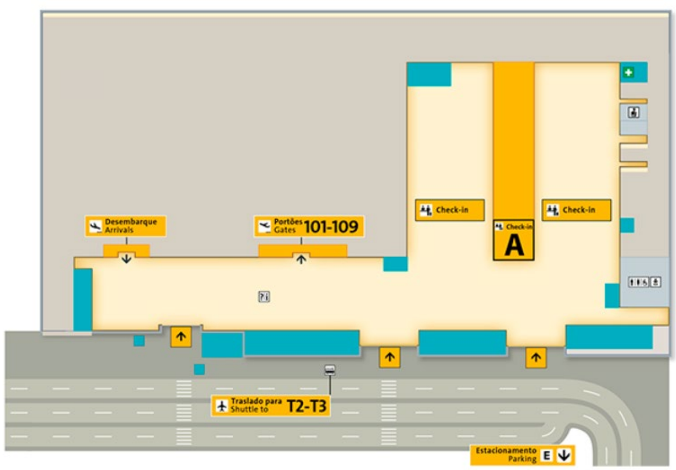

Figure 4: GRU Airport Terminal 1

Terminal 2: Domestic and International Flights

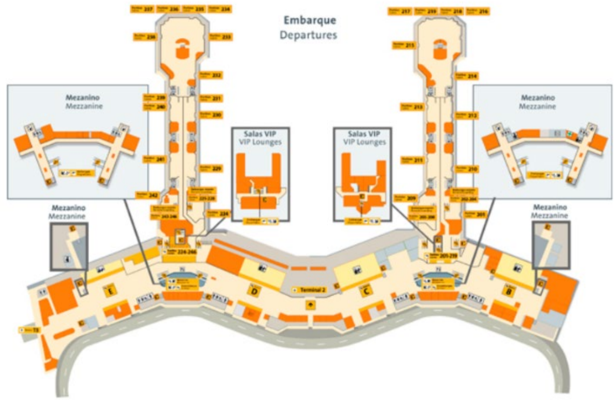

Figure 5: GRU Airport Terminal 2

Terminal 3: International Flights

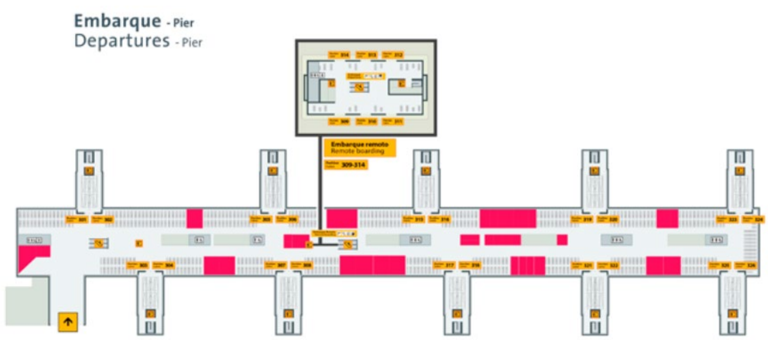

Figure 6: GRU Airport Terminal 3

The airport has nine departure gates in Terminal 1, 42 in Terminal 2, and 26 gates in Terminal 3. Terminal 2 is also divided on the west and east side, and the international and domestic areas also share the west side. Both types of operations use some of the gates in different moments of the day. The airport has 126 park positions, making the board by bus necessary in some cases.

For the connections, the airport has two points of re-check in (point to dispatch the baggage after arriving in an international flight, connecting to a domestic flight), one in Terminal 2, and the other in Terminal 3. The airport also has fast passed through Terminal 2 and 3 without leaving the gate area and immigration, emigration, and tax checkpoint, making it easy for the passengers to connect between a domestic and an international terminal.

A relevant Brazilian airline - with a market share of 38% in GRU Airport, used to transport more than 23,000 passengers per day in 138 flights in 2018. The distribution of 52% of passengers making connections at GRU Airport (detailed data). This scenario shows how relevant is the connection management in this airport.

Hub-Spoke Operation

According to Cook and Goodwin (2008), there are many advantages from the hub-spoke operation adopted by many carriers for both the companies and the passengers. The increase in the number of cities served allows for more efficient use of resources. They explain that "Route architecture choice is the foundation of an airline's product." While the point-to-point model connects the passenger from city A to city B directly, the hub-spoke model can reach more cities because it allows the passengers to transfer to the second flight in a hub airport. It also affects the supply and demand, once adding more destinations in the network – fostering even the loyalty programs – and bettering the assets, such as the aircraft.

According to Dennis Nigel (1994), applying a hub model to a three point-to-point market could significantly increase the number of markets attended. Figure 7 above illustrate the citation:

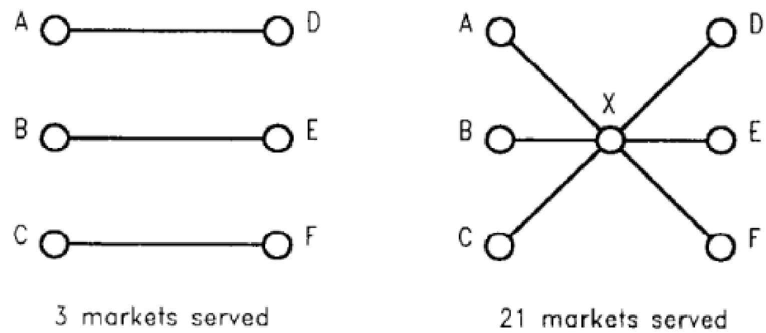

Figure 7 - Market Coverage considering Point to Point and Hub Model

On the other hand, this kind of network can be more susceptible to disruption because the delay of a single flight can impact the network and the connections, so the airlines need to have ways and tools to solve these problems.

Customer Satisfaction and Lost Connection

According to Cook et al. (2015), the airport system is affected by many factors correlating the original flight to the connection one, as aircraft rotations, crew dependencies, and passenger connectivity. Taylor (1994) explains that delays evoke two groups of feelings: uncertainty reactions, anxiety, and anger reactions, as irritation. Even though a 15 minutes delay is considered "on time" by the statistics, the passenger with a scheduled connection might have a different perception if he or she misses the connecting flight (Cook et al., 2015).

On average, more than 11,960 passengers make a connection in GRU Airport. This passenger experiences all the airline processes of arriving, deboarding, connecting, and boarding again. Thus, per 400 400 Resolution of ANAC, customer satisfaction can also be understood as the airlines' capacity to ensure the scheduled connection to avoid her or his frustration and expenses.

400 Resolution of ANAC

According to 400 Resolution of ANAC, Section III, Art. 26, and Art. 27, the airline must offer material assistance to the passenger in case of a flight delay, flight cancellation, service interruption, and passenger's passing. By material assistance, the 400 Resolution states that the airline must provide free according to the passenger waiting time:

- more than one hour: communication facilities
- more than two hours: food (meal or voucher)
- more than four hours: accommodation and transfer in case of an overnight stay.

At GRU Airport, the average cost of food is R$36,00 per passenger. The cost of accommodation is R$250,00 per passenger (detailed data), so for each passenger for delays over four hours, the total cost is R$322,00 (two alimentation voucher and one shelter).

Minimum Connection Time and On-Time Performance

As commented above, the MCT is calculated as a standard number, considering the worst-case scenario for the variables above:

- Different carriers
- Airport size and layout
- Changing of terminals
- Security checks
- Immigration checks
- Size of the aircraft

According to Lernbeiss (2016), the hub-and-spoke operation works appropriately if the service is running according to the plan, managing the service correctly to avoid deviations in the airport operation. Lernbeiss (2016) also said that passengers naturally prefer direct flights, so the airport using the hub-and-spoke concept tries to get a remote connection to spend less time at the airport, but this can cause the disconnection of the passengers or even a flight delay.

In theory, with a reasonable right MTC calculation, the number of disconnected passengers should be zero. According to the OAG, the OTP of GRU Airport is 75%. It means that 25% of flight departures with a delay of 15 or more minutes from the planned time, generating disconnected passengers.

A disconnected passenger that fits in one of the ANAC 400 Resolution conditions means an extra cost to the company. The issue is that this passenger usually waits in the airport for over 4 hours because the hub airports are set with peaks of operation. It means that this passenger usually arrives at a peak maximum of a departure at the next summit. Thus, the airlines have an appropriate number of disconnected passengers and, consequently, costs related to food and accommodation.

Hub airports usually have an area called HCC (Hub Control Center) responsible for all kinds of operational problems. They must make the best decision to ensure high OTP and passengers' satisfaction. The airport management, working correctly with the HCC, keeps evaluating variabilities that could affect the OTP and the connections. To protect this indicator, the HCC uses the MCT between the flights to take the binary choice of go or no-go of a connection. Most of the time, the connection flight doesn't wait for the inbound link because it would affect the OTP, and consequently, it would affect the next flight OTP and create more disconnected passengers. Because of this, in general, these passengers are relocated to the other plane to the same destination later. It means that the decision is exclusively based on the worst scenario that the MTC considers, which does not apply in every single connection. So, it is essential to have tools to make operational decisions that analyze each contingency scenario individually.

In operation, two possibilities could happen at the hub-and-spoke operation. First, the anticipated arrival, making it possible for every passenger to connect, and the late arrival, could be crucial and disconnect the passengers depending on the MCT. Both cases have costs. The first one has the opportunity cost because the seats could have sold to a new range of passengers connecting to previous flights, and the second has the price for the disconnected passengers, as we can see in the following Figure 8 (Lernbeiss, 2016):

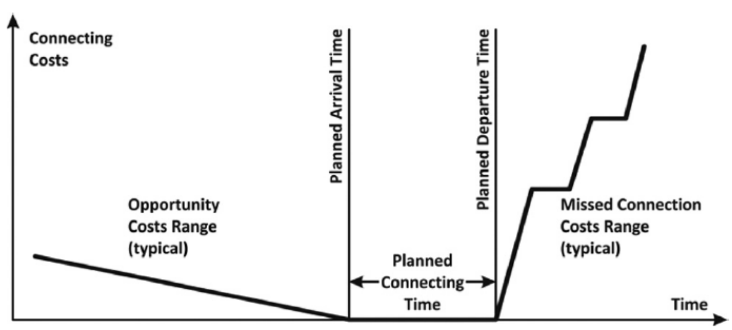

Figure 8: Cost of connections (Lernbeiss, 2016)

Similar Decision-Making Matrix Studies

Study 1 – Methods to Measure Connectivity Index in Maritime Transportation

Frazila and Zukhruf (2015) presented a study comparing different methods to measure connectivity index in maritime transportation. The study aimed to improve Indonesia's domestic maritime connectivity, reduce transportation costs, and accelerate economic growth. The authors argue that connectivity has a significant impact on transport costs and can improve in this strategy. It brings cost reductions to lower the price of products and expand the market.

The research presented three different methods for calculating a province connectivity index. The plans are described below:

- **Graph Theory-Based Approach**
    - Connectivity is determined mainly due to the region (distance and costs are not considered in this method).
- **Gravity Based Approach**
    - This method also considers the region (flow between Origin-destination) and distance, time, and cost between them.
- **Linear Shipping Connectivity Index (LSCI)**
    - A modified version of this method was used to fit with the condition of domestic shipping. In this method, it is considered five components to identify the connectivity index: container carrying capacity of the ships, maximum vessel size, number of services (representing the demand – ship call/year), number of companies, and deepest port-channel or full draft of the vessel that can berth at the port.

As a result, the authors considered that the adapted LSCI method was the most realistic one. Even though it was applied in other transportation models, this study shows that the adaptation of study methods and parameters can generate more natural results.

Study 2 - Network Effects in Railways

As air transport, the railway system is positively affected by trains (Landex, 2012). Many studies focused on one unique railway, but the reality is that the system is composed of many railways that affect all the connectivity. For example, the nationwide timetable in Denmark depends on the trains to and from Germany and Sweden. It means that the higher the analyzed area, the higher the risks regarding timetable changes and infrastructure. This high index of connectivity affects the network and the network and passengers, and one of the study's objectives was to understand these effects. The author suggests that the difference between the actual timetable and the best-analyzed timetable determines the network effect on passengers and can improve timetables.

Study 3 – Decision-making for Alternative Monorail Routes

In a study made by Hamurcu and Tamer Eren in 2018, the authors proposed multicriteria decision-making to better study eight monorail routes in Ankara, Turkey's capital city. The methods Analytic Network Process (ANP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a multicriteria decision-making method, were used to define the criteria and alternative routes the public transport. Applying these public transportation methods is relevant because it has high social impacts once an efficient public transportation network reduces car traffic and carbon emissions. In this context, the decision matrix supports the strategic planning for 10-20 years, once it involves high investment regarding new structures of roads, railways, and ports.

Study 4 - The performance analysis of public transport operators in Tunisia using the AHP method

This study was conducted in 2015 by Younes Boujelbene and Ahmed Derbel. It aimed to find the best performing public transport operator in Tunisia through the method of Analytic Hierarchy Process (AHP), a multicriteria decision method.

The authors defined the criteria and sub-criteria used to measure performance; then, we applied the AHP method. This method was selected due to the simplicity and flexibility, considering that each criterion and sub-criteria may be viewed as a different parameter.

This research presents a matrix for the flexibilization of MCT to GRU Airport. As the studies commented above were also done based on different criteria with a decision-making matrix as the main output. The matrix was created based on a specific airport. However, other comparable airports can use it by adjusting some of the variables.

Chapter III

Methodology

The MCT is the primary reference metric that drives this research. The GRU Airport MCT was calculated by an airline during a study at the beginning of 2019 through field time measurement methodology, considering the displacement time of 1m/s. This time was defined as the airline reference time to connect or disconnect passengers. The MCT varies according to the combination of domestic and international flights and the airport configuration.

Besides the MCT, the project's primary data comes from secondary sources previously collected by an airline operational area from December of 2019 and March of 2020. It is common for the airlines to track disconnected passengers to measure network planning's assertiveness based on the original MCT. This information is used to develop analysis to find better solutions to the service and reduce disconnected passengers' costs, which is the main goal of this research. All the information regarding connected and disconnected passengers originate from a sheet filled by the operational area. Hence, it faithfully represents the airline's routine and how many passengers were disconnected during the period studied.

The research also discloses the estimated displacement time between gates' areas to be compared with the RCT (Real Connection Time) during the decision to connect or not. A decision to connect a passenger should not affect the OTP, one of the airline industry's most relevant KPIs. According to OAG, OTP is a metric that can affect an airline's productivity, cost, brand loyalty, ticket sales, and, consequently, customer satisfaction. It is also important to remember that a delayed flight can affect all the consecutive networks, so most companies make great efforts to ensure that they depart and arrive on time.

Experimental Design

Once the airline has defined the MCT for each possible combination of flights, this research analyzes the disconnected passengers' database to find patterns on the variables that most disconnect passengers. The matrix proposes the flexibilization of some variables simulating possible scenarios to find the flexible connection time (FCT). Unlike the MCT, it considers the previously calculated displacement time between two airport areas where both aircraft will arrive and depart. With this information, it is possible to calculate the flexibilization tolerates' savings.

Figure 9 explains the Matrix of Flexibilization proposed in this research. During network planning, the MCT is used as the minimum time required to schedule connection flights. However, the same standard time is used in daily operations. During an IROP, if the original flight is delayed, all the passengers with an RCT shorter than MCT would be automatically disconnected. According to the matrix, the RCT should be considered instead of MCT and analyzed to connect or not, once the connection time between gates is variable.

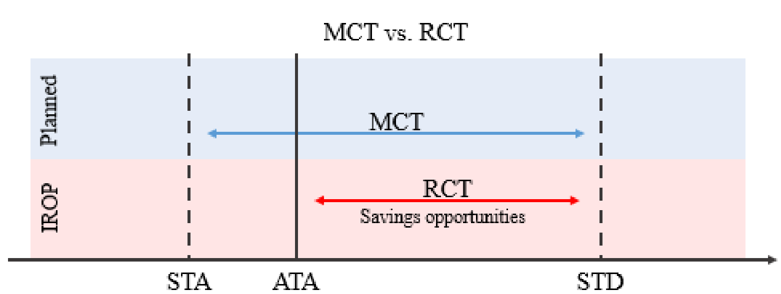

Figure 9: Matrix of MCT Flexibilization

Data Source(s), Collection, and Analysis

Inside the HCC area of a big airline at GRU Airport, specific roles are divided by tasks better to control the airline's operation's further steps. One of them is the Connection Controller, responsible for managing all connections, checking the arrivals delays, and informing the handling and ground handling team of the connection's decision. The decision is based totally on the MCT, so every passenger with a connection time shorter they the MCT will be automatically disconnected and protected by Resolution 400 of ANAC, generating airlines' costs. Every Connection Controller's decision to connect or not is filled in a sheet and used to see the decision matrix's earning potential. These variables compose the data:

- Date
- Airport of the origin flight
- Number of the original flight
- ETA (Estimated time of arrival)
- Park position of the original flight
- Airport of the destination flight
- Number of the destination flight
- ETD (Estimated time of departure)
- Park position of the destination flight
- Number of passengers in connection
- Number of baggage in connection
- Type of connection (domestic or international)
- MCT
- RCT

- The decision to connect or disconnect

The MCT is calculated by the airline as a standardized time that considers the worst-case scenario to make it possible for every passenger to connect. Thus, it is essential to follow, simulate, and measure each connection step in the airport. One of the most significant MCT variables is the park position because it directly affects the passenger's displacement time.

On the other hand, the RCT is calculated considering the ATA (Actual Time of Arrival) and the STD (Scheduled Time of Departure) of the connection flight. This shows how much time the passenger will have to make a connection:

$$RCT = ATA - STD$$

Tables 1-4 detail the MCT to each type of connection: domestic to domestic flights, domestic to international flights, international to domestic flights, and finally, international to domestic flights. In general, passengers connecting from or to a global time takes longer than a domestic to domestic connection because of the emigration or immigration steps.

D_D: Connection between Domestic to Domestic Flights

The Dom_Dom MCT has 50 minutes. It considers the measured times of push-in and the open door of 3 minutes, the deboarding time considering the last passenger of 12 minutes, the displacement time using the worst case of parking position of 25 minutes, and the closing door plus push back of 10 minutes (that is the time between the boarding of the last passenger and the push-out).

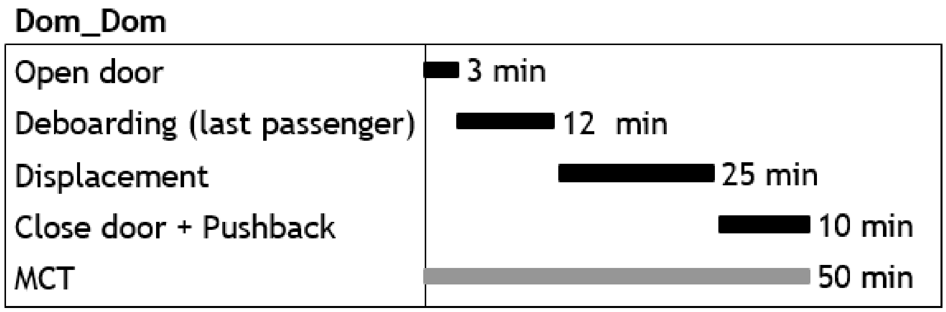

Table 1: MCT Domestic – Domestic Flights

D_I: Connection between Domestic to International Flights

The Dom_Int MCT calculation has the open-door time of 3 minutes, the deboarding process considering the last passenger of 12 minutes, the time of displacement of the aircraft to the security checkpoint of 7 minutes, the average security process of 7 minutes, the emigration process of 10 minutes, the removal time between the immigration and the departure gate of 18 minutes and finally, the closing door and pushback time of 18 minutes. Considering the worst displacement time between the aircraft, this MCT has a total time of 75 minutes.

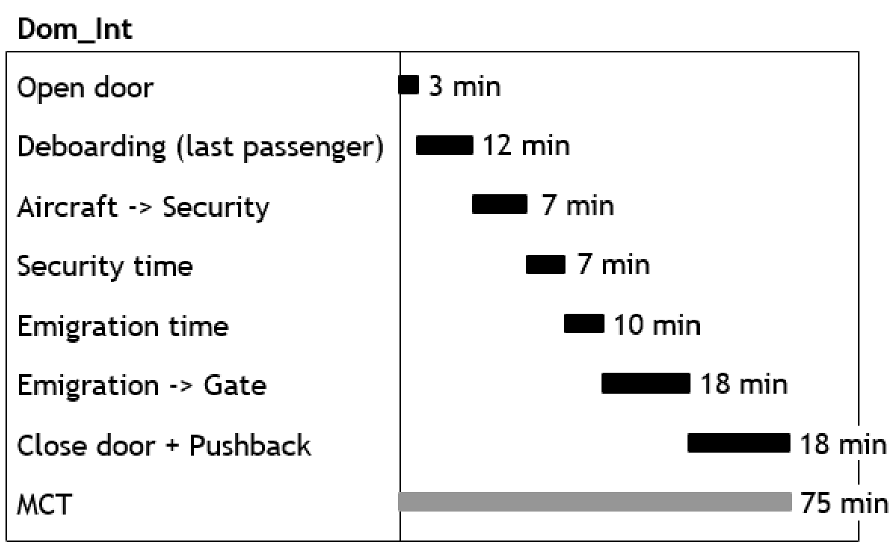

Table 2: MCT Domestic – International Flights

I_D: Connections between International and Domestic Flights

According to the Brazilian procedures, in the case of Int_Dom connections, all the passengers arriving need to retake the baggage and dispatch at the check-in. All these times are included in the MCT calculation. In this case, the MCT ensures that the passengers arrive in the check-in position 40min before the STD, which impacts the MCT total time of 105 minutes.

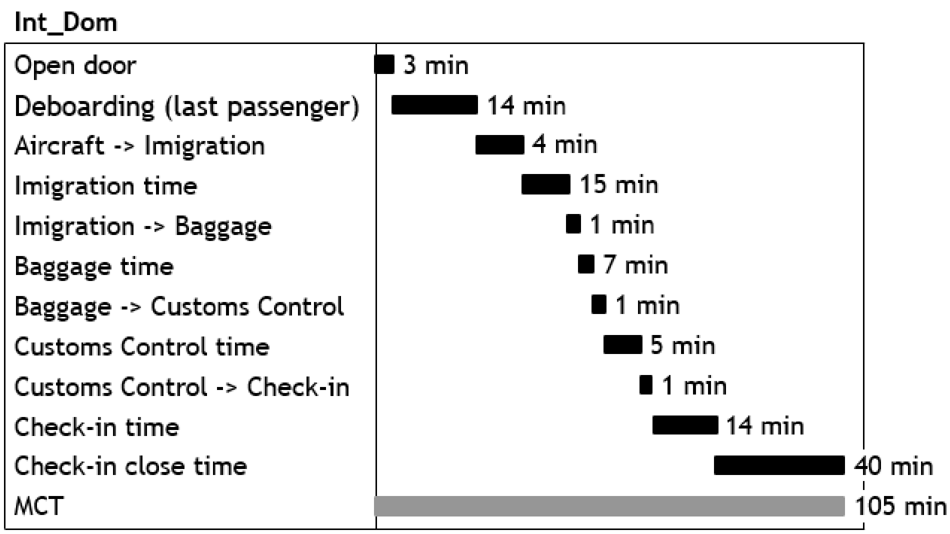

Table 3: MCT International – Domestic Flights

I_I: Connections between International to International Flights

In this model, the passengers don't have to take the baggage, so they just need to pass through the security checkpoint to bring the destination flight. In the end, the Int_Int MCT is shorter than the Int_Dom one.

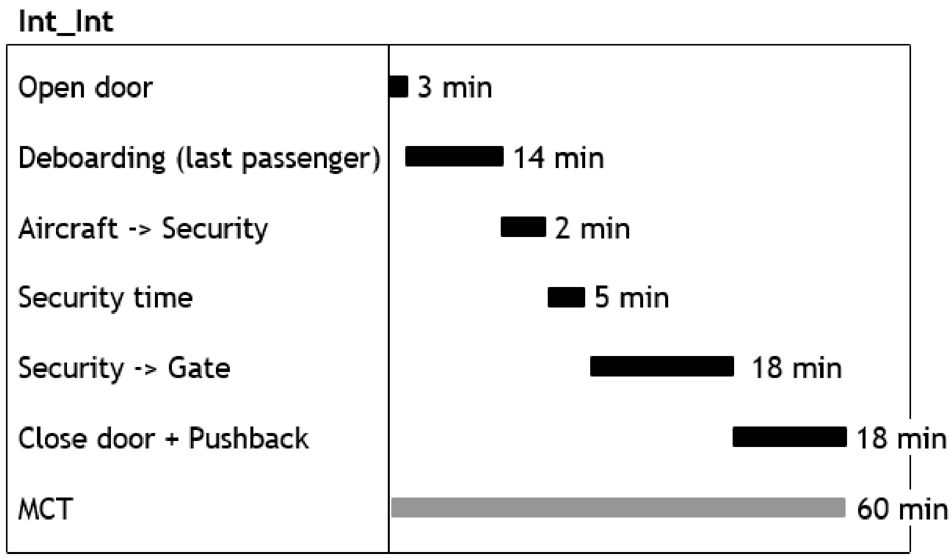

Table 4: MCT International – International Flights

Table 5 above shows the percentage of disconnected passengers according to the type of connection. The Dom_Dom connection type represents 53% of all connections done in GRU Airport from December of 2019 to March of 2020.

Type	D_D	D_I	I_D	I_I
Connection	1191	494	110	62
Miss Connection	5267	1014	3503	535
Total	6458	1508	3613	597

Table 5: Percentage of Disconnected Passengers According to the Type of Trip

This data will be used to develop two studies presented in the next chapters.

Chapter IV

Outcomes

Summary

In this chapter, the information was divided into two scenarios. Scenario 1 analyses the possibility of connecting more passengers by considering the RCT instead of the MCT. In a step further, Scenario 2 proposes an optimizing aircraft parking position using a Linear Programming Model. Using both RCT and optimization with the Linear Programming Model, we have 70% more passengers connecting, which means a R$4,200,000.00 ($953,800.00) total savings to the airline in a year.

Project Outcomes

The research analyzed 12.472 flights in connections to GRU Airport between December 2019 and March 2020. The database contains several data regarding each flight: origin, destination, arrival and departure date, arrival and departure time, arrival and departure gate, and the number of passengers and bags connecting to GRU Airport. After analyzing the data, we divided flights into four different scenarios, according to the type of connection: domestic to domestic flights, domestic to international flights, international to domestic flights, and international to international flights.

As shown in Chapter III, the MCT was calculated for each connection combination considering their processes. This analysis made it possible to calculate how many passengers had a miss connection in the period. Table 6 shows the percentage of passengers who had a connection and a miss connection considering the MCT in the jet bridge operation as decision making. The data base only considered jet bridge flights because there would be other variables that could avoid the shorter connections in the bus flights option.

MCT Scenario	# Passangers	%
Connection	1.857	15,25%
Miss Connection	10.319	84,75%
Total	**12.176**	**100,00%**

Table 6: Connected and Misconnected Passengers

However, GRU Airport has 12 different parking areas. It means that the aircraft will not be parked in the most distant positions in all the connection cases. To better understand the possible benefits of having an FCT, the research considered the displacement time between each pair gates, as discussed in Scenario 1. Figure 10 illustrates how the boarding and deboarding areas at the airport are designed.

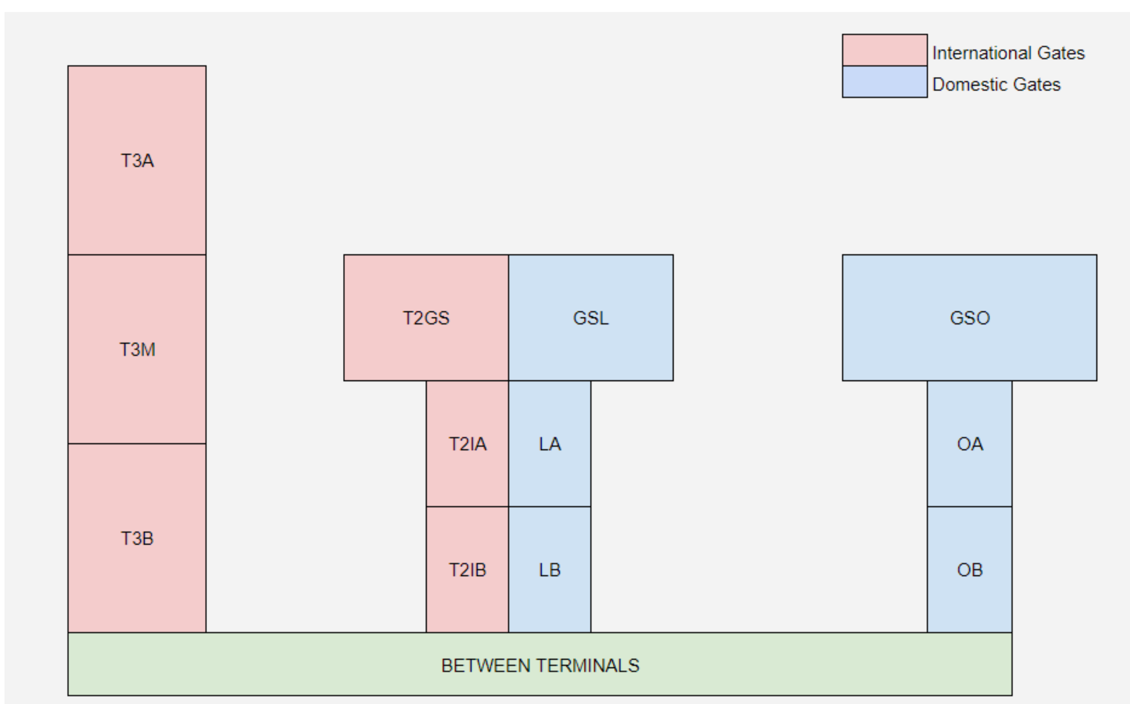

Figure 10: Gates' Map at GRU Airport

Scenario 1 – Using the RCT to Passengers' Displacement instead of MCT

Despite the type of connection, the MCT was defined based on several variables' "worst" conditions, as discussed in previous topics. As an example, Table 1 above shows that the Domestic-Domestic connection considers 25 minutes needed for the displacement process and more than 25 minutes for all the other steps – open door, deboarding, and close door and pushback – totalizing an MCT of 50 minutes.

On the other hand, Table 7 illustrates, as an example, the estimated total connection time measured from and to domestic gates, what was called FCT. This measurement was made locally, using the passenger route and the same matric of speed (1m/s) of the MCT calculation. The results in Table 7 reveal the estimated connection time combining each pair of gates, already considering the 25 minutes needed for other steps of connection, just like Table 1. Tables regarding the three different types of connections are presented in the appendix area of this research.

The only area combination that needs 50 minutes of connection – the same as the MCT – is from/to GSL to GSO. All the other combinations are lower than that, indicating a great opportunity for shorter connections.

	Domestic Gates					
From/To	GSL	LA	LB	OB	OA	GSO
GSL	00:27:00	00:29:00	00:33:00	00:42:00	00:46:00	00:50:00
LA	00:29:00	00:27:00	00:29:00	00:37:00	00:42:00	00:46:00
LB	00:33:00	00:29:00	00:27:00	00:33:00	00:37:00	00:42:00
OB	00:42:00	00:37:00	00:33:00	00:27:00	00:29:00	00:33:00
OA	00:46:00	00:42:00	00:37:00	00:29:00	00:27:00	00:29:00
GSO	00:50:00	00:46:00	00:42:00	00:33:00	00:29:00	00:27:00

Table 7: Flexible Connection Time (FCT) Between Gates' Areas

Once these new metrics are known, the matrix compares the RCT with the FCT. Figure 11 explains that any passenger with the RCT equal or longer than the FCT can connect according to the new matrix.

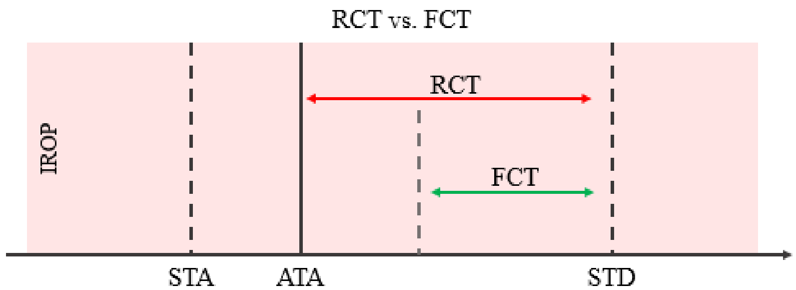

Figure 11: Flexible Connection Time

Here is an example: a passenger traveling from FLN to SSA (domestic to domestic flights) connecting in GRU has an MCT of 50 minutes, as shown in Table 1. If the origin flight arrives delayed and the RCT is shorter than 50 minutes, this passenger will be automatically disconnected when considering the MCT. If the original flight was expected to arrive at 11 a.m. but arrive at 11:20 a.m., and the connection flight STD is at noon, the passenger would be disconnected once the 40 minutes connection is shorter than the 50 minutes of MCT. However, if his connection happens from the LA area to LB, he will take only 29 minutes to connect. Considering the FCT matrix solution proposed in the research, the HCC area would consider this passenger connected instead of disconnected once the 40 minutes' connection available is greater than the 29 minutes needed between areas, according to Table 7.

Therefore, Table 8 shows that the airline could increase 189% connected passengers from December 2019 to March 2020 using the RCT of Table 7 instead of MCT.

MCT vs RCT	WITHOUT MATRIX (MCT)	WITH MATRIX (RCT)	VARIATION	
Connection	1.857	5.384	**3.527**	**189,93%**
Miss Connection	10.319	6.792		
Total	**12.176**	**12.176**		

Table 8: Comparison between MCT and RCT

The 400 Resolution of ANAC establishes that companies are responsible for accommodation, food, and transportation for passengers who had a misconnection, depending on the passengers' time in the connection city. To calculate the potential savings in this research, we assumed that 50% of the passengers who had a misconnection would have the right to stay in a hotel, 40% of passengers would have transportation, and 100% of them have the right to food.

With these premises, the research expanded the calculated opportunity cost of 3 months to a year. Thus, the company could save more than R$2,200,000.00 (around $500,000.00) in a year if the RCT were considered in the decision process of connecting or disconnecting a passenger instead of MCT.

Tables 9 and 10 illustrate the results:

COST FOR EACH MISCONNECTED PASSENGER		
	PERCENTAGE	COST
HOTEL	50%	200
TRANSPORTATION	40%	20
ALIMENTATION	100%	50

Table 9: Cost of Misconnected Passengers

Increase of connections (RCT vs MCT)	3.527
Oportunity Cost (3 months)	R$ 557.266
Oportunity Cost (1 year)	**R$ 2.229.064**

Table 10: Possible Savings in a Year

Scenario 2 – Park Position Optimization

The first part of this research showed a considerable opportunity to improve the airline's connection by considering the FCT of passengers' displacement instead of the MCT. Furthermore, we understood that the company could increase its savings by optimizing the aircraft parking position, making the displacement time even shorter, and minimizing the number of misconnected passengers.

This research used a Linear Programming Model software. We have chosen a specific week from the database to perform this optimization process, precisely 20 – 28 of January 2020, excluding weekends because we have fewer connections on Saturdays and Sundays. The range of time 11 a.m. and 2 p.m. due to many passengers connecting was also chosen.

The optimization scenario considered only passengers with a real potential connection (passengers with connection time between MCT and the shortest FCT – 27 minutes for Dom_Dom connection, for example). It automatically disregarded all the passengers with a connection time longer than MCT (because they will connect anyway) and the passengers with an RCT shorter than the shortest FCT.

Figure 11 shows the total passengers connecting in the week studied and the number of passengers connecting time between MCT and the shortest FCT. The optimization scenario considers 473 passengers as a sample.

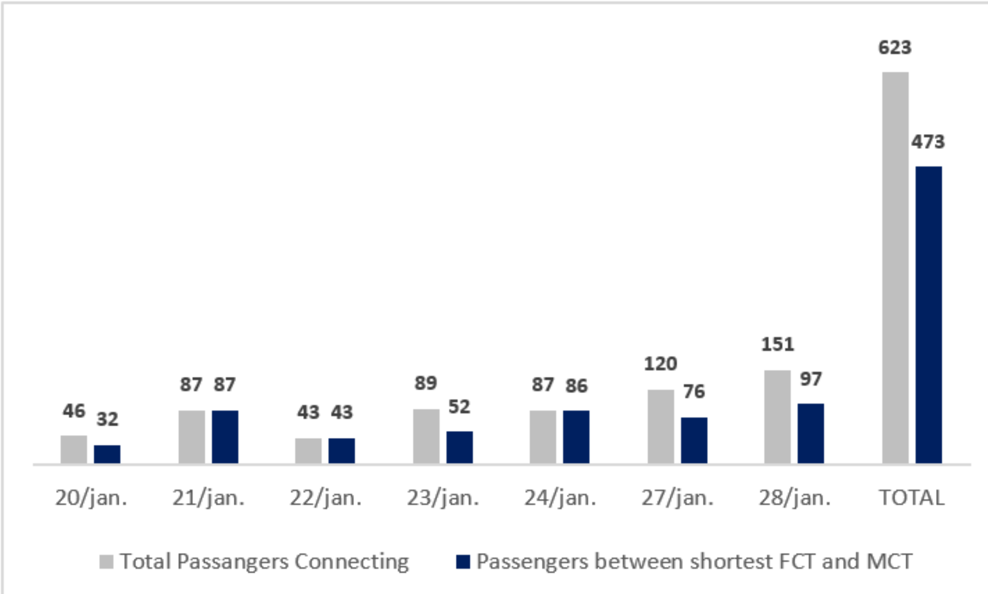

Figure 12: Possible Passengers Connecting per Day

The scenario using Linear Programming Model was performed individually, one for each day. All the steps above and the Linear Programming Model considered January 28 as an example. We first organized the connection matrix according to Table 11, which illustrates how many passengers needed to connect from each arrival flight (A_y) to each departure flight (D_x):

CONNECTION PASSENGERS		DEPARTURE FLIGHTS					
		D1	D2	D3	D4	D5	D6
ARRIVEL FLIGHTS	A1	7					
	A2	4					
	A3			1	7	17	12
	A4	1	1	5		4	5
	A5			12	6	10	5

Table 11: Connection Passengers from 11 a.m. to 2 p.m. on January 28, 2020

We have chosen the arrival park position as the variable once we know that it is operationally more feasible to define the departure position than the arrival one in GRU Airport. Based on that, Table 12 details the real park position optimization to each departure flight:

Departure Flights	Real Park Position
D1	GSL
D2	LB
D3	LA
D4	OA
D5	GSO
D6	GSL

Table 12: Real Park Position

Based on Table 7, we can find the connection time between each gate to each departure flight's real park position. This model has the objective of reducing the passengers' walking distance, so we needed to minimize the natural connection for every possibility of the arrival park position. Therefore, we multiplied the connection time between the gates by connecting passengers, setting Table 13.

CONNECTION TIME x PASSENGERS		POSSIBLE PARK POSITIONS					
		GSL	LA	LB	OB	OA	GSO
ARRIVEL FLIGHTS	A1	189	203	231	294	322	350
	A2	108	116	132	168	184	200
	A3	1525	1451	1398	1203	1276	1308
	A4	540	522	538	602	639	639
	A5	1259	1181	1155	1158	1186	1246

Table 13: Connection Time Times Number of Passengers in Connection on January 28, 2020

The same process was applied for the rest of the week, and the detailed Linear Programming Model studies are available in the Appendix.

Linear Programming Model

First, the objective function must minimize the sum of each possibility showed in Table 13, in other words, the passengers' connection time between positions:

189A1GSL+203A1LA+231A1LB+294A1OB+322A1OA+350A1GSO+108A2GSL+116A2LA+132A2LB+168A2OB+184A2OA+200A2GSO+1525A3GSL+1451A3LA+1398A3LB+1203A3OB+1276A3OA+1308A3GSO+540A4GSL+522A4LA+538A4LB+602A4OB+639A4OA+639A4GSO+1259A5GSL+1181A5LA+1155A5LB+1158A5OB+1186A5OA+1246A5GSO

A1 GSL: Flight A1 assigned to the position GSL

The constraints must ensure that each flight has just one gate assigned and that each gate has just one flight positioned and as just one gate assigned and that each gate is just one flight positioned. Thus, two types of constraints were set:

- Single gate for each flight:

A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1

- Single flight for each gate:

A1LA+A2LA+A3LA+A4LA+A5LA<=1

The "<=1" sing was used because there are more positions than flights, so there is the possibility of a position that does not have an assigned flight. Moreover, every variable on the system was set as binary. If the system answers that the variable is "1", it means that the flight should be assigned to that specific position.

Linear Programming Model Results

Table 14 shows the best options for gate assignment for this operation, according to the Linear Programming Model. The complete answer is in Appendix 3.

Flight	Position
A1	GSL
A2	LA
A3	OB
A4	LB
A5	OA

Table 14: Gate Assignment Result

Moreover, Figure 15 details ' number of connected passengers increase if the flights were assigned as the Linear Programming Model suggested in Table 14.

PASSENGERS	REAL POSITION	OPTIMIZED POSITION
CNX	44	75
MIS_CNX	53	22
TOTAL	97	97

Table 15: Utilization of FCT for the Optimized Position

In this sample, the number of connected passengers could increase to 75 instead of 44, considering the FCT results of Scenario 1 combined with the optimized park position of Scenario 2, which means an improvement of 50% in the number of connected passengers. It also means that a total of 31 passengers who would lose their connections, even with the FCT, would connect with a better gate assignment, representing an increase of 20 p.p. in this sample.

Table 16 summarizes the Linear Programming Model results, combined with the FCT scenario (Scenario 1). The sample consisted of 623 passengers connecting between 20 and 28 of January 2020 (excluding weekends). Four hundred seventy-three passengers had its connection time between the shortest FCT and the MCT, sample used for Scenario 2. Applying only Scenario 1, the airline could increase 48.15% in the number of passengers connecting. Applying both studies, the airline could increase 69.66% of the number of successful connections, representing in a week 434 more connections.

Day	Total Cnx Passengers	Cnx Maybe (cnx time between RCT and MCT)	Connection with FCT (Study 1)	% Pax connected with FCT	Connected with FCT + PP Optimization (Study 2)	% Pax connected with FCT and PP Optimization
20/jan.	46	32	13	28,26%	32	69,57%
21/jan.	87	87	77	88,51%	82	94,25%
22/jan.	43	43	18	41,86%	43	100,00%
23/jan.	89	52	43	48,31%	47	52,81%
24/jan.	87	86	55	63,22%	81	93,10%
27/jan.	120	76	50	41,67%	74	61,67%
28/jan.	151	97	44	29,14%	75	49,67%
TOTAL	**623**	**473**	**300**	**48,15%**	**434**	**69,66%**

Table 16: Scenarios 1 and 2 Results for Seven days

Table 17 shows that the results represent a potential saving in a year of R$4.200,000.00 ($953,800.00) and an increase of 55 p.p. in the percentage of connected passenger, as shown in Figure 13:

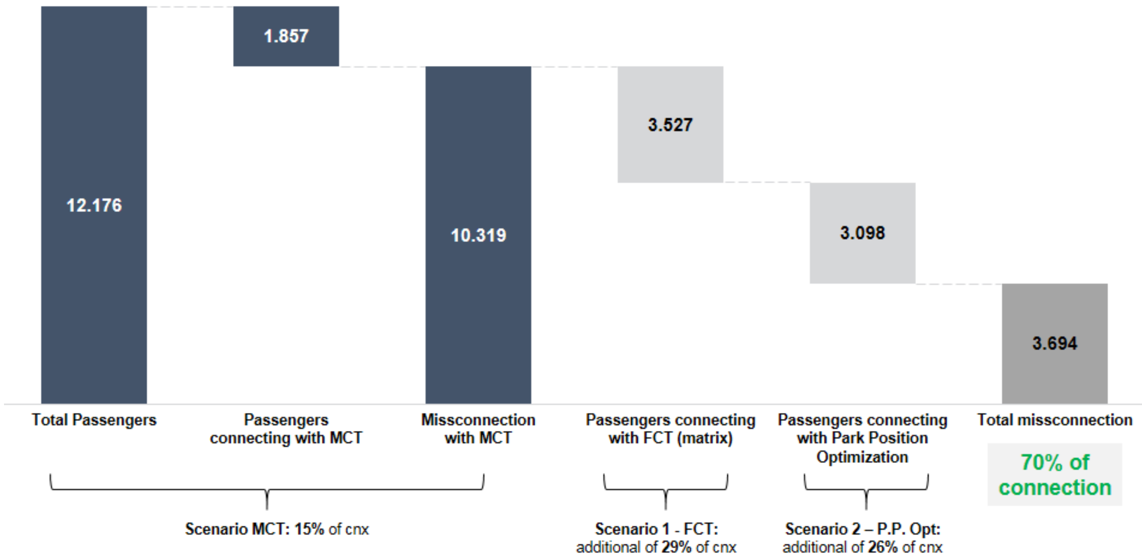

Figure 13: Increase in the Number of Passengers Connected in Scenario 1 and 2

MCT vs FCT	WITH MATRIX (FCT)	WITH LINDO OPTIMIZATION	TOTAL (Study 1+ Study 2)
Connected Variation	**3.527**	**3.098**	6.625
Oportunity Cost (3 months)	R$ 557,266	R$ 489,484	R$ 1,046,750
Oportunity Cost (1 year - R$)	**R$ 2,229,064**	**R$ 1,957,936**	**R$ 4,187,000**
Oportunity Cost (1 year $)	**$ 507,759.45**	**$ 445,999.09**	**$ 953,758.54**

Table 17: Potential Financial Results of Scenarios 1 and 2

Chapter V

Conclusions and Recommendations

This research discussed MCT's concept, a standard time used for network planning and the daily operational decision to connect or disconnect a passenger. When we look further at the airport's day-to-day operation, we learn that the passengers' displacement time varies according to the gates' areas where the original flight arrived. The connecting flight will depart. It suggests that the MCT should be used in the network planning step, but when used in IROP, it can prevent possible connections to happen.

Furthermore, the displacement time between gates is one of the variables that most contribute to lengthening MCT. The research also evaluates the possibility of optimizing both aircraft park positions to shorten the passengers' displacement time and allow more passengers to connect according to the RCT in the FCT Matrix.

When looking deeply at this discussion, the companies can propose a new operational procedure that allows flexibility to connect decision-making, aiming to connect more passengers – respecting the OTP – and avoiding relevant costs regarding 400 ANAC Resolution. A training schedule would be required to implement the new process in the operational area, called HCC. It was a calculated opportunity cost of R$2,229,064.00 ($507,759.45), just considering the FCT instead of the MCT, which means no investment costs necessary, but only training the personnel. To optimize the parking position, the airline would probably need to invest in a programming tool and negotiate the airport operator's execution to have an additional opportunity cost of R$1,957,936.00 ($445,999.09). Based on that, the research suggests that the company first implement the FCT Matrix, once it only involves internal processes changes.

In case of further studies, the researchers could analyze the other variables that compose the MCT, such as making the boarding and deboarding processes faster and the relationship between the aircraft load factor with them. In the end, the idea is to make the FCT shorter to allow more passengers to connect, resulting in more and more savings for the airline.

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Appendix

1. Connection Time Between GRU Airport Gates, Divided by The Type of Connection

Domestic Gates - Domestic Gates						
From/To	GSL	LA	LB	OB	OA	GSO
GSL	00:27:00	00:29:00	00:33:00	00:42:00	00:46:00	00:50:00
LA	00:29:00	00:27:00	00:29:00	00:37:00	00:42:00	00:46:00
LB	00:33:00	00:29:00	00:27:00	00:33:00	00:37:00	00:42:00
OB	00:42:00	00:37:00	00:33:00	00:27:00	00:29:00	00:33:00
OA	00:46:00	00:42:00	00:37:00	00:29:00	00:27:00	00:29:00
GSO	00:50:00	00:46:00	00:42:00	00:33:00	00:29:00	00:27:00

Domestic Gates - International Gates						
From/To	GSL	LA	LB	OB	OA	GSO
GSL	00:58:00	00:56:00	00:55:00	00:58:00	01:00:00	01:01:00
T2IB	00:55:00	00:53:00	00:52:00	00:55:00	00:57:00	00:58:00
T2IA	00:56:00	00:54:00	00:53:00	00:56:00	00:58:00	00:59:00
T3B	01:08:00	01:06:00	01:05:00	01:08:00	01:10:00	01:11:00
T3M	01:10:00	01:08:00	01:07:00	01:10:00	01:12:00	01:13:00
T3A	01:12:00	01:10:00	01:09:00	01:12:00	01:14:00	01:15:00

International Gates - Domestic Gates	
To/ From	Check-in Dom
T2IB	01:42:00
T2IA	01:43:00
T2GS	01:44:00
T3B	01:42:00
T3M	01:44:00
T3A	01:45:00

International Gates - International Gates						
From/ To	T2IB	T2IA	GSL	T3B	T3M	T3A
T2IB	00:42:00	00:42:00	00:43:00	00:42:00	00:42:00	00:43:00
T2IA	00:43:00	00:43:00	00:44:00	00:43:00	00:43:00	00:44:00
GSL	00:45:00	00:45:00	00:46:00	00:45:00	00:45:00	00:46:00
T3B	00:55:00	00:55:00	00:56:00	00:55:00	00:55:00	00:56:00
T3M	00:57:00	00:57:00	00:58:00	00:57:00	00:57:00	00:58:00
T3A	00:59:00	00:59:00	01:00:00	00:59:00	00:59:00	01:00:00

2. Linear Programming Model Detailed Study for January 20, 2020

MIN

```
324A1GSL+348A1LA+396A1LB+504A1OB+552A1OA+600A1GSO+231A2GSL+203A2LA+18
9A2LB+231A2OB+259A2OA+294A2GSO+381A3GSL+377A3LA+399A3LB+501A3OB+553A3
OA+610A3GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A1GSL+A2GSL+A3GSL<=1
A1LA+A2LA+A3LA<=1
A1LB+A2LB+A3LB<=1
A1OB+A2OB+A3OB<=1
A1OA+A2OA+A3OA<=1
A1GSO+A2GSO+A3GSO<=1
END
INT 18
LP OPTIMUM FOUND AT STEP      8
OBJECTIVE VALUE =   890.000000

NEW INTEGER SOLUTION OF    890.000000     AT BRANCH      0 PIVOT       8
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1)      890.0000

VARIABLE        VALUE          REDUCED COST
A1GSL        1.000000        324.000000
A1LA         0.000000        348.000000
A1LB         0.000000        396.000000
A1OB         0.000000        504.000000
A1OA         0.000000        552.000000
A1GSO        0.000000        600.000000
A2GSL        0.000000        231.000000
A2LA         0.000000        203.000000
A2LB         1.000000        189.000000
A2OB         0.000000        231.000000
A2OA         0.000000        259.000000
A2GSO        0.000000        294.000000
A3GSL        0.000000        381.000000
A3LA         1.000000        377.000000
A3LB         0.000000        399.000000
A3OB         0.000000        501.000000
A3OA         0.000000        553.000000
A3GSO        0.000000        610.000000

ROW   SLACK OR SURPLUS     DUAL PRICES
2)         0.000000           0.000000
3)         0.000000           0.000000
4)         0.000000           0.000000
5)         0.000000           0.000000
6)         0.000000           0.000000
```

7) 0.000000 0.000000
8) 1.000000 0.000000
9) 1.000000 0.000000
10) 1.000000 0.000000

NO. ITERATIONS= 8
BRANCHES= 0 DETERM.= 1.000E 0

3. Linear Programming Model Detailed Study for January 21, 2020

MIN
938A1GSL+870A1LA+840A1LB+804A1OB+801A1OA+815A1GSO+927A2GSL+845A2LA+779A2LB+697A2OB+670A2OA+676A2GSO+618A3GSL+614A3LA+678A3LB+864A3OB+964A3OA+1052A3GSO+920A4GSL+840A4LA+740A4LB+580A4OB+540A4OA+580A4GSO+50A5GSL+46A5LA+42A5LB+33A5OB+29A5OA+27A5GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A5GSL+A5LA+A5LB+A5OB+A5OA+A5GSO=1
A1GSL+A2GSL+A3GSL+A4GSL+A5GSL<=1
A1LA+A2LA+A3LA+A4LA+A5LA<=1
A1LB+A2LB+A3LB+A4LB+A5LB<=1
A1OB+A2OB+A3OB+A4OB+A5OB<=1
A1OA+A2OA+A3OA+A4OA+A5OA<=1
A1GSO+A2GSO+A3GSO+A4GSO+A5GSO<=1
END
INT 30

NEW INTEGER SOLUTION OF 2676.00000 AT BRANCH 0 PIVOT 20
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 2676.000

VARIABLE	VALUE	REDUCED COST
A1GSL	0.000000	938.000000
A1LA	0.000000	870.000000
A1LB	0.000000	840.000000
A1OB	1.000000	804.000000
A1OA	0.000000	801.000000
A1GSO	0.000000	815.000000
A2GSL	0.000000	927.000000
A2LA	0.000000	845.000000
A2LB	0.000000	779.000000
A2OB	0.000000	697.000000
A2OA	0.000000	670.000000

A2GSO	1.000000	676.000000
A3GSL	0.000000	618.000000
A3LA	1.000000	614.000000
A3LB	0.000000	678.000000
A3OB	0.000000	864.000000
A3OA	0.000000	964.000000
A3GSO	0.000000	1052.000000
A4GSL	0.000000	920.000000
A4LA	0.000000	840.000000
A4LB	0.000000	740.000000
A4OB	0.000000	580.000000
A4OA	1.000000	540.000000
A4GSO	0.000000	580.000000
A5GSL	0.000000	50.000000
A5LA	0.000000	46.000000
A5LB	1.000000	42.000000
A5OB	0.000000	33.000000
A5OA	0.000000	29.000000
A5GSO	0.000000	27.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	1.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	0.000000	0.000000
11)	0.000000	0.000000
12)	0.000000	0.000000

NO. ITERATIONS= 20
BRANCHES= 0 DETERM.= 1.000E 0

4. Linear Programming Model Detailed Study for January 22, 2020

MIN
29A1GSL+27A1LA+29A1LB+37A1OB+42A1OA+46A1GSO+297A2GSL+261A2LA+243A2LB
+297A2OB+333A2OA+378A2GSO+108A3GSL+116A3LA+132A3LB+168A3OB+184A3OA+20
0A3GSO+1418A4GSL+1298A4LA+1182A4LB+933A4OB+841A4OA+807A4GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A1GSL+A2GSL+A3GSL+A4GSL<=1
A1LA+A2LA+A3LA+A4LA<=1
A1LB+A2LB+A3LB+A4LB<=1
A1OB+A2OB+A3OB+A4OB<=1

```
A1OA+A2OA+A3OA+A4OA<=1
A1GSO+A2GSO+A3GSO+A4GSO<=1
END
INT 24
```

LP OPTIMUM FOUND AT STEP 8
OBJECTIVE VALUE = 1185.00000

NEW INTEGER SOLUTION OF 1185.00000 AT BRANCH 0 PIVOT 8
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 1185.000

VARIABLE	VALUE	REDUCED COST
A1GSL	0.000000	29.000000
A1LA	1.000000	27.000000
A1LB	0.000000	29.000000
A1OB	0.000000	37.000000
A1OA	0.000000	42.000000
A1GSO	0.000000	46.000000
A2GSL	0.000000	297.000000
A2LA	0.000000	261.000000
A2LB	1.000000	243.000000
A2OB	0.000000	297.000000
A2OA	0.000000	333.000000
A2GSO	0.000000	378.000000
A3GSL	1.000000	108.000000
A3LA	0.000000	116.000000
A3LB	0.000000	132.000000
A3OB	0.000000	168.000000
A3OA	0.000000	184.000000
A3GSO	0.000000	200.000000
A4GSL	0.000000	1418.000000
A4LA	0.000000	1298.000000
A4LB	0.000000	1182.000000
A4OB	0.000000	933.000000
A4OA	0.000000	841.000000
A4GSO	1.000000	807.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	1.000000	0.000000
10)	1.000000	0.000000

11) 0.000000 0.000000

NO. ITERATIONS= 8
BRANCHES= 0 DETERM.= 1.000E 0

5. Linear Programming Model Detailed Study for January 23, 2020

MIN
189A1GSL+203A1LA+231A1LB+294A1OB+322A1OA+350A1GSO+273A2GSL+271A2LA+276A2LB+297A2OB+311A2OA+337A2GSO+150A3GSL+138A3LA+126A3LB+99A3OB+87A3OA+81A3GSO+405A4GSL+368A4LA+338A4LB+283A4OB+274A4OA+280A4GSO+693A5GSL+609A5LA+567A5LB+693A5OB+777A5OA+882A5GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A5GSL+A5LA+A5LB+A5OB+A5OA+A5GSO=1
A1GSL+A2GSL+A3GSL+A4GSL+A5GSL<=1
A1LA+A2LA+A3LA+A4LA+A5LA<=1
A1LB+A2LB+A3LB+A4LB+A5LB<=1
A1OB+A2OB+A3OB+A4OB+A5OB<=1
A1OA+A2OA+A3OA+A4OA+A5OA<=1
A1GSO+A2GSO+A3GSO+A4GSO+A5GSO<=1
END
INT 30

OBJECTIVE VALUE = 1382.00000

NEW INTEGER SOLUTION OF 1382.00000 AT BRANCH 0 PIVOT 15
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 1382.000

VARIABLE	VALUE	REDUCED COST
A1GSL	1.000000	189.000000
A1LA	0.000000	203.000000
A1LB	0.000000	231.000000
A1OB	0.000000	294.000000
A1OA	0.000000	322.000000
A1GSO	0.000000	350.000000
A2GSL	0.000000	273.000000
A2LA	1.000000	271.000000
A2LB	0.000000	276.000000
A2OB	0.000000	297.000000
A2OA	0.000000	311.000000
A2GSO	0.000000	337.000000
A3GSL	0.000000	150.000000
A3LA	0.000000	138.000000

A3LB	0.000000	126.000000
A3OB	0.000000	99.000000
A3OA	0.000000	87.000000
A3GSO	1.000000	81.000000
A4GSL	0.000000	405.000000
A4LA	0.000000	368.000000
A4LB	0.000000	338.000000
A4OB	0.000000	283.000000
A4OA	1.000000	274.000000
A4GSO	0.000000	280.000000
A5GSL	0.000000	693.000000
A5LA	0.000000	609.000000
A5LB	1.000000	567.000000
A5OB	0.000000	693.000000
A5OA	0.000000	777.000000
A5GSO	0.000000	882.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	1.000000	0.000000
11)	0.000000	0.000000
12)	0.000000	0.000000

NO. ITERATIONS= 15
BRANCHES= 0 DETERM.= 1.000E 0

6. Linear Programming Model Detailed Study for January 24, 2020

MIN
1077A1GSL+1000A1LA+1028A1LB+1219A1OB+1355A1OA+1483A1GSO+276A2GSL+268A2LA+286A2LB+344A2OB+377A2OA+407A2GSO+976A3GSL+893A3LA+865A3LB+896A3OB+937A3OA+992A3GSO+130A4GSL+116A4LA+103A4LB+83A4OB+85A4OA+95A4GSO+455A5GSL+449A5LA+473A5LB+541A5OB+577A5OA+615A5GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A5GSL+A5LA+A5LB+A5OB+A5OA+A5GSO=1
A1GSL+A2GSL+A3GSL+A4GSL+A5GSL<=1
A1LA+A2LA+A3LA+A4LA+A5LA<=1
A1LB+A2LB+A3LB+A4LB+A5LB<=1

A1OB+A2OB+A3OB+A4OB+A5OB<=1
A1OA+A2OA+A3OA+A4OA+A5OA<=1
A1GSO+A2GSO+A3GSO+A4GSO+A5GSO<=1
END
INT 30
LP OPTIMUM FOUND AT STEP 32
OBJECTIVE VALUE = 2722.00000

NEW INTEGER SOLUTION OF 2722.00000 AT BRANCH 0 PIVOT 32
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 2722.000

VARIABLE	VALUE	REDUCED COST
A1GSL	0.000000	1077.000000
A1LA	1.000000	1000.000000
A1LB	0.000000	1028.000000
A1OB	0.000000	1219.000000
A1OA	0.000000	1355.000000
A1GSO	0.000000	1483.000000
A2GSL	0.000000	276.000000
A2LA	0.000000	268.000000
A2LB	1.000000	286.000000
A2OB	0.000000	344.000000
A2OA	0.000000	377.000000
A2GSO	0.000000	407.000000
A3GSL	0.000000	976.000000
A3LA	0.000000	893.000000
A3LB	0.000000	865.000000
A3OB	1.000000	896.000000
A3OA	0.000000	937.000000
A3GSO	0.000000	992.000000
A4GSL	0.000000	130.000000
A4LA	0.000000	116.000000
A4LB	0.000000	103.000000
A4OB	0.000000	83.000000
A4OA	1.000000	85.000000
A4GSO	0.000000	95.000000
A5GSL	1.000000	455.000000
A5LA	0.000000	449.000000
A5LB	0.000000	473.000000
A5OB	0.000000	541.000000
A5OA	0.000000	577.000000
A5GSO	0.000000	615.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000

5) 0.000000 0.000000
6) 0.000000 0.000000
7) 0.000000 0.000000
8) 0.000000 0.000000
9) 0.000000 0.000000
10) 0.000000 0.000000
11) 0.000000 0.000000
12) 1.000000 0.000000

NO. ITERATIONS= 32
BRANCHES= 0 DETERM.= 1.000E 0

7. Linear Programming Model Detailed Study for January 27, 2020

```
MIN
693A1GSL+609A1LA+567A1LB+693A1OB+777A1OA+882A1GSO+693A2GSL+609A2LA+56
7A2LB+693A2OB+777A2OA+882A2GSO+1354A3GSL+1254A3LA+1158A3LB+942A3OB+84
6A3OA+802A3GSO+162A4GSL+174A4LA+198A4LB+252A4OB+276A4OA+300A4GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A1GSL+A2GSL+A3GSL+A4GSL<=1
A1LA+A2LA+A3LA+A4LA<=1
A1LB+A2LB+A3LB+A4LB<=1
A1OB+A2OB+A3OB+A4OB<=1
A1OA+A2OA+A3OA+A4OA<=1
A1GSO+A2GSO+A3GSO+A4GSO<=1
END
INT 24
```

LP OPTIMUM FOUND AT STEP 11
OBJECTIVE VALUE = 2140.00000

NEW INTEGER SOLUTION OF 2140.00000 AT BRANCH 0 PIVOT 11
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 2140.000

VARIABLE	VALUE	REDUCED COST
A1GSL	0.000000	693.000000
A1LA	0.000000	609.000000
A1LB	1.000000	567.000000
A1OB	0.000000	693.000000
A1OA	0.000000	777.000000

A1GSO	0.000000	882.000000
A2GSL	0.000000	693.000000
A2LA	1.000000	609.000000
A2LB	0.000000	567.000000
A2OB	0.000000	693.000000
A2OA	0.000000	777.000000
A2GSO	0.000000	882.000000
A3GSL	0.000000	1354.000000
A3LA	0.000000	1254.000000
A3LB	0.000000	1158.000000
A3OB	0.000000	942.000000
A3OA	0.000000	846.000000
A3GSO	1.000000	802.000000
A4GSL	1.000000	162.000000
A4LA	0.000000	174.000000
A4LB	0.000000	198.000000
A4OB	0.000000	252.000000
A4OA	0.000000	276.000000
A4GSO	0.000000	300.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000
3)	0.000000	0.000000
4)	0.000000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	1.000000	0.000000
10)	1.000000	0.000000
11)	0.000000	0.000000

NO. ITERATIONS= 11
BRANCHES= 0 DETERM.= 1.000E 0

8. Linear Programming Model Detailed Study for January 28, 2020

MIN
189A1GSL+203A1LA+231A1LB+294A1OB+322A1OA+350A1GSO+108A2GSL+116A2LA+13
2A2LB+168A2OB+184A2OA+200A2GSO+1525A3GSL+1451A3LA+1398A3LB+1203A3OB+1
276A3OA+1308A3GSO+540A4GSL+522A4LA+538A4LB+602A4OB+639A4OA+639A4GSO+1
259A5GSL+1181A5LA+1155A5LB+1158A5OB+1186A5OA+1246A5GSO
ST
A1GSL+A1LA+A1LB+A1OB+A1OA+A1GSO=1
A2GSL+A2LA+A2LB+A2OB+A2OA+A2GSO=1
A3GSL+A3LA+A3LB+A3OB+A3OA+A3GSO=1
A4GSL+A4LA+A4LB+A4OB+A4OA+A4GSO=1
A5GSL+A5LA+A5LB+A5OB+A5OA+A5GSO=1
A1GSL+A2GSL+A3GSL+A4GSL+A5GSL=1
A1LA+A2LA+A3LA+A4LA+A5LA<=1
A1LB+A2LB+A3LB+A4LB+A5LB<=1

```
A1OB+A2OB+A3OB+A4OB+A5OB<=1
A1OA+A2OA+A3OA+A4OA+A5OA<=1
A1GSO+A2GSO+A3GSO+A4GSO+A5GSO<=1
END
INT 30
```

LP OPTIMUM FOUND AT STEP 16
OBJECTIVE VALUE = 3232.00000

NEW INTEGER SOLUTION OF 3232.00000 AT BRANCH 0 PIVOT 16
RE-INSTALLING BEST SOLUTION...

OBJECTIVE FUNCTION VALUE

1) 3232.000

VARIABLE	VALUE	REDUCED COST
A1GSL	1.000000	189.000000
A1LA	0.000000	203.000000
A1LB	0.000000	231.000000
A1OB	0.000000	294.000000
A1OA	0.000000	322.000000
A1GSO	0.000000	350.000000
A2GSL	0.000000	108.000000
A2LA	1.000000	116.000000
A2LB	0.000000	132.000000
A2OB	0.000000	168.000000
A2OA	0.000000	184.000000
A2GSO	0.000000	200.000000
A3GSL	0.000000	1525.000000
A3LA	0.000000	1451.000000
A3LB	0.000000	1398.000000
A3OB	1.000000	1203.000000
A3OA	0.000000	1276.000000
A3GSO	0.000000	1308.000000
A4GSL	0.000000	540.000000
A4LA	0.000000	522.000000
A4LB	1.000000	538.000000
A4OB	0.000000	602.000000
A4OA	0.000000	639.000000
A4GSO	0.000000	639.000000
A5GSL	0.000000	1259.000000
A5LA	0.000000	1181.000000
A5LB	0.000000	1155.000000
A5OB	0.000000	1158.000000
A5OA	1.000000	1186.000000
A5GSO	0.000000	1246.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	0.000000

```
3)        0.000000          0.000000
4)        0.000000          0.000000
5)        0.000000          0.000000
6)        0.000000          0.000000
7)        0.000000          0.000000
8)        0.000000          0.000000
9)        0.000000          0.000000
10)        0.000000          0.000000
11)        0.000000          0.000000
12)        1.000000          0.000000

NO. ITERATIONS=      16
BRANCHES=    0 DETERM.=  1.000E    0
```

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