Acta Manilana 68 (2020), 39–49

ISSN: 0065–1370

Acta Manilana

journal homepage: journals.ust.edu.ph

Solving the air cargo space allocation problem of a digital logistics company by mathematical programming

Ma. Alessandra D. Abaya, Kowji Ann Iekki P. Bajao, Kyra Ashley T. Manuel, Maria Bianca Paris U. Murphy, & Marilyn C. Mabini*

Industrial Engineering Department, Faculty of Engineering, University of Santo Tomas, España Boulevard, 1015 Manila, The Philippines

Graphical Abstract

Abstract

This paper presents an integer quadratic programming model for solving the air cargo allocation problem of a digital logistics company. The objective is to minimize the average annual cost of booking air cargo space, which the subject company pays while also getting the optimal space to be reserved by the company monthly in a year. The model includes constraints on satisfying the demand in terms of gross weight, and the required order multiples. Results for the three destinations selected for the present study by the Operations Department of the company indicate a significant reduction in the average annual air cargo booking cost.

Keywords: air cargo space allocation, logistics, integer quadratic programming

Corresponding author at: Research Center for the Natural and Applied Sciences, University of Santo Tomas, Manila, The Philippines
Email address: *mcmabini@ust.edu.ph*

Introduction

Electronic commerce (e-commerce) has become a widely utilized business platform because of the ever-increasing number of consumers who prefer online transactions. Such transactions include selling products, services, and information through computer telecommunication networks [1].

According to a report by the International Air Transport Association (IATA), e-commerce is a future growth driver for the air cargo industry, as the demand for parcel delivery services increases worldwide through the emergence of online shopping. As the number of online shoppers grows, the need for cross-border parcel transportation increases [2].

Along with these developments, logistics and supply chain management (LSCM) has been continuously improving to cater to the expectations of the consumers in terms of their business dealing experience with the company [3].

Shipping of items can become very expensive, and managing supply chains, logistics, and reverse logistics involved in e-commerce is often complex and involves a lot of factors to consider. This practice has proven to be a challenge for logistics providers to understand the newly emerging trends and patterns in logistics, better anticipate expectations and volumes, and adapt logistics services, network coverage, and service level agreements accordingly.

According to Yuan, Low, & Tang [4], logistics companies do not confine their services to road transport as their only mode of shipment. As mentioned in their study, air cargo industry has grown productively over the last two decades. The same study further indicates that by 2006, airfreight has accounted for approximately 35% of global merchandise trade by value. One of the reasons for this observation is the presence of an industry trend towards the production of high-value lightweight goods.

Boeing, in 2014, foretold that the air cargo market will continue to expand by 4.7% annually and with that, the revenue will triple by 2033. This growth is largely attributed to the expansion in Asian markets [5].

In a study by Huang & Lu [6], it was mentioned that the demand rate for air-cargo transportation is rising as well, and it was forecasted that cargo airplanes would be more in demand. Airlines are now looking for ways to improve their ways and strategies to achieve their business goals related to cargo shipments. The main objectives of those companies are the optimization of aircraft container loading and maximization of goods or parcel allotment per aircraft, which have a significant importance to achieve operations goals and at the same time satisfy safety and stability requirements.

Smith, Gunther, Rao, & Ratliff [7] stated that, "one of the e-commerce principles that was pioneered in the airline industry was the first business-to-business electronic information exchange and marketplace." This principle gave way to operations research (OR) modeling. Airlines used historical shopping data to forecast demand and analyzed strategies with simulation.

In a study by Feng, Li, & Shen [8], it was stated that a typical service flow of air cargo transport begins when cargo is delivered by forwarders to the airport cargo terminal of origin by trucks in containers or as bulk cargo. The cargo is then unloaded and sorted according to its destination, and other information on the shipping documentation, such as weight, dimensions, number of pieces, and type of freight. Finally, the airline transports the cargo to the destination airport.

The processes related to air cargo transport are more intricate compared to passenger transport, since cargo transportation involves more sophisticated procedures and a greater number of data requirements, such as the weight and volume of the items to be transported [9].

He, Leung, Hui, & Chen [10] stated that, "resource planning is a vital aspect of airfreight forwarding." Seventy to ninety percent of logistics costs come from the costs of acquiring air cargo space [11]. The common way for freight forwarders to acquire air cargo space is through allotment bookings, which are done several months in advance. Freight forwarders sign long-term contracts with airline companies, which cover the spaces to be reserved.

In a study by Fok, Ka, Chun, and Wai [12], one of the main objectives of the Cargo Load Plan and Analysis System (CLPA) project was to explore the use of mathematical optimization in improving cargo and mail load factor. Improving the load factor will certainly improve business performance.

Freight forwarders play a big role in the capacity booking model. As stated by Feng, Li, & Shen [13], "the air cargo operations of freight forwarders include specific decision problems, such as capacity booking, supply strategies for airlines, container loading, integration and consolidation strategies, and truck routing and scheduling." Capacity booking must accommodate both long-term contracts and ad hoc demands in consideration of the changing market. Cost is one of the major considerations in making mathematical models for capacity allocation, Patomtummakan & Nananukul [14] explained that fixed costs and surcharge are the factors that affect air cargo fare. Fixed costs include transportation costs, and the surcharge costs are beyond the airlines' control. In addition to the previous study, Gupta [15] also added the factors that affect charges of carriers, which include: volume and type of goods to be transported, competition and season. If the forwarders/shippers' cargo go beyond the allocated space for them, carriers allot extra available spaces but at a higher cost.

Chew, *et al.* [16] developed a stochastic dynamic programming model that determines the optimal short-term space needed to accommodate the uncertain demand given the space from long-term contracts. Their model focused on the short-term problem because demand forecasts can be unreliable and may only be applicable for a specific range of time. Their paper tackles the trade-off between the cost of buying additional air cargo space and the penalty cost of offsetting the excess cargo for the next shipment, which means the orders, will be backlogged. The decision variable in this study was the additional space to be obtained, and the backlogged orders were considered parameters. Also considered were the costs of acquiring additional space, penalty costs of backlogging orders, and the forecasted demand. The study applied the control limits for specific variables (demand, available space, etc.) Results of the study showed that the model can be used to determine the amount of air cargo space needed to strike a balance between the cost of backlogging orders and the cost of having too much space.

The literature on the use of mathematical models for the air cargo capacity booking problem is indeed still limited. The papers found relevant to the present study offer stochastic mathematical models. Among the factors considered in modelling were the following: the demand quantity or volume forecast of shipments, capacity limits, capacity availability, schedule, freight and penalty costs.

Air cargo capacity booking studies normally seek answers to questions on one or more of the following: planning under certainty or uncertainty, maximization of capacity utilization, and minimization of costs.

The article by Chew, *et al.* for short-term capacity booking is most relevant to the present study. Most long-term booking models usually pertain to contracts within the airlines and multiple freight forwarders, which always satisfy the airlines.

The present paper proposes a mathematical model to solve the air cargo space allocation problem of a digital logistics company based in Makati City, Philippines, and serving customers in Luzon, Visayas, and Mindanao. This company is referred to as Company X in this paper. The model is concerned with determining the amount of block spaces to be reserved with airline companies, to minimize annual airfreight costs and accommodate the demands at destinations where air cargo is the company's chosen mode of transporting its orders.

Subject Company

Company X, our subject company in this study, runs a cross-border digital logistics and e-commerce business. It serves as the delivery partner of 124,108 merchants who sell online. The company has multiple hubs in the Philippines; "hubs" are invariably called "destinations" in this study.

The logistics process

The logistics process is shown in Fig 1. The parcels are picked up by riders from different merchants. These parcels are scanned and collected in their designated pick-up hubs and then they are transferred to the sorting center, which is currently located in Pasig. Here, the parcels are registered and sorted according to their designated delivery hubs. For example, when the pick-up area of the parcel is in Pasay City and the delivery area is in Pasig City, the parcel is picked up in Pasay City and sent to the Central Hub, which covers the Pasay City area. It is then transported

Figure 1. The logistics process

to the sorting center where it undergoes the sorting process. The parcels are then transported to the designated delivery hubs and subsequently delivered by riders to the customers.

Around 30–40% of the parcels to be delivered are transported by air. Parcels which are picked up from the hubs located in Luzon and are bound for delivery to hubs located in Visayas and Mindanao are transported via air cargo.

Company X signs a contract with an airline company specifying Block Space Agreements (BSA), which indicate the amount of air cargo space (in terms of kg) reserved by the company for transporting parcels. The yearly contract also contains the freight costs per destination. The chargeable weight, which is the weight to be paid for, depends on which one is greater between the gross weight and the volumetric weight. Gross weight is defined as the actual weight of the cargo while the volumetric weight is the amount of space the cargo occupies when placed inside the aircraft. In cases where both the gross weight and the volumetric weight are lower than the BSA, the company still pays for the BSA which has been reserved. Changes in reservation can be made at least 15 days before the changes take effect.

In situations where the gross weight exceeds the BSA, the excess parcels are transported through general cargo. The time of shipment is not guaranteed when parcels are moved to the general cargo since those parcels would not be on the airlines' priority list. Presently, the decisions made on reserving BSA are only based on historical utilization. There is no systematic model used for computing the optimal BSA for air cargo.

Currently, Company X has seven destinations, three of which have been chosen by the Operations Team of the company for consideration in this study. Henceforth in this paper, the three flight destinations shall be called Destination A, Destination B, and Destination C. Destinations A and B are provinces in the Visayas, while Destination C is a province in Mindanao.

Based on the company's historical data for the said three destinations, the volumetric weight is usually greater than the gross weight. Figure 2 depicts this observation for Destination A. The historical data for Destinations B and C have been found to exhibit a similar trend.

Mathematical formulation

This study uses deterministic mathematical modelling and quantitative analysis for the booking of air cargo space in the perspective of Company X. The booking model is considered deterministic because the input parameters, such as the gross weight, volumetric weight and rates, are assumed known and fixed within the planning horizon identified for this model. The variables in this study are the monthly booking quantities known as the BSAs, and the binary variables introduced to handle the either/or constraints.

The mathematical formulation developed for the problem is non-linear. It is a pure integer quadratic programming (IQP) model with a cost-based objective function, and constraints representing demand and booking policies. The model was solved using LINGO 18.0, a solver by Lindo Systems, Inc.

Assumptions

- The gross weights and volumetric weights are known, and daily fluctuations are reasonably low to justify the use of monthly average values.
- The volumetric weight is higher than the gross weight on a monthly average basis.
- There are 30 operating days each month.
- The monthly BSA rates are known.
- There is ample capacity in the aircraft for the company's BSA reservations.
- There is no budget constraint for airfreight costs across all destinations.
- There is enough warehouse capacity at each destination hub to accommodate the parcels transported there.

Notation

GW_i	Average daily gross weight for month i, kilograms/day
BSA_i	Block Space Agreement (BSA) for month i, kilograms/day
VW_i	Average daily volumetric weight for month i, kilograms/day
$Rate_i$	Airfreight charge for month i, ₱/kilogram
N_i	Integer variable employed to make the BSA for month i, a multiple of 50
X_i, Y_i	Binary variables for the either/or constraints, such that

$$X_i = \begin{cases} 1, & BSA > VW \\ 0, & BSA \leq VW \end{cases} \qquad Y_i = \begin{cases} 1, & BSA \leq VW \\ 0, & BSA > VW \end{cases}$$

Z	Average annual airfreight cost, ₱/year

Mathematical model

The model developed in this study is an IQP model. The objective function to be minimized represents the average annual airfreight cost of the parcels. This cost is a function of the BSA or the volumetric weight, whichever is higher. The model is designed for one destination at a time, since the destinations are independent relative to the air cargo space allocation problem. The model includes constraints to accommodate demand in terms of the gross weight of the parcels to be transported, and to meet desired BSA multiples.

The mathematical model for the air cargo space allocation problem in the present study is given below:

Minimize

$$Z = \Sigma_{i=1}^{30}\ 30 * ((Rate_i * X_i * BSA) + (Rate_i * Y_i * VW_i)) \quad (1)$$

subject to:

$BSA_i * Y_i <= VW_i$,	for i = 1, 2, …, 12	(2)
$BSA_i >= VW_i * X_i$,	for i = 1, 2, …, 12	(3)
$BSA_i >= GW_i$,	for i = 1, 2, …, 12	(4)
$BSA_i/50 = N_i$,	for i = 1, 2, …, 12	(5)
$X_i + Y_i = 1$,	for i = 1, 2, …, 12	(6)
$BSA_i, N_i >= 0$, integer	for i = 1, 2, …, 12	(7)
$X_i, Y_i = 0$ or 1	for i = 1, 2, …, 12	(8)

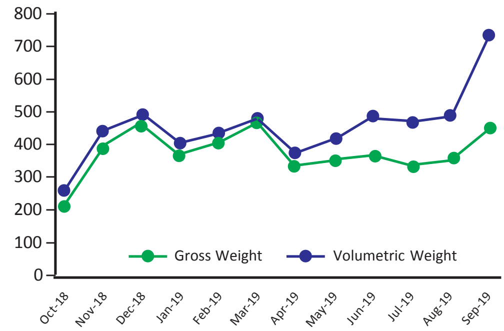

Figure 2. Average daily gross weight and volumetric weight for Destination A.

In (1), the model seeks to minimize the total annual average cost of air cargo space. Constraint sets (2) and (3) are either/or constraints. Constraints (2) ensure that when the value of the BSA is less than or equal to the Volumetric Weight, Y_t will be equal to 1. Constraints (3) are included so that when the value of the BSA is greater than the Volumetric Weight, X_i will be equal to 1. The set of constraints in (4) is applied to ensure that there is enough aircraft space reserved (BSA) to accommodate demand (the gross weight). The constraints in (5) are included for the purpose of generating BSAs which are multiples of 50, as observed in practice at Company X. Constraints (6) are necessary to make the either/or constraint sets in (2) and (3) work. Finally, the set of constraints in (7) provides for the non-negativity and integrality requirements of the variables.

Data

Data were gathered from the historical records of Company X, from inquiries with people in-charge of middle mile operations, and from interviews with the Company's staff working in the loading area for domestic air cargo located in Ninoy Aquino International Airport Terminal 4 (Pasay City, Philippines).

The model was solved for Company X using air cargo transportation data for Destinations A, B, and C, over a period of 12 months, from October 2018 to September 2019. These data are summarized in Table 1, Table 2, and Table 3.

From these Tables, it is evident that the volumetric weight is always greater than the gross weight and the air cargo rates and the current BSAs are usually higher around the peak season (September to December).

Results

The problem was solved using Lingo 18 from Lindo Systems, Inc. The results for the three destinations are given in Table 4, Table 5, and Table 6.

Table 1. Data for 12 months for Destination A

Destination A				
Month (i)	*Rate$_i$ (₱/Kg)*	*GW$_i$ (Kg/mo.)*	*VW$_i$ (Kg/mo.)*	*Current BSA (Kg/mo.)*
Oct 2018	20	203	252	500
Nov 2018	20	390	435	500
Dec 2018	20	463	483	500
Jan 2019	20	364	397	500
Feb 2019	19	400	425	400
Mar 2019	19	452	472	400
Apr 2019	19	326	364	400
May 2019	19	347	412	400
Jun 2019	19	358	479	400
Jul 2019	19	327	462	400
Aug 2019	19	348	483	500
Sep 2019	20	447	731	500

Table 2. Data for 12 months for Destination B

Destination B				
Month (i)	*Rate$_i$ (₱/Kg)*	*GW$_i$ (Kg/mo.)*	*VW$_i$ (Kg/mo.)*	*Current BSA (Kg/mo.)*
Oct 2018	20	883	1055	1400
Nov 2018	21	1566	1751	2000
Dec 2018	21	1632	1708	2000
Jan 2019	19	1328	1632	1400
Feb 2019	19	1444	1523	1400
Mar 2019	19	1496	1564	1400
Apr 2019	19	1043	1159	1400
May 2019	19	1086	1242	1400
Jun 2019	19	1150	1500	1400
Jul 2019	19	1144	1610	1400
Aug 2019	19	1334	1697	1400
Sep 2019	20	1353	1771	1400

Table 3. Data for 12 Months for Destination C

Destination C				
Month (i)	*Rate$_i$ (₱/Kg)*	*GW$_i$ (Kg/mo.)*	*VW$_i$ (Kg/mo.)*	*Current BSA (Kg/mo.)*
Oct 2018	29.5	414	525	1000
Nov 2018	31	821	1007	1000
Dec 2018	31	896	984	1000
Jan 2019	27	794	823	1000
Feb 2019	27	791	805	850
Mar 2019	27	850	896	850
Apr 2019	27	749	820	850
May 2019	27	837	994	850
Jun 2019	27	923	1249	850
Jul 2019	27	748	1087	850
Aug 2019	27	804	1096	850
Sep 2019	29.5	862	1333	1200

Table 4. Optimal solution to the problem for Destination A

Destination A					
Month	*BSA$_i$ (Kg/mo.)*	*X$_i$*	*Y$_i$*	*N$_i$*	*Z (₱/year)*
Oct 2018	250	0	1	5	₱3,160,050.00
Nov 2018	400	0	1	8	
Dec 2018	500	1	0	10	
Jan 2019	400	1	0	8	
Feb 2019	400	0	1	8	
Mar 2019	500	1	0	10	
Apr 2019	350	0	1	7	
May 2019	400	0	1	8	
Jun 2019	400	0	1	8	
Jul 2019	400	0	1	8	
Aug 2019	400	0	1	8	
Sep 2019	550	0	1	11	

Table 5. Optimal solution to the problem for Destination B

Destination B					
Month	*BSA$_i$ (Kg/mo.)*	*X$_i$*	*Y$_i$*	*N$_i$*	*Z (₱/year)*
Oct 2018	950	0	1	19	₱10,673,160.00
Nov 2018	1650	0	1	33	
Dec 2018	1700	0	1	34	
Jan 2019	1500	0	1	30	
Feb 2019	1450	0	1	29	
Mar 2019	1550	0	1	31	
Apr 2019	1100	0	1	22	
May 2019	1150	0	1	23	
Jun 2019	1500	1	0	30	
Jul 2019	1400	0	1	28	
Aug 2019	1500	0	1	30	
Sep 2019	1550	0	1	31	

Table 6. Optimal solution to the problem for Destination C

Destination C					
Month	*BSA$_i$ (Kg/mo.)*	*X$_i$*	*Y$_i$*	*N$_i$*	*Z (₱/year)*
Oct 2018	450	0	1	9	₱9,789,660.00
Nov 2018	900	0	1	18	
Dec 2018	950	0	1	19	
Jan 2019	800	0	1	16	
Feb 2019	800	0	1	16	
Mar 2019	850	0	1	17	
Apr 2019	800	0	1	16	
May 2019	900	0	1	18	
Jun 2019	1050	0	1	21	
Jul 2019	900	0	1	18	
Aug 2019	950	0	1	19	
Sep 2019	1100	0	1	22	

Table 7. Cost comparison of present system and proposed system for Destination A.

Destination A			
Month	*(1) Actual airfreight cost (in ₱)*	*(2) Cost computed from Z using actual BSA & optimal X_i & Y_i (in ₱)*	*(3) Optimal cost from the model (in ₱)*
Oct 2018	310,040.00	300,000.00	151,200.00
Nov 2018	368,500.00	300,000.00	261,000.00
Dec 2018	337,980.00	300,000.00	300,000.00
Jan 2019	318,706.00	285,000.00	228,000.00
Feb 2019	274,949.00	242,250.00	242,250.00
Mar 2019	296,704.00	269,040.00	285,000.00
Apr 2019	226,214.00	228,000.00	207,480.00
May 2019	255,094.00	234,840.00	234,840.00
Jun 2019	278,350.00	273,030.00	273,030.00
Jul 2019	288,857.00	263,340.00	263,340.00
Aug 2019	329,042.00	285,000.00	275,310.00
Sep 2019	475,260.00	438,600.00	438,600.00
TOTAL	**3,759,696.00**	**3,419,100.00**	**3,160,050.00**

Table 8. Cost comparison of present system and proposed system for Destination B

Destination B			
Month	*(1) Actual airfreight cost (in ₱)*	*(2) Cost computed from Z using actual BSA & optimal X_i & Y_i (in ₱)*	*(3) Optimal cost from the model (in ₱)*
Oct 2018	894,840.00	840,000.00	633,000.00
Nov 2018	1,383,615.50	1,260,000.00	1,103,130.00
Dec 2018	1,321,782.00	1,260,000.00	1,076,040.00
Jan 2019	2,973,974.00	930,240.00	930,240.00
Feb 2019	890,758.00	868,110.00	868,110.00
Mar 2019	985,150.00	891,480.00	891,480.00
Apr 2019	774,174.00	798,000.00	660,630.00
May 2019	831,516.00	798,000.00	707,940.00
Jun 2019	907,288.00	855,000.00	855,000.00
Jul 2019	993,415.00	917,700.00	917,700.00
Aug 2019	1,032,498.00	967,290.00	967,290.00
Sep 2019	1,239,720.00	1,062,600.00	1,062,600.00
TOTAL	**14,228,730.50**	**11,448,420.00**	**10,673,160.00**

Table 4, Table 5, and Table 6 show the optimal solutions for Destinations A, B, and C, respectively. The pattern observed for the BSA values for all destinations is consistent with the corresponding pattern for the respective gross weight per month, meaning the greater the gross weight, the higher the BSA. As expected, Y_i values are mostly equal to 1, which happens when the volumetric weight exceeds the gross weight. For the months where X_i is equal to 1, the BSAs are higher than the volumetric weights.

Table 7, Table 8, and Table 9 show a cost comparison among (1) the actual cost paid by the company, (2) the cost computed using the model solution for X_i and Y_i and the actual BSAs, and (3) the optimal cost from the proposed mathematical model for each of Destinations A, B, and C, respectively.

Table 9. Cost comparison of present system and proposed system for Destination C

Destination C			
Month	*(1) Actual airfreight cost (in ₱)*	*(2) Cost computed from Z using actual BSA & optimal X_i & Y_i (in ₱)*	*(3) Optimal cost from the model (in ₱)*
Oct 2018	914,500.00	885,000.00	464,625.00
Nov 2018	1,090,549.00	936,510.00	936,510.00
Dec 2018	1,067,733.00	930,000.00	915,120.00
Jan 2019	709,911.00	810,000.00	666,630.00
Feb 2019	716,202.00	688,500.00	652,050.00
Mar 2019	802,548.00	725,760.00	725,760.00
Apr 2019	719,415.00	688,500.00	664,200.00
May 2019	923,319.00	805,140.00	805,140.00
Jun 2019	1,026,756.00	1,011,690.00	1,011,690.00
Jul 2019	928,800.00	880,470.00	880,470.00
Aug 2019	943,056.00	887,760.00	887,760.00
Sep 2019	1,219,677.50	1,179,705.00	1,179,705.00
TOTAL	**11,062,466.50**	**10,429,035.00**	**9,789,660.00**

It is clear in Table 7, Table 8, and Table 9 that the minimum annual cost is given by the solution from the proposed model, for each of the three destinations. The actual freight cost paid by the company is higher than the cost computed using the model solution for X_i and Y_i and the actual BSAs. This means that if the proposed model is applied in their actual operation, then the company would still have paid lower than they paid originally.

Conclusion

The study has addressed the air cargo space allocation problem of a digital logistics company based in Makati City, Philippines, and servicing customers throughout the country. The company, called Company X in this study, currently plans its BSAs with its contact airline companies, based on historical utilization.

Company X needs a more effective and reliable approach to find the monthly BSAs which will meet the demand-driven air cargo space requirements. An IQP model has been developed in this study to address this need.

The model was tested and solved using LINGO 18.0, an optimization software from Lindo Systems, Inc. Optimal BSAs were found for Destinations A, B, and C, the air cargo destinations chosen by Company X for this study. The optimal air cargo costs for these destinations were found to be significantly lower than the corresponding actual costs.

There are at least three good reasons to recommend to Company X, the adoption of the Operations Research based approach in this study for solving the air cargo space allocation problem:

1. The IQP model developed for the said purpose consistently generated a significantly lower cost solution for each of the three destinations considered.
2. Whereas the said IQP model is deterministic, employing average values for monthly gross and volumetric weights, the same model can easily be extended to cover daily transactions, thereby capturing daily fluctuations in gross and volumetric weights, and more. This exercise was actually done in the model verification phase of this study.
3. The IQP model in this study can be used for BSA planning, where changes in gross and volumetric weights and airfreight charges are expected, provided the new values for these parameters are known.

For future research, the stochastic properties of the air cargo space allocation problem may be investigated and an appropriate model developed.

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