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# Optimizing Air Cargo Load Planning and Analysis

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## ABSTRACT

This paper describes our work in using mathematical optimization to assist air cargo load planning for an air cargo company, one of the world's top 10 air cargo carriers. The airline handles roughly 80 to 90 thousand tones of cargo each month. With this volume of cargo, even the slightest improvement in the load planning process will have a major impact to overall performance and efficiency. In this project, we developed a Web-based application to firstly perform long-term forecasting based on an analysis of historical data and then secondly operational load planning with mathematical optimization. Forecasting is important as the data will assist the airline in drafting its long-term contracts and determination of allotments. Load planning, on the other hand, is for operational term planning of how ULDs (Unit Load Devices – air cargo containers/pallets) are loaded into aircrafts. This process is usually done roughly 2 hours before departure when all the details of the cargo are present. Therefore, the performance of the application is crucial. In this project, in order to help users to get more data dimensions to analyze, a data warehouse was built. Load planning was performed using MATLAB and Mosek.

**Keywords**: Operations Research, Optimization, Air Cargo, Load Planning, Load Analysis.

## 1. INTRODUCTION

One of the main objectives of this Cargo Load Plan and Analysis System (CLPA) project is to investigate how cargo and mail load factor [7, 8] can be improved through the use of mathematical optimization. Obviously, improving load factor will directly impact business performance.

For air cargo, many factors and parties can have an effect on the cargo load factor. Starting from sales – how their allotments are distributed to different ports/stations, the terms of the long-term agent contracts, the amounts of the bookings – all these decisions affect both cargo loading and the most importantly cargo revenue. Once cargo arrives at the airport, the efficiency which staffs collect the pre-packed containers, how they queue up goods to fill the container, the way they help pack goods into ULDs, all affect the utilization of the containers [5].

Next, the Cargo Space Division helps plan which container should be loaded. The weights of all the containers going into an aircraft are known. Cargo Space uses this list of containers to prioritize preferences and how the cargo will be loaded. Constraints relating to transit goods and allotments are considered. These constraints can sometimes lead to under-loading of aircrafts. The last party involved in this cargo loading process is the Load Control Section. They perform load-balancing of the aircraft. In some cases, containers might need to be offloaded and will lead to under-loading.

Our project objective is to design a software application to help evaluate actual flight utilization from the Cargo Sales Department to the Cargo Space Control.

The CLPA System is a decision support system that can be used to evaluate past historical data on cargo space utilization so as to plan for long-term cargo sales strategies, such as cargo allotment, contract amount with cargo agents and cargo rating. CLPA will also be used during operations to formulate the load plan using booking data to perform space optimization. At the current stage of the project, CLPA is only being tested for cargo load planning of passenger planes.

## 2. RESEARCH BACKGROUND

There are many approaches to solve the cargo loading problem. We will compare a few popular approaches and then explain our approach. Without computer systems, airlines have to rely on human expertise for cargo load planning. Unfortunately, the quality of the load plan will greatly depend on the experience of the person on duty [5]. For simple cases [4], the quality of the plan did not really have an impact. However, as the weight and volume to be carried increases, the task becomes increasingly complex.

**Heuristic Methods**

One computerized approach is to use Heuristic Methods. This can generate a reasonably good solution in a short time. Larsen and Mikkelsen [11] and Amiouny et al. [1] have suggested heuristic approaches to determine a feasible load plan for a single aircraft. Larsen and Mikkelsen [11] developed an interactive, computer-based procedure for solving variant of vehicle loading problem encountered when loading containers and pallets into an aircraft. It used two heuristics concerning ground stability, combined load limits, position and compartment capacity constraints and balance.

Amiouny et al. [1] presented an approach for the one-dimensional loading problem where the constraint is to balance around the aircraft's midpoint. It is concerned with the following cases, (a) all given containers must be loaded; (b) containers are to be positioned on a one-dimensional hold. The problem considered was airlift cargo, which must be entirely loaded, in a specified prioritized sequence (through branch and bound – take into account of expertise of highly trained loadmasters.) Martin-Vega, L.A. [12] mainly focused on generating a feasible plan rather than an optimal one. It considered a manually dominated process. The heuristic method involves experienced ground personnel trying to obtain an acceptable loading (satisfy the above stated constraints) by manual trial and error process without maximizing.

Clive Thomas, Kevin Campbell, Gail Hines, Michael Racer for Federal Express [4] developed a heuristic method (with branch-and-bound) for loading containers into positions on the aircraft to address loading preferences and maintain feasibility constraints – determine a feasible packing which minimized nonproductive time. Time is a critical factor for overnight couriers, such as Federal Express. Their ground crews usually start packing planes even before all the containers arrive. However, this assumption may not be applied for airlines. Before all the containers arrive, airline ground crew need to load baggage containers, mail containers and containers with preferred positions (e.g., transferred containers offloaded in next leg). Moreover, in Hong Kong, the distance from the container packing area to the plane is short. Therefore, we assume containers with no preferred position would not be preloaded before the load plan is issued.

Moreover, [4] is concerned with the loading of lighter and more fuel efficient aircrafts. Therefore, there is no static limit on the weight to be placed in each cargo zone: the zone limits on the weight are a stepwise-linear function of the center of gravity. This yields nonlinear constraints on the position of the center of gravity. In order to avoid an integer nonlinear programming problem, they assumed, in a phase-1 sub-problem, that the list of containers to be loaded was, again, known a priori. This phase-1 sub-problem must then be repeatedly solved after removing containers from the list until the feasible packing was found. The heuristic method they presented used a spreadsheet interface to find a solution satisfied the constraints (rather than maximizing the weight loaded). When it is not possible to solve in phase1, the ground crew must select one or more containers to remove from the set (and repeat phase 1). Preferred-positions constraints were then added in phase 2. Such constraints were recursively removed until a feasible load plan was found.

According to Uwe H. Suhl and Leena M. Suho [10], in order to solve airline-fleet scheduling problems with mixed-integer programming, they have proposed the following heuristic algorithms:

- First-in-first-out (FIFO): the aircraft which arrived first, will leave first
- Last-in-first-out (LIFO): the aircraft which arrived last, will leave first
- Best-first (BF): choose that flight from available (not yet planned) flights which can be flown by an aircraft with the shortest standing time

The heuristics they stated could also be applied to load planning:

- First-in-first-out (FIFO): the filled container which arrived first, will leave first
- Last-in-first-out (LIFO): the filled container which arrived last, will leave first
- Best-first (BF): choose filled container from available (not yet planned) list which high priority of the container is loaded first.

FIFO and LIFO are used when time is the main constraint of loading and all are "express" goods whereas space is a low cost factor. However, these heuristics could not be applied to airlines as space is expensive. In addition, the best-first method proposed above ignores the factors of center of gravity and load balancing.

**Optimization Algorithms**

Marcel Mongeau and Christian Bes [3] addressed the problem of cargo loading and load balancing with the objective to minimize fuel consumption and to satisfy stability and safety requirements. Their formulation methodology solved this problem within 10 minutes using off-the-shelf integer linear programming software.

Given a list of containers, with their respective weights and volumes, a subset of the containers must be assigned to a finite number of possible container locations (also given, for the specific aircraft under consideration) in the cargo holds [3]. The two following objectives were optimized:

1. as much weight as possible should be loaded - for airline companies, freight income is generally related to the weight loaded, as opposed to volume.
2. the resulting center of gravity of the aircraft should be as far aft as possible - to minimize fuel consumption, but not behind a limit imposed by stability requirements.

Various constraints had been included in the mathematical formulation [3], like structural constraints including compartment-volume and compartment-weight capacities, and total aircraft maximal weight once loaded. The allowable total weight depends on the weight of the empty aircraft plus passengers, fuel, and bulk freight. For instance, a given subset of the container list can be specified to be loaded. Furthermore, some given containers for which can be constrained would be placed in some specified compartments. Other constraints that can easily be modeled include requiring some given containers, already loaded by the ground crew, not to be displaced, in order to expedite the plane's departure (where time is critical factor). $M_{misc}$

[3] purposed use mathematical programming formulation for addressing aircraft container loading – solved by optimality, not by heuristic method. Unlike assumptions made in [1, 13, 14], they did not assume that the containers to be loaded are known a priori. The system determines which containers are to be loaded and which are to be left on the ground for a subsequent flight.

**Algorithm Used in This Project**

We decided to also use an optimization algorithm, as it considers all factors that affects load planning, i.e. efficient use of space and load balancing, center of gravity, etc., to make the best load plan. All factors are included using integer programming to determine the optimal load plan – minimize remain capacity (under-load).

This project extends the work of Marcel Mongeau and Christian Bes [3] in the following areas:

- Passenger and fuel weights may be changed in the final decision. For an airline, the number and weights of passengers are the critical factors affecting the load plan. Therefore, constraints relating to passengers' weights and fuel are separated in our model.
- Mainly focus on minimizing under-load, rather than to maximize total cargo load.
- Lists out the containers identifier, its location and the configuration chosen (e.g. 4 containers 1 pallets) and generates the load plan sheet.
- Our system assigns priority to different cargo. Cargo like express cargo, firmed booking, etc. should have a higher priority.
- In Hong Kong, the hold and compartment concepts proposed by [3] are different. Our system uses the local hold and compartment data.

## 3. OPTIMIZATION ALGORITHM

The CLPA System aims at minimizing the cargo loading residual (i.e. under-load) – $M_{res}$. A linear program model similar to [3] is used. The system has the following input data:

$N_{cont}$ - number of containers on the list (with priority)
$N_{comp}$ - number of compartments
$N_{hold}$ - number of holds
$H_k$ - ($\subseteq\{1,2,\ldots, N_{hold}\}$) are the holds in compartment k ($k = 1,2,\ldots., N_{comp}$)
$M_a$ - mass of the aircraft (before loading)
$M(x)$ - mass of cargo loaded
$M_{res}$ - mass of residual (i.e. under-load)
$M_i$ - mass of container i ($I = 1,2,\ldots, N_{cont}$)
$M_{pax}$ - mass of the total number of aircraft passengers
$M_{fuel}$ - mass of fuel injected into the aircraft
$M_{misc}$ - mass of other miscellaneous items (example: mail, baggage, etc)
$M_{max}$ - maximal mass of freight that can be loaded

$M_{max}^{k}$ maximal mass of freight that can be loaded in compartment k (k = 1,2,…., N compartment)

In addition, we also have the following information provided by aircraft manufacturers:

1. The dimensions and weight of each of the given $N_{cont}$ containers
2. All the possible locations of the containers in the cargo holds
3. A given subset I of the container list that the user wishes to be loaded (containers that cannot be left on the ground). This would impose additional freight constraints.
4. List of couples (i,k) for any given container i that the user wants to be in a specific hold k. This allows for the possibility of requiring some given containers, already loaded by the ground crew, not to be displaced so as to expedite the plane's departure.

Besides the above, we also have the optimization variables (decision variables), which are binary: $x_{ij} \in \{0,1\}$. The value is 1 if container i is to be placed in hold j, and 0 otherwise (i=1,2,…., $N_{cont}$; j=1,2,…., $N_{hold}$).

To achieve our objective, the total mass residual can therefore be presented in the following mathematical form to minimize $M_{res}$:

Minimize $M_{res}$ subject to $M_{max} - (M_{pax} + M_{fuel} + M_{misc} + M(x))$ where $M_{res} \geq 0$ and M(x) is:

$$M(x) = \sum_{I=1}^{N_{cont}} \sum_{J=1}^{N_{hold}} M_i X_{ij}$$

Behind this mathematical model, there are different kinds of physical constraints defining the center of gravity and load and shear restrictions. There are also aircraft constraints [3] that define the mass capacity, uniqueness constraints that restrict each cargo to be loaded only once, freight constraints that determines what needs to be loaded, and volume capacity constraints that depends on the aircraft type.

To sum up, we should bear in mind that we are focusing on volume and weight restrictions. However, realistic solution must rely on additional constraints that depend on the specifications of the aircraft. For instance, the need for balance, axle weight restrictions, pounds per linear-foot limits, dangerous goods restrictions and so on.

Our CLPA System provides user with the optimal values of cargo weight, number of small (container) and large (pallet) pieces of cargo that can be loaded, and minimum value of under-load in a user-friendly and real-time manner, while considering all the various criteria and conditions for each flight. The system uses iterative integer programming to generate optimal values.

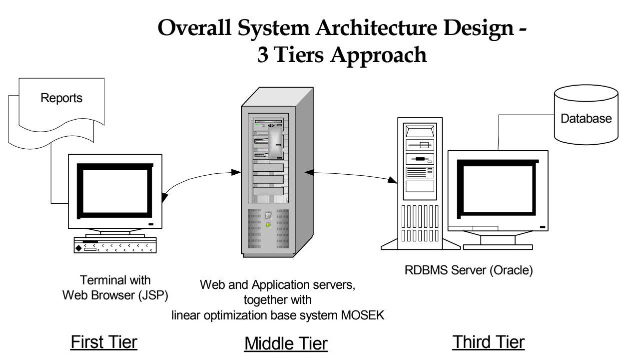


Fig.1. Overall Architecture of CLPA

# 4. SYSTEM DESIGN

The CLPA System has a three-tiered architecture (see Fig.1). Users interact with CLPA via a standard Web-browser. Client pages were implemented as JSP pages.

The backend database warehouse was implemented using Oracle. Two factors are important for load planning: weight and capacity. Therefore, the design of the database warehouse and reports highlight columns for under-load (i.e. total weight – fuel weights – passenger weights – cargo weights), no fit (i.e. total space – space occupied), baggage ratio (use to estimate the weight left for cargo) and passenger load factor. This data warehouse has 9 dimensions tables for analysis:

1. Carrier Dimension: if the company is a group company, users could use this dimension to compare the result for each of their subsidies.
2. Flight Dimension: this table contains static data related to that flight, like flight type, departure and arrival date and time, aircraft type, aircraft tail. This dimension could help users to compare the loading result among each flight.
3. Position Dimension: this is a static table showing all positions in the upper deck and main deck, and for different aircraft type.
4. Cargo Type Dimension: this is also a static table showing the cargo type by using AHM 510. It contains over 20 cargo types. In order to analyze data easily, I have grouped load data by using the column cargo type group, like BAGGAGE, CARGO, MAIL, OTHERS. By using this dimension, user could identify their revenue items, i.e. in cargo session, CARGO and MAIL would be identified and could compare the trends by different flights and date.
5. Date Dimension: this is a static table and should be reused by other data warehouses. By using this date dimension table, users could compare all data by day, by week, by month and by year. For the airline industry, by day of week is also important because weekend results are usually quite different to weekday results.
6. Deck Version Dimension: this is a static table to store the flight capacity for each aircraft type / aircraft tail number.
7. Container Dimension: this table could find container tare weight (empty container weight) for analysis, and also some special categories and requirements will be put under this table
8. SPL Dimension: this table could help users to highlight some cargo with special handling codes, like AAX (express), BUP, for comparison and to see the trend
9. Station Dimension: this dimension could be reused by other data warehouses to help users analyzing data by station, region, and country. In this project, this dimension could also help to identify those ex-HKG and in-HKG flights.

In terms of workflow, the following processes are supported:

- Raise request to prepare cargo load plan – gather flight and cargo information
- Perform load planning and analysis - submit user requirements into the system, based on the pre-defined business logics and constraints. Information is collected from both the user and backend database
- Suggest optimal solution - system generates the optimal solution to the user for decision making. Results are presented as Web pages.
- Execute the plan – users, based on suggested plan, perform physical cargo arrangement within the holds. Aim to minimize the cost of under load.

Figure 2 shows the key features offered by the CLPA System.

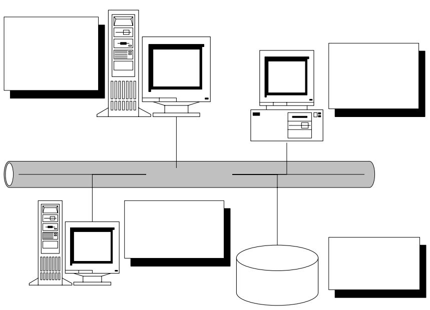

Fig. 2. – Key Features of the CLPA System

There are numerous screens in CLPA to display various analysis and forecasting results. Figure 3, shows the final results from the mathematical optimization. The user can also display an aircraft floor plan to visualize the results.

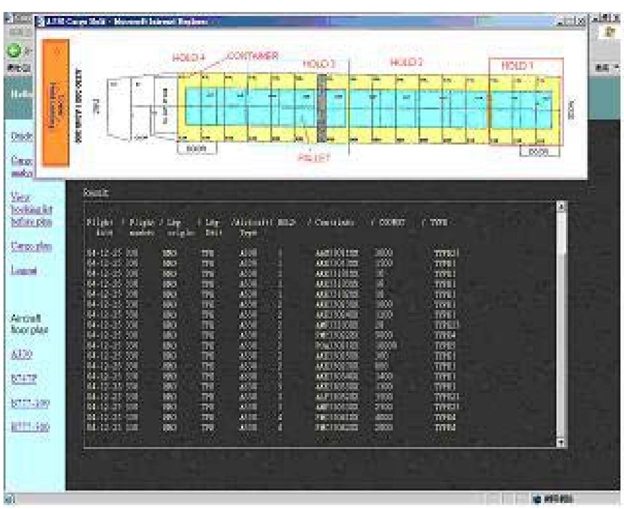


Fig. 3. – Results Displayed in CLPA System

## 5. PERFORMANCE

For the current research version of CLPA, the performance is already quite acceptable. Load analysis on roughly 36,000 records in the data warehouse took 10 to 20 seconds, depending on the analysis performed. Load planning for a single aircraft took, on average, roughly 40 seconds on a PC-class server.

## 6. CONCLUSIONS

In this paper we presented the design and prototype of a Web-based application for air cargo load analysis and planning, which we call the CLPA System. The project verified the technical and performance feasibility of using mathematical optimization for the complex and time critical task of aircraft load planning. Actual data from air cargo company was used for testing. The ability to return an optimized plan within less than a minute was totally acceptable to the user.

## 7. ACKNOWLEDGEMENT

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