Fleet Sizing for Large Express Shipment Airlines

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Recently, express shipment airlines such as FedEx Express and the United Parcel Service (UPS) have begun upgrading their aircraft fleets by buying large numbers of new freighter aircraft. This marks a shift in the aircraft acquisition practices of these companies, which previously enlarged their fleets by retrofitting retired passenger aircraft. This shift to buying more expensive new aircraft leads to the question, "Given a current aircraft fleet, which aircraft should be retired, and which aircraft should be purchased to improve the fleet's performance?" This work presents an analysis to answer that question using a detailed operations optimization model, and demonstrates the effectiveness of that approach by modeling a full day of operations for a realistically-sized fictitious express shipment airline. Finally, we compare the effect of adding from one to ten additional candidate aircraft of four different aircraft types to a baseline fleet in terms of the reduction in objective function value, daily operating cost and fleet size.

I. Introduction

Express shipment carriers such as FedEx, the United Parcel Service (UPS) and Deutsche Post DHL fly forty percent of the widebody freighters within the air cargo industry.[1] Recently, aging aircraft and high operating costs have encouraged express shipment airlines to upgrade their aircraft fleets. In the past, these companies typically purchased retired passenger aircraft and retrofitted them as freighter aircraft. Now, express shipment carriers have begun buying large numbers of new aircraft. For example, in 2015, FedEx announced an agreement with The Boeing Company to buy fifty new 767-300F aircraft with an option to buy up to fifty more.[2] That constitutes the largest single order for the 767 since it came onto the market in 1982.[3] Additionally, UPS and Boeing recently announced a deal to buy fourteen Boeing 747-8F freighter aircraft for $5.3 billion, thus revitalizing the previously slumping 747 production line.[4] These recent large purchases show a shift in the aircraft acquisition practices of express shipment airlines.

This work explores the primary upgrade-related question facing these express shipment airlines: "*Given a current aircraft fleet, which aircraft should be retired, and which aircraft should be purchased to improve the fleet's performance?*" This paper presents an approach to answer this question using an operations model that captures the interconnected package routing, fleet allocation and flight scheduling needs of large express shipment airlines, and demonstrate its effectiveness using a realistically-sized data set.

II. Express Package Delivery Operations

Figure 1 shows the series of activities express shipment companies use to move packages from their origins to their destinations. A package first enters the custody of the package delivery company at a pick up location such as a shipping location, private residence, office building, etc. The package is then transported via small ground vehicle to an origin station[a], where all local packages are sorted by service type (express, ground, etc.). The express packages are then transported via truck to a nearby airport. This airport is the collection point for all of the stations in a region. The packages are then loaded onto aircraft and flown to a large sorting facility located a hub airport. At the sorting facility, all of the aircraft are unloaded and packages bound for the same destination are consolidated and repacked into shipping containers bound for

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[a]Stations are alternatively called "ground centers."

their destination. After the sorting is completed, a similar process is used for delivery: aircraft deliver the consolidated packages to the destination airport and from the destination airport; then packages are moved via truck to a destination station where they are loaded onto a small ground vehicle for final delivery.

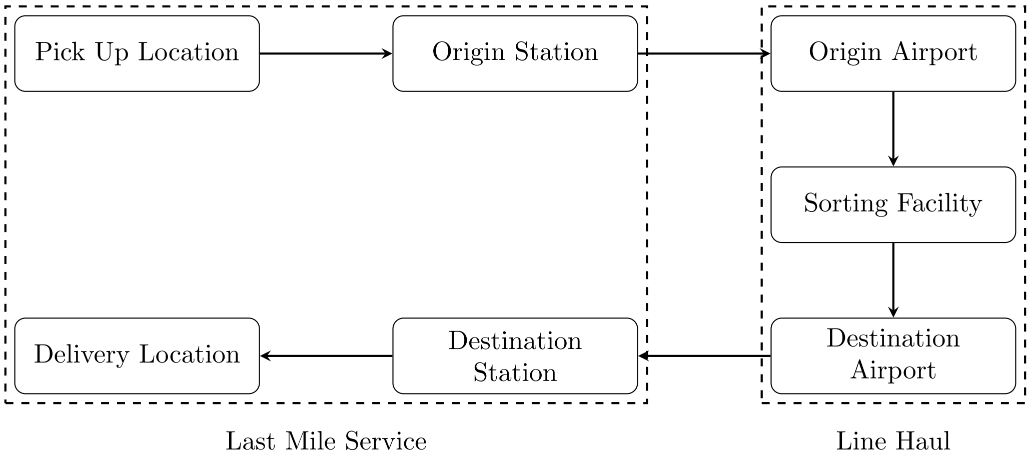


Figure 1: Package activities from origin to destination

The package routing activities can be categorized into two groups: 1) last mile service, and 2) line haul. Last mile service is local, ground-based service that interfaces directly with the customer. Line haul service is what moves the packages between local regions and is done primarily by aircraft for express shipment packages.[b] This work will focus on the line haul portion of the package activity sequence.

Express shipment airlines fly (nearly exclusively) in hub-and-spoke or multi-hub-and-spoke networks. Operating in a point-to-point network would be prohibitively expensive and necessitate an exceptionally large number of flights, many of which would be only lightly loaded. With the hub-and-spoke network topology, all package sorting can happen in bulk, thus better utilizing the sorting equipment, manpower and aircraft fleet.

III. Approach Overview

The decision to retire or purchase a aircraft has major financial implications for an airline. In an ideal model, the ripple effects of such a decision could be captured through every facet of the company. Such a model would provide decision makers the best possible understanding of their choices and reduce the uncertainty in their decision.

Unfortunately, such a model is computationally intractable. Large express shipment companies operate large international fleets that move millions of packages each day and employ thousands of people.[5] To model every facet of their operations including package routing, fleet allocation, flight scheduling, crew scheduling, maintenance scheduling, ground operations, hub operations, last mile delivery, etc. would create such a complex model that no information could be computed in a useful time frame. Not only are the companies large, but they have so many "moving parts" that capturing the whole picture is not practical.

In light of these intractability issues, we chose to focus on the three most critical facets: package routing, fleet allocation and flight scheduling. This was for three reasons. First and foremost, without those three aspects, the other aspects of the airline would be meaningless and thus they form a good foundation for future expansion. Second, all three facets are closely intertwined and cannot be meaningfully separated. Third, this study focuses on the effects of upgrading the aircraft fleet on express shipment operations, so it was critical that at least the first-order effects of those decisions were captured in the model. Of all the aspects of express shipment operations, fleet allocation, flight scheduling and package routing are the most sensitive to the available aircraft fleet.

While not optimized, the feasibility of some of the other aspects of operations, namely ground operations, hub operations and last mile delivery was ensured through the use of time-based constraints. That is, package

[b]The term "line haul" is most often associated with LTL (less-than-truckload) shipping, but applies to aircraft-based shipping as well.

available and due times were set for the origin, destination and hub locations. These times were set based on observed current operations, with the assumption that those operations allow enough time for pickup, sorting and delivery. These facets could be comfortably reduced to critical times because their only impact on package routing, fleet allocation or flight scheduling was timing. Other facets such as crew and maintenance scheduling, which are specific to aircraft types and tail numbers, could not be easily separated from package routing, fleet allocation and flight scheduling, and were therefore excluded from the model.

The package routing, fleet allocation and flight scheduling operations were modeled as a single integer program (IP) in the form of a service network design problem (SNDP) called the Express Shipment Service Network Design Problem (ESSNDP)[c]. Previous work on the ESSNDP includes Barnhart and Schneur,[6] Kim et al.[7] and Armacost.[9] A more in-depth survey of the literature is featured in Section IV.

Using this ESSNDP model as a test bed, the major effects of upgrading a express airline fleet were studied for a single day of average midweek operations. A baseline fleet with four different kinds of trunk aircraft, one kind of feeder aircraft and a trucking option was generated. Then, the effects of adding from one to ten additional candidate upgrade aircraft to the baseline fleet were studied. The different candidate fleet options were evaluated based on their reduction in objective function value, fleet size and operating cost compared to the baseline fleet. Based on these evaluations, conclusions were made regarding the suitability each aircraft as an addition to the baseline fleet.

IV. Express Shipment Service Network Design Problem

The ESSNDP optimizes the package routing, fleet allocation and flight scheduling aspects of daily express shipment operations, and ensures the feasibility of last mile service, hub operations and ground operations through the use of time-based constraints. According to the categorizations set forth for freight transportation models by Crainic and Laporte,[10] it is a tactical-level model, since it balances the "big picture" approach of strategic models with the highly-detailed approach of operational models.

The precedent for using an operations model like the ESSNDP to study questions related to express shipment airlines is limited. Taylor and de Weck[11] present a methodology for "coupled vehicle design and network flow optimization" in which a cargo aircraft is designed with a network flow optimization module in the loop. Yang and Kornfeld[12] examine the hub-and-spoke network for overnight package delivery between seven large cities. The ESSNDP formulation presented in this work is a more detailed model of express shipment airline operations and the data set used to perform the studies is more realistically sized, though this does come at the expense of longer computation times.

A. Service Network Design Problems

The operations problem can be modeled as a Service Network Design Problem (SNDP) with additional constraints to become the Express Shipment Service Network Design Problem (ESSNDP). Magnanti and Wong[13] discuss the application of Network Design Problems, of which the SNDP is a descendant, to transportation planning. Cordeau et al.,[14] Crainic and Rousseau,[15] Crainic,[16] Crainic et al.,[17] and Wieberneit[8] discuss the application of the SNDP to freight transportation problems. Kim and Barnhart,[18] Kim,[19] Kim et al.[7] and Barnhart et al.[20] discuss the application of the SNDP specifically to express package delivery.

The objective of a Service Network Design Problem is to use a set of vehicles to move a set of commodities from their origins to their destinations with the lowest cost. This is modeled through the use of a graph $G = (N, A)$ in which vehicles provide capacity on the arcs and commodities flow on those arcs to move from their origin node to their destination node. Depending on the application of the SNDP, different types of graphs may be used. For the ESSNDP, a time-space network is the most commonly used graph.

In a time-space network, each node represents a point in time and space, and each arc represents a feasible connection between those points in time and space. There are two types of arcs: 1) ground arcs, which connect points in time at one location and are unlimited in capacity, and 2) movement arcs, which connect locations and are limited by the capacity and transit time of the vehicle assigned to the arc.

Figure 2 shows an example of a time-space network representing pick up options for two spoke airports in an express shipment network. The hub and the two spokes, A and B, are locations and their associated

[c]Within the literature, this problem goes by a number of similar names: Express Service Design problem (ESD),[6] Express Package Service Network Design problem (EPSND),[7] Express Shipment Delivery Problem (ESDP),[8] and Express Shipment Service Network Design problem (ESSND).[9] We chose to use the name Express Shipment Service Network Design Problem (ESSNDP) because it best illustrates the lineage of the problem as well as its relationship to similar classes of problems.

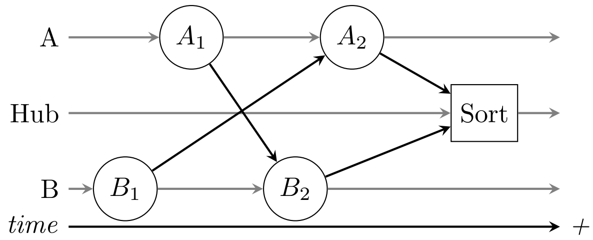


Figure 2: Time-Space Network

nodes correspond to points in time at those locations. For example, A_1 may be the time when packages first become available at spoke A and A_2 may represent the last possible departure time at the hub for the sorting activity. The black arcs, which are movement arcs, represent feasible movements between the locations subject to the travel time, and the gray arcs are ground arcs.

A commodity originating at spoke A enters the network at the node A_1 and has two routing options to the sorting activity at the hub. It can either take the gray arc and wait at location A until it must depart for the hub at the time represented by node A_2, or it can take the black arc and fly to the hub via a different spoke, B. This latter option represents a "consolidation activity," which is discussed in greater detail in Subsection C.

The SNDP optimization problem can be summarized as: given the graph G, which represents all possible options, select the optimal subgraph F subject to flow conservation, forcing, vehicle balance, flow nonnegativity and vehicle integrality constraints. Therefore, for the example in Figure 2, the objective is to choose the best routing options for the commodities originating at spokes A and B, and the lowest-cost vehicles that enable those routings (i.e. provide sufficient capacity on the necessary movement arcs while ensuring that the commodities will arrive at the hub on time).

In the SNDP, the flow conservation constraints stipulate that a commodity flow can only enter or leave the network at its origin (source) or destination (sink) so that there is no "accumulation" of commodities within the network. The forcing constraints require that the commodity flow on an arc be no greater than the capacity of the arc. Finally, similar to the flow conservation constraints, the vehicle balance constraints ensure that vehicles do not "disappear" and "reappear" within the network. The flow nonnegativity constraints ensure that there are no negative volume commodities, and the vehicle integrality constraints ensure that there are no fractional or negative vehicles.

B. Creating the ESSNDP from the SNDP

As a special case of the SNDP, the ESSNDP inherits all of the constraints of the SNDP in addition to those specific to the express shipment problem. Within the literature, there is no singly-defined ESSNDP formulation and the constraints added to the SNDP formulation are a result of the needs of the specific application or simplifying assumptions. Notable formulations include those presented by Kuby and Gray,[21] Barnhart and Schneur,[6] Kim,[19] Kim et al.,[7] Armacost,[9] Armacost et al.,[22] and Barnhart et al.[20]

For this study, we added hull count, feeder count, and "wrap-around" constraints to the those inherited from the SNDP formulation. Other formulations may include other constraints such as a sorting capacity at the hubs, hub landing capacity, airport parking capacity, and commodity exclusions for certain aircraft types. For this study, we chose to add only the hull count and wrap-around constraints since the others were only tangential to our ultimate goal of studying the effect of fleet upgrades.

The hull count constraint is universally included in ESSNDP formulations and limits the number of aircraft that can be used constrained by the fleet size and composition of the carrier. In this study, the hull count constraint was only enforced for trunk aircraft because large express shipment airlines typically have many fewer of them. Feeder aircraft and trucks were unlimited in total availability. The feeder count constraint is a looser version of the hull count constraint, and it limits the number of feeders on an arc. The "wrap-around" constraint requires aircraft to end the day in the same location as where they started. This constraint was included to approximate setting up the aircraft for the next day's operations.

Commodities in the SNDP are synonymous with packages for the ESSNDP and are defined by the origin, destination and product type. The product types considered were same-day, overnight and two-day packages.

In order to reduce the problem size, commodities were tracked on an aggregate level rather than an individual level. That is, rather than tracking each package from its origin to its destination, all packages of the same product type and the same origin-destination pair were treated as one commodity with an aggregate volume.

Finally, in this formulation, a package routing is the path a package takes from a spoke airport to a hub or vice versa, and therefore two routings are needed to express the full path that each package takes from its origin to destination. There are two types of package routings, 1) direct between a hub and spoke, and 2) via a consolidating airport. A consolidating airport is one in which demand from neighboring smaller airports is aggregated for pick up or distributed for delivery routes. In our implementation of the ESSNDP, not all commodities were given the option of a consolidation route, and whether or not a commodity was given the option was dependent on size of the demand and the distance to larger airports. Commodities with small demand were allowed to consolidate at larger nearby non-hub airports for which there was enough time to fly to that consolidating airport. To keep the model from getting too large, commodities eligible for consolidation routes were only given one consolidation route and one direct route to and from the hub (for a total of four options).

C. Express Shipment Service Network Design Problem Mathematical Formulation

Within the mathematical model, there are two types of decision variables: vehicle-specific and commodity-specific. The vehicle-specific decision variable, y^f_{ij}, represents the number of vehicles of type f installed on arc (i, j). The commodity-specific decision variables, x^k_ϕ, are the binary commodity routing variables which are 1 when commodity k is on the routing ϕ and 0 otherwise. This formulation of the ESSNDP pre-defines a set of routing options for each commodity and all of the commodity volume must move along that route. Routings are composed of the movements to and from the hub, therefore each commodity needs one pick-up routing and one delivery routing. Other ESSNDP formulations allow the commodity volume to be divided amongst routings, making it a mixed integer program, or use a node-arc formulation. The binary routing approach was used in this study in order to allow for multi-leg flights without drastically increasing the problem size.

The objective function in this ESSNDP formulation is different from the typical ESSNDP objective function in order to represent the objectives of both minimizing the operating cost and reducing the total fleet size. Most ESSNDP formulations only consider the reduction in operating cost in the objective function. To handle these two objectives, there is a cost variable for both. The operating cost, c^f_{ij}, is the cost of using one vehicle of type f on the arc (i, j). The fleet size cost, d^f_{ij}, is the cost of including an aircraft of type f to the fleet, and is used as a penalty to encourage the optimizer to use fewer aircraft. The mathematical notation used to describe the ESSNDP is as follows,

Decision Variables

- y^f_{ij}: number of vehicles of type f installed on arc (i, j)
- $x^k_\phi = \begin{cases} 1, & \text{if commodity } k \text{ is chosen to be on the routing } \phi \\ 0, & \text{otherwise} \end{cases}$

Sets

- $i \in N$: node in the set of nodes
- $i^+ \in N^+$: source node in the set of source nodes
- $i^- \in N^-$: sink node in the set of sink nodes
- $(i, j) \in A$: arc in the set of arcs
- $f \in F$: vehicle in the set of vehicles
- $k \in K$: commodity in the set of commodities
- $\phi \in \Phi$: package routing in the set of package routings
- $\theta \in \Theta$: airport in the set of airports

Cost Parameters

- c^f_{ij}: cost of using one vehicle of type f on the arc (i, j)
- d^f_{ij}: cost of including an aircraft of type f to the fleet

Additional Parameters

- u_f: capacity of vehicle type f
- n_f: number of vehicles of type f
- b_k: volume of commodity k

Indicator Variables

- $\delta_{\phi}^{ij} = \begin{cases} 1, & \text{if routing } \phi \text{ includes arc } (i,j) \\ 0, & \text{otherwise} \end{cases}$
- $\delta_{i^+}^{\theta} = \begin{cases} 1, & \text{if source node } i^+ \text{ is the source node for airport } \theta \\ 0, & \text{otherwise} \end{cases}$

Using this notation, the mathematical formulation for this application of the ESSNDP is,

$$\min \quad \sum_{f \in F} \sum_{(i,j) \in A} c_{ij}^f y_{ij}^f + \sum_{\theta \in \Theta} \sum_{i^+ \in N^+} \delta_{i^+}^{\theta} d_{ij}^f y_{ij}^f \tag{1a}$$

$$\text{s.t.} \quad \sum_{\phi \in \Phi_k} x_{\phi}^k = 1 \qquad \forall k \in K, \tag{1b}$$

$$\sum_{k \in K} \sum_{\phi \in \Phi} \delta_{\phi}^{ij} b_k x_{\phi}^k - \sum_{f \in F} u^f y_{ij}^f \leq 0 \qquad \forall (i,j) \in A, \tag{1c}$$

$$\sum_{j:(i,j) \in A} y_{ji}^f - \sum_{j:(i,j) \in A} y_{ij}^f = 0 \qquad \forall f \in F_{trunk}, \forall i \in N, \tag{1d}$$

$$\sum_{\theta \in \Theta} \sum_{i^+ \in N^+} \delta_{i^+}^{\theta} y_{ij}^f - n_f \leq 0 \qquad \forall f \in F_{trunk}, \tag{1e}$$

$$\sum_{f \in F_{feeder}} y_{ij}^f \leq 2 \qquad \forall (i,j) \in A, \tag{1f}$$

$$\sum_{j:(i_{\theta}^+, j) \in A} y_{i_{\theta}^+ j}^f - \sum_{j:(j, i_{\theta}^-) \in A} y_{j i_{\theta}^-}^f = 0 \qquad \forall \theta \in \Theta, \forall f \in F_{trunk}, \tag{1g}$$

$$x_{\phi}^k \in \{0,1\}, \tag{1h}$$

$$y_{ij}^f \in \mathbb{Z}_+ \tag{1i}$$

The objective function, Equation 1a, is the sum of the operating costs and the fleet size penalties. Fleet size penalties are only assessed at the airport source nodes, where they "originate". The cover constraints, represented by Equation 1b, ensure that each commodity is assigned to a routing. The forcing constraints, represented by Equation 1c, ensure that the total volume on an assigned aircraft does not surpass the aircraft capacity. Equation 1d represent the aircraft balance constraints, which ensure that aircraft are only ever "created" at an airport source node and "destroyed" at an airport sink node. Equation 1e describe the hull count constraints which ensure that number of trunk aircraft used does not exceed the number available in the fleet. Equation 1f limits the number of feeder aircraft on an arc to no more than two. Equation 1g symbolize the wrap-around constraints which force aircraft to end each day where they started. The final constraints, Equations 1h and 1i ensure the nonnegativity of package flows and the nonnegative integrality of aircraft, respectively.

This formulation of the ESSNDP captures all of the necessary facets of express shipment operations for the purposes of this study. It includes the interconnected package routing, fleet allocation and flight scheduling aspects critical to understanding the effects of changing the aircraft fleet, it incorporates the join objectives of minimizing daily operating costs and minimizing the fleet size, and it ensures the feasibility of other facets of operations through time-based constraints. The generation of the data set required to use this mathematical operations model will be described in Section V.

V. Data Set

In order to perform this study, we needed a realistically-sized data set. Unfortunately, there are no suitable express shipment data sets publicly available. Previous research efforts involving express shipment carriers either used unrealistically small data sets, or used proprietary data and normalized the results. Therefore, in order to satisfy our needs we generated a complete and realistically-sized data set from public domain sources.

From the ESSNDP mathematical formulation and the route generation method, the following data and parameters needed to be generated:

- Equipment and their properties:
  - Cruise Speed
  - Maximum volume capacity
  - Maximum weight capacity
  - Maximum range
  - Turn time
  - Use cost
  - Fleet minimization penalty
- Airports
- Commodity demand
- Transit times between airports for all equipment types
- Available and due times of origin, destination and hub activities

When creating this data set, only service within the contiguous United States was considered.[d] Alaska and Hawaii have comparatively small populations and long flight times so those markets were excluded from consideration. Domestic express shipment was a large and complex enough problem to adequately satisfy the needs of this study without the added complication of international service.

A. Equipment Properties and Cost Model

For this study, there were two categories of equipment: 1) the baseline fleet, and 2) the aircraft under consideration to upgrade the baseline fleet. Under these categories, we chose the following equipment:

Baseline Equipment

- 747-400F
- 767-300F
- 757-200PF
- 737-300SF
- ATR 72-200
- LTL Truck

New Aircraft

- 747-8F
- 777F
- 787-9F
- 737-300C

In the group of new aircraft under consideration, we included a fictional aircraft: the Boeing 787-9F. Currently, the 787 family is only composed of passenger aircraft, but Boeing commonly adds a freighter to its aircraft families after the initial passenger model is unveiled. According to an article in *Bloomberg* from 2013, Boeing is considering a 787 freighter based on the 787-9 though there has been scant mention of a freighter since then and the time line was set for “some point in the far distant future.”[23] However, the recent addition of 787s to passenger fleets and increased fuel economy made it an interesting addition to the study. Where appropriate, metrics from the current 787-9 were used; otherwise metrics were scaled from the slightly larger 777F.

We confined ourselves to considering only Boeing freighters because both FedEx and UPS have recently made large purchases of Boeing freighters, and because Boeing publishes a large amount of information about their aircraft in the *Airplane Characteristics for Airport Planning* guides.[24] These Boeing resources provide information about the aircraft under consideration including the maximum range, weight capacity

[d] We will refer to this as “domestic service” even though it excludes Alaska and Hawaii.

and volume capacity, as well as the aircraft turn time. The cruise speed information was obtained from Boeing marketing materials posted on the *Start Up Boeing* web page.[25]

The equipment characteristics for the ATR 72-200 feeder were obtained through marketing materials from ATR.[26,27,28] The truck characteristics were obtained from a technical report by the American Transportation Research Institute (ATRI).[29] The maximum payload capacities were obtained from the standard characteristics of 53 foot trailer sizes.[30]

Cost Model In the ESSNDP, there are two types of "cost" in the objective function: 1) vehicle use cost, and 2) fleet size penalty cost. The fleet size penalty cost was set to be \$100,000 for a trunk aircraft, \$1,000 for a feeder aircraft and \$0 for a truck in order to drive the optimizer to reduce the fleet size, but not exert so much pressure that it introduced numerical issues in the solver.

The other type of cost, the vehicle use cost, captures the operating cost of using an aircraft. The largest and most commonly modeled aspects of operating cost are fuel cost, pilot salaries, ground crew wages, maintenance costs, depreciation, and landing fees. These costs can be categorized into two categories: 1) per hour, and 2) per cycle, where a cycle is a single flight. Fuel, pilot salaries and maintenance costs are hourly costs, and ground crew wages, depreciation and landing fees are cycle costs. The total cost per flight is therefore,

$$c_{ij}^f = \eta^f x_{ij}^f + \zeta^f$$

where η is the hourly cost, x is the transit time from i to j, and ζ is the cycle cost. All values are vehicle-specific. An explanation of the transit time calculation is presented in Subsection B.

To calculate the fuel cost per hour, we used the fuel burn along the maximum volume payload weight contour of the aircraft payload range diagram to obtain the fuel burned per hour. From that metric and the average fuel price for CY2015 quoted in the FedEx Corporation "Q3 Fiscal 2017 Statistics"[31] report to investors, the fuel cost per hour was calculated. Using the relative cost of maintenance to fuel cost in the same FedEx Express investor report, maintenance cost per flight hour was obtained. Pilot salaries were based on the advertised salary negotiations that the UPS pilot union, the Independent Pilots Union, had in 2016.[32] For our study, the sum of these three costs constituted the cost per flight hour.

For the cycle cost, we found the average landing fee cost for all of the airports included in the study. The landing fee information was collected from the FAA Certification Activity Tracking System (CATS) database.[33] As with maintenance cost, the depreciation cost was calculated based on the ratio of depreciation to landing fee costs in the FedEx Express investor report. Ground crew wages were also similarly calculated from the wages published by the UPS teamsters union, the International Brotherhood of Teamsters.[34] These costs, summed together, constituted the cycle cost.

The feeder cost model was computed as described above for the trunk aircraft, using fuel burn metrics from ATR. For the truck cost model, the hourly cost was taken as the one found in the ATRI study[29] and the cycle cost was taken as the estimated manpower cost to load the truck.

B. Airports and Related Data

The list of airports was generated from the FAA list "CY2015 All-Cargo Airports by Landed Weight".[35] The FAA list was filtered to only include public airports that were at least 50 miles from each other. Additional airports were added to ensure that almost all states had at least one airport and in areas with noticeable geographical voids such as the northern Midwest and southeastern coast.

Hub Location We chose a single-hub network topology centered at Cincinnati/Northern Kentucky Airport (CVG). This choice was based on the observations that both UPS and FedEx have major hubs in that area (SDF and IND, respectively), and Amazon Prime Air has chosen CVG has its hub. Support for hub placement in the Ohio Valley area is also present in the literature. Hall[36] and Bowen[37] both study the geographic aspects of express shipment networks. As Bowen says of Hall's work, "He finds that sorting costs are minimized by having a primary hub in the Eastern Time Zone and that centrality within the US population favors hubs located near the western edge of that time zone. Together, these two factors go far to explain the concentration of air cargo hubs. . . in the greater Ohio Valley region."[37] Finally, according to the U.S. Census Bureau, the population centrality mentioned by Hall in 1989 has not shifted away from that region.[38] For reference, see Figure 3, where the median center of population according to the 2010 census is marked with a green square.

Transit Times Aircraft transit times, or more exactly, block times, were calculated using the great circle distance multiplied by the cruise speed of the aircraft plus a thirty minute time to account for taxi, climb, descent and landing. Transit times for the trucks were calculated using the road mileage from Google Maps multiplied by the average truck speed from the ATRI report.[29]

Critical Times Four critical times needed to be determined: origin available time, hub due time, hub available time and destination due time. The hub critical times form the basis for the other two times, and are estimated from the flight tracking website *FlightAware* for the FedEx Express and UPS airlines.

Following the operations schedule of FedEx and UPS, we chose to have two sorting activities each day: a nighttime sort for overnight packages and a daytime sort for same day and two-day packages.[e] Correspondingly, there are two package origination activities and two package destination activities per day. The timing of these activities was based on the timing of the sort and the transportation time to and from the airport.

C. Commodity Demand

The commodity demand was calculated in an approach inspired by the demand model used by Kuby and Gray[21] in which they sized demand based on population size and "economic factors that would be expected to influence a city's volume of packages." We chose to size the package demand by population and the FAA-reported total yearly cargo landed.[35]

Whereas Kuby and Gray used population data based on the Metropolitan Statistical Area (MSA) tables provided by the U.S. Census, we found that data set to be too coarse, particularly in lower density population areas in the West. Instead, we used the U.S. Census data for 2010 in which population was listed by ZIP Code Tabulation Area (ZCTA).[39] The centroid of each ZCTA was mapped to its closest airport weighted by each airport's yearly landed cargo (i.e. airports that annually land more cargo "appear" closer). Airports too small to be included on the FAA "CY2015 All-Cargo Airports by Landed Weight" list were given a weight of zero. This weighted mapping of population to airports was used to generate a "market size" metric. Each market size metric was then multiplied by each other to get a "city pair demand size" metric.

The city pair demand size metric was then multiplied by the total daily volume to get the total volume moved between cities each day. The total daily volume was calculated using the BTS T-100 "On-Flight Market Freight Enplaned" and "On-Flight Market Mail Enplaned" summary tables for the FedEx Express airline.[40] The BTS T-100 data are summary tables for the total yearly enplaned cargo. In order to obtain the daily total volume, we assumed that each pound of cargo was enplaned twice, cargo was only moved on weekdays, and that each weekday was equivalent. Additionally, we made holiday weekdays (Black Friday to Christmas Eve) count for double volume based on the fact, published by FedEx that, "FedEx average daily volume will double during this timeframe."[41]

Finally, to obtain the demand for each commodity, each daily city pair demand total was split between the three package types: 1) same-day, 2) overnight, and 3)two-day. Same-day and two-day volume are both moved during the day and overnight is moved during the night. The total city pair demand volume was divided evenly into nighttime volume (overnight packages) and daytime volume (same-day and two-day packages), and the daytime volume was evenly split again into same-day and two-day volume. The resulting relative demand originating at each airport is shown in Figure 3.

[e] See subsection C for more information on the package types.

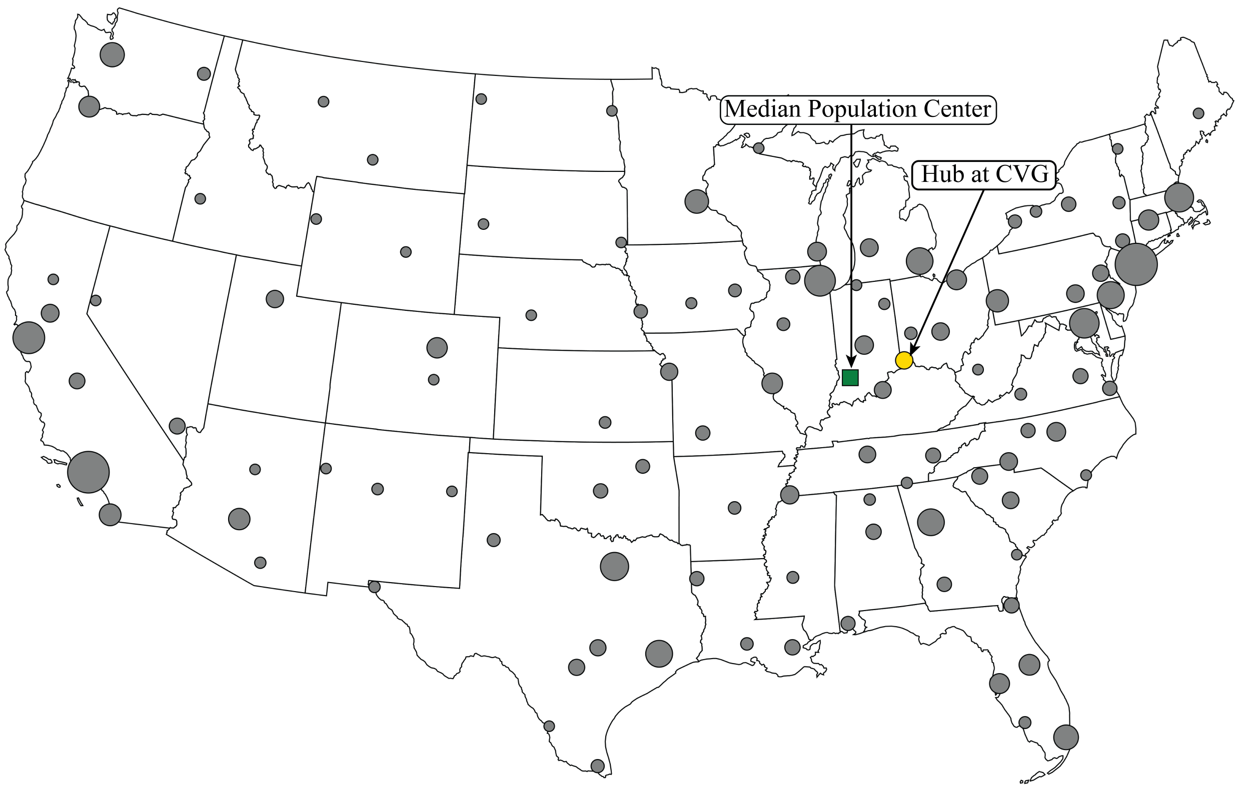


Figure 3: Overnight domestic demand and U.S. median center of population

VI. Experimental Set Up

As outlined in Section III, we investigated the effect of adding new aircraft to a baseline express shipment fleet through the use of a tactical-level operation model and a realistically-sized public domain data set. In order to accomplish these aims, we first established a baseline fleet as detailed in subsection B. Then, from this baseline fleet, we added between one and ten new candidate aircraft and re-solved the ESSNDP. With four candidate aircraft types, this resulted in a total of forty cases. Finally, we compared the fleet upgrades based on the objective function cost, operations cost reduction and fleet size.

A. Solving the ESSNDP

Solving the ESSNDP for even a single day of operations resulted in a large integer program, and solving such a large IP required a sophisticated solver. We used Gurobi 7.0, a commercially available mathematical programming solver. Each case was run on one server node with 24 cores, each of which was allocated 10GB of memory. We noticed that, on average, after an hour of runtime, the optimizer had generally converged so we set the Gurobi time limit for ninety minutes to ensure that it reached a high-quality solution with a stable fleet.

B. Establishing the Baseline Fleet

To establish the baseline fleet, a relaxation of the ESSNDP was solved in which the hull count constraint for the trunk aircraft was omitted and only the baseline equipment types were considered. This gave us the best possible fleet configuration of baseline aircraft.

Beginning with a fleet optimized in this way isolates the results of introducing new aircraft to the fleet. If the fleet composition was poor to begin with, the effects of a poor initial fleet would be compounded with the effects of adding a new aircraft. For example, if the baseline fleet was initially too large, it would not be clear whether an aircraft was removed because it should have not been initially included or whether it was supplanted by a superior new aircraft. By starting with an optimal, or near-optimal baseline fleet, changes to the fleet could be directly attributed to the addition of the new aircraft.

C. Metrics of Comparison

For this study, the three primary metrics were the objective function and its two constituent parts: the total operating cost for a single day of operations and the fleet size. Since we had previously established these as the basis of our optimization, they were the natural choice for comparison.

Beyond these three cost-related metrics, other metrics provide insight on *how* the operations change. The final solution is very detailed – which aircraft were used and on which routes, which aircraft carried which packages, how every package arrived at its destination, and the time that everything occurred. One such metric is the final fleet composition. This answers the question, "Which old aircraft did the new aircraft replace?" Due to the inclusion of the fleet size penalty, there was an incentive to *replace* old aircraft rather than only add new capacity.

Another valuable metric is the allocation of aircraft types to routes. Given a single new aircraft, the optimizer will replace the worst match of aircraft type to route compared to the new aircraft. This gives an indication of which flights were using aircraft inefficiently. Inefficient use could mean a low load factor, the use of multiple small aircraft instead of a single large aircraft, or a fuel-inefficient aircraft on a long route. Studying the changes induced by the addition of a new aircraft gives an indication of non-ideal aspects of the baseline solution and the best types of uses for the new aircraft.

VII. Results

In this section, the results of the forty cases are compared to the baseline. Each candidate aircraft type is compared to the baseline and each other in terms of the objective function value, which indicates how well an aircraft performed relative to the operating cost and fleet size objectives. Additionally, the candidate aircraft's performance relative to the operating cost and fleet composition individually is also considered. Finally, some conclusions are drawn concerning the effects of adding candidate aircraft to the baseline fleet by analyzing the changes in aircraft routings compared to the baseline.

A. Objective Function

The objective function (Eq. 1a) is the sum of the operating cost and the fleet size penalty and therefore represents the aggregate of our two objectives. As shown in Fig. 4, the addition of the 747-8F produces the most improvement to the fleet in all but the ten-aircraft case in which it is narrowly worse than the addition of ten 787-9F aircraft.

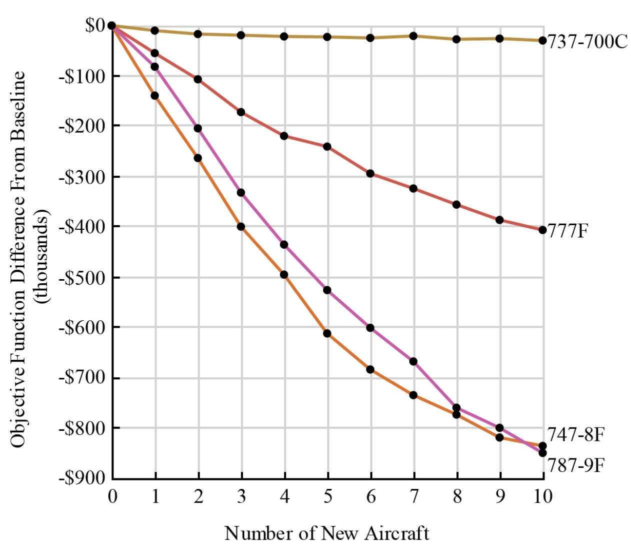


Figure 4: Objective function difference from baseline in thousands of dollars

Overall, the addition of 787-9F and the 747-8F produce similar results in terms of the objective function and the 777F and 737-700C provide significantly less improvement. The 737-700C provides almost no improvement compared to the other aircraft. Considering how similar the 737-700C is to its predecessor, the 737-300SF, as shown in Figure 5, this is not surprising. The new 737 aircraft did not bring any new capability to the fleet and so it did not have much effect.

In contrast, the 747-8F has significantly greater cargo capacity for nearly the same cost compared to its predecessor as seen in Figure 5. This increased cargo capacity made the new 747-400F well-suited for high volume routes and consolidation from smaller cities in which it could take the place of multiple aircraft in the fleet.

The addition of the 787-9F also significantly improved the fleet performance, but rather than replacing multiple aircraft, the 787-9F achieved these improvements through its superior cost efficiency and a maximum capacity situated in the gap between the 767-300F and 747-400F. Thanks to these properties, the 787-9F could fly both 767-300F and underloaded 747-400F routes at a lower cost, thus reducing the objective function.

Finally, the 777F, which also has a maximum capacity in the gap between the 767-300F and 747-400F, also improved the objective function by providing more diversity to the capacity options. As a result, the optimizer did not have to decide between an underloaded 747-400F and flying multiple aircraft on a route with more volume than could be carried by a 767-300F. However, the 777F was not effective at reducing the fleet size so it underperformed compared to the 787-9F.

Objective Function Shape Figure 4 also shows that our decision to terminate the optimization solver early still produced high-quality results. Since the optimal value was never proven, we cannot know whether the values in Figure 4 are optimal, but they behave as expected. That is, the improvement slope flattens with the addition of more aircraft and there are no “local maxima” within the curves. “Local maxima” in this situation would be points that are more costly than the points to either side of them. This behavior would indicate that the optimizer was not given enough time in the branch-and-bound tree to find a better solution.

If all the solutions were optimal, each would be no worse than the solutions with fewer aircraft of the same type. This is because the optimizer is not required to use every aircraft available. Within our study, only two points were local maxima: seven 737-700Cs and nine 737-700Cs. We hypothesize that the optimizer did not find better solutions for these cases because the new 737s were so similar to the old aircraft and so the optimal improvement was not yet explored in the branch-and-bound tree. The flattening of the improvement slope and its implications are discussed in greater detail in subsection E.

B. Fleet Size & Composition

One of the two metrics of interest within the objective function was fleet size, which we enforced through a penalty. Of the four aircraft types, the addition of the 747-8F had the greatest impact on reducing the fleet size as seen in Figure 6. The addition of ten 747-8F aircraft reduced the fleet size by six aircraft (124 to 118). Considering the high acquisition and maintenance costs of aircraft, this could result in significant savings to an express shipment airline. The addition of the B787-9F also reduced the total fleet size, but only by, at most, three aircraft. The addition of the 737-700C or 777F did not change the fleet size though it did alter the fleet composition.

The 747-8F primarily reduces the fleet size by flying more multi-leg routes and replacing multiple smaller aircraft on large-volume, long-distance routes. This fleet size reduction is the primary driver of the low objective function values for the 747-8F. As explained in subsection C, flying fewer aircraft more often typically results in larger operating costs than a one-for-one aircraft replacement.

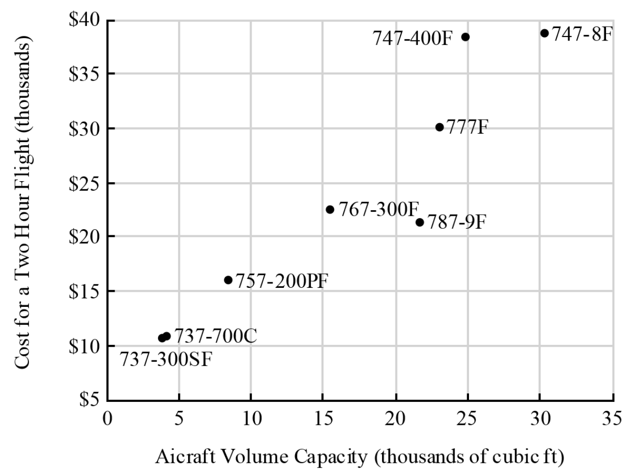
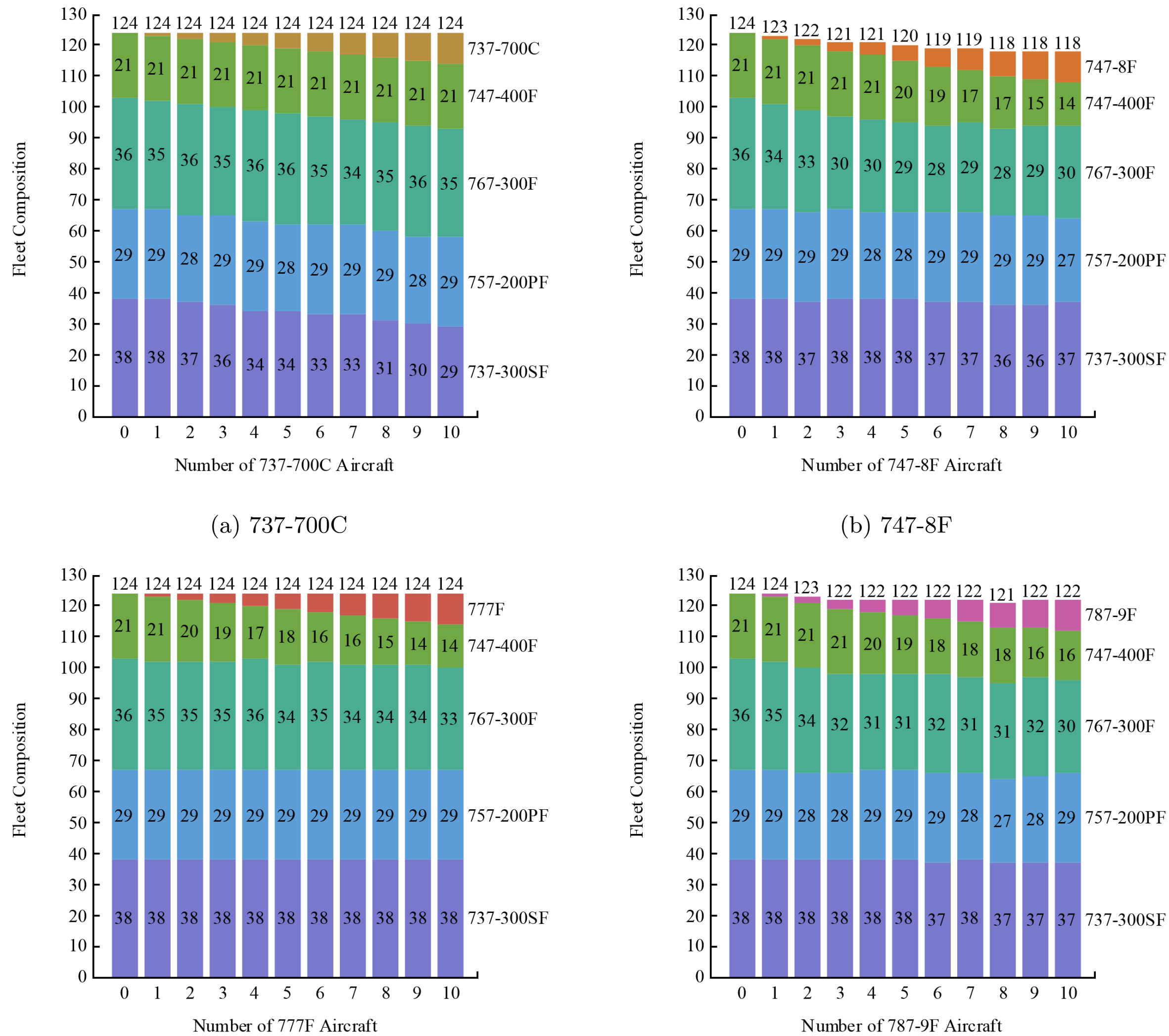


Figure 5: Aircraft cost vs. volume capacity

Fleet Composition Although the other three aircraft do not reduce the fleet size by as much (or at all) as the addition of the 747-8F, their addition does impact the fleet composition. In general, the 737-700Cs replace the 737-300SF aircraft. This is not surprising considering how small the B737s are compared to the rest of the fleet and how similar the new aircraft is to the old.

The 777F, which also does not reduce the fleet size from the baseline, primarily replaces 747-400Fs and some 767-300Fs. This makes sense considering that the 777F is larger than the 767-300F and smaller than the 747-400F. This makes it well-suited to carry volume previous carried by underloaded 747-400Fs



(a) 737-700C

(b) 747-8F

(c) 777F

(d) 787-9F

Figure 6: Effect of candidate aircraft addition on the fleet composition

Of the four aircraft, the 787-9F has the most distributed impact on fleet composition though, in general, it also primarily replaces the 747-400F and 767-300F for the same reasons as the 777F. It also reduces some of the smaller aircraft numbers, probably because it takes on more multi-leg flights.

Finally, the addition of the 747-8F, primarily replaces the 747-400C, as expected, but it also replaces several smaller aircraft as well. This, like the 787-9F, is because it is flying multi-leg flights that are flown by two individual aircraft in the baseline solution.

C. Total Operating Cost

The other metric of interest within the objective function is the operating cost for a single average weekday. This is the total cost of moving all of the overnight, same-day and two-day packages for an average mid-week, non-holiday day for a large express shipment airline. Figure 7 shows the operating cost difference for an upgraded fleet compared to the baseline fleet as more aircraft are added.

In terms of operating cost, the overall result is that, when purchasing four or more aircraft, the 787-9F most greatly reduces the operations cost of the fleet. This is a result of several aircraft properties. First, the 787 family has very good fuel efficiency which reduces the flight hour cost of the aircraft. This makes it out perform the similarly-sized 777F and (to a lesser extent) 767-300F on long-distance routes. Second, the 787 family is also much lighter than older aircraft which reduces the cycle cost of each flight compared to a similarly sized aircraft. Finally, the 787-9F fills a niche in the capacity gap of the baseline fleet between the 767-300F and the 747-400F. The 747-400F is much larger than the 767-300F so for routes with volume greater than a 767-300F, the optimizer had to choose between sending a partially-loaded 747-400F or two smaller aircraft. Adding an aircraft to the fleet that provides an intermediate capacity results in large reductions in the cost of operations.

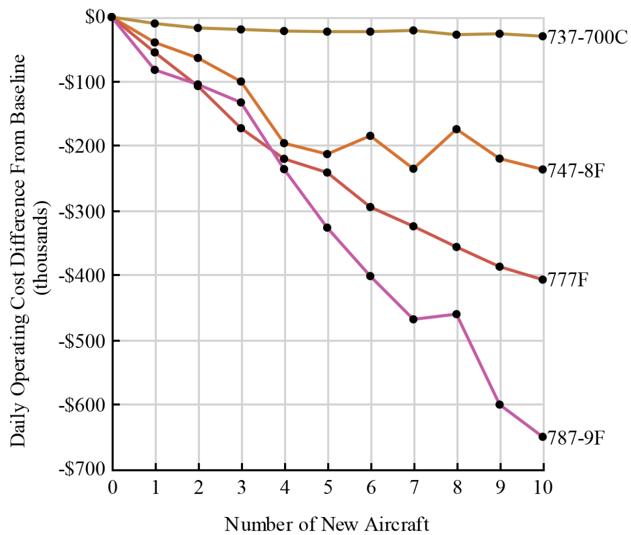


Figure 7: Operating cost difference from baseline in thousands of dollars

This also accounts for why the 777F is the second-best option. It is slightly larger than the 787-9F and occupies the same niche, but has higher costs than the 787-9F on account of its weight so its improvements are not *as* pronounced. It is interesting to note that both the 787-9F and 777F outperform the intra-family upgrade aircraft, the 737-700F and the 747-8F in terms of total daily operations cost.

The 737-700C is an improvement on the 737-300SF, but the effects on the total operational cost are small, especially compared to the other aircraft. The new aircraft does not provide an appreciably different capability to the fleet and so the gains are limited. Additionally, the 737 family is composed of small, narrow-body aircraft which makes them relatively low-cost. As a result, on a per-plane basis, each B737 does not have a large contribution to the overall operations cost compared to other aircraft. Therefore, even a large relative improvement within 737-related costs would equate to only a modest improvement in the total operation cost.

The 747-8F is an improvement on the 747-400F and provides greater operations cost improvements than the 737-700C even though it is also an intra-family upgrade. This is because the B747 is a large and expensive aircraft. Large amounts of volume are moved on each flight, and each 747 flight costs substantially more than a 737. Even moderate improvements to the aircraft would have an appreciable effect on the overall operations cost because the 747 has a large per-plane effect on the cost of operations.

D. Tradeoff Between Operating Cost and Fleet Size

As seen in Figure 7, there are five local maxima in the plot of operations cost difference versus the number of new aircraft: seven 737-700Cs, nine 737-700Cs, six B747-8Fs, eight B747-8Fs and eight 787-9Fs. Of these local maxima, only the local maxima of the seven and nine 737-700Cs is a result of a local maximum in the objective function. The other three local maxima do not correspond to local maxima in the objective function and are a direct result of the fleet size penalty. In these cases, the optimizer chose to operate a smaller fleet more often rather than operate a larger fleet less often. In the case of the eight 747-8Fs, this came in the form of a repositioning flight. In the cases of the six 747-8Fs and eight 787-9Fs, this was the result of flying more consolidation routes by trunk aircraft instead of flying direct routes by multiple aircraft.

A final example of this tradeoff is in the relative performance of the 747-8F based on the operating cost compared to the composite objective function. In terms of the objective function, adding the 747-8F to the fleet consistently results in the best benefit per new aircraft in all but the final case, in which the 787-9F *narrowly* performs better, as seen in Fig. 4. However, in terms of operating cost, the 747-8F is only consistently better than the 737-700C. This is because the addition of the 747-8F provides the highest benefit by reducing fleet size. The newer 747 is larger and slightly cheaper per flight hour so it often lowers the objective function by replacing combinations of smaller aircraft flying the same route. This results in a moderate performance in terms of operating cost, but a strong performance in terms of the objective function.

E. Diminishing Returns with More Aircraft

In general, for each new aircraft type, as the number of new aircraft increases, the per-plane benefit of that addition is reduced. This is seen on Figures 7 and 4 as a flattening of the curve. This translates to diminishing returns as more aircraft are added to the fleet. Therefore, at some point there is little to no improvement gained from adding another aircraft of a certain type. The usefulness of that aircraft type has been saturated.

This occurs because the optimizer first chooses the option with the most improvement for the first aircraft, second best option for the second aircraft, and so forth. The least efficient uses of the fleet will be addressed first because they improve the objective function the most over the baseline. As more new aircraft are added, the gains per new aircraft decrease because the next most beneficial choice is inherently less beneficial than the previous. If it were not, it would have been chosen earlier.

Both of the intra-family upgrades, the 737-700C and 747-8F reach this state sooner than the non-intra-family upgrades for operating cost. The B747-8F has a very strong initial slope in terms of the objective function, but flattens significantly after about six new aircraft, suggesting that is the maximum number of multi-aircraft replacements it can make in the solution. This intra-family behavior compared to the non-intra-family behavior is a result of the "niche size" the aircraft can occupy within the fleet. The intra-family aircraft have small niches because they must compete against aircraft with similar characteristics, thus limiting their ability to make improvements past a certain, early, point.

In contrast, both non-intra-family aircraft fit in the niche between the 747-400F and the 767-300F. This is a much larger niche because there is no other similar aircraft already in the fleet. Fleet allocations that are well-suited for these large wide-body aircraft were particularly ill-suited for their assigned aircraft in the baseline fleet. They introduce diversity into the fleet and therefore still have a relatively large impact at large numbers of new aircraft. Between the two, the 787-9F performs better than the 777F because it is significantly cheaper in flight hour and cycle cost.

F. Routing Changes with the Addition of New Aircraft

In addition to the objective function, fleet size and operating cost values, the routing choices of each solution further illuminate the effect that adding a new aircraft has on the daily operations. The routing differences from the baseline case are shown in Figure 8 for the addition of the 787-9F. Each map encompasses both the nighttime and daytime pickup and delivery flights.

In Figure 8, there are several noticeable trends. First, adding a new aircraft to the fleet has ripple effects beyond the routes covered by the new aircraft. Second, the majority of the 787-9F routes involve west coast airports. This is intuitive considering that these are the longest (and therefore most costly) routes and the 787-9F is a particularly low-cost aircraft. Third, although the majority of new aircraft are allocated to west coast routes, the addition of the first two 787-9Fs replace routes on the east coast, which results in large reductions in the objective function. This shows that while replacing the long west coast flights with lower cost options is the intuitive answer, valuable fleet allocation and routing changes can also be found among east coast flights. Furthermore, both of the east coast routes are multi-leg loops which shows that the aircraft are being used in consolidation routes in addition to “out and back” direct routes. Finally, the placement of each new aircraft is generally stable from one solution to the next. This shows some independence in how the 787-9Fs are used. Having two 787-9Fs does not change what the optimizer found to be the best use of just one 787-9F, and so on as more aircraft are added.

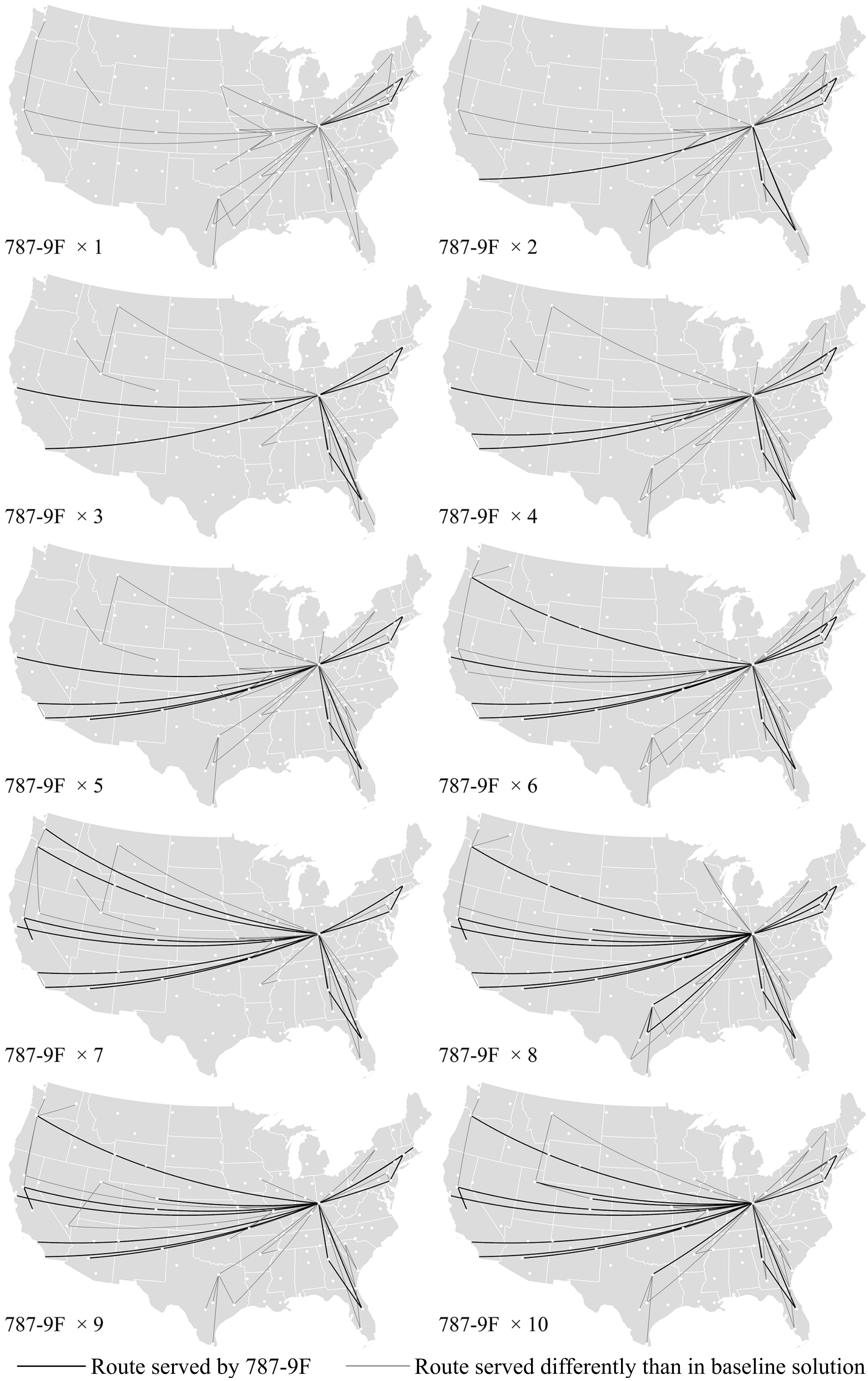


Figure 8: Changes in the Routes Compared to the Baseline

VIII. Conclusion

In this work, we explored the primary question facing express shipment airlines when they look to upgrade their fleet: "*Given a current aircraft fleet, which aircraft should be retired, and which aircraft should be purchased to improve the fleet's performance?*" To answer this question, a tactical-level operations model, the Express Shipment Service Network Design Problem, was presented. That mathematical operations model captures the interconnected package routing, fleet allocation and flight scheduling needs of large express shipment airlines.

Furthermore, in order to demonstrate the effectiveness of this approach, a realistically-sized, detailed data set which was developed. That data set included a baseline fleet and set of candidate aircraft, the equipment properties of those aircraft, a set of airports out of which the airline operated, the demand between those airports, and the critical times at each airport. In the baseline fleet, the trunk aircraft types were the 747-400F, 767-300F, 757-200PF and the 737-300SF, and the candidate trunk aircraft types were the 747-8F, 777F, 787-9F and the 737-700C.

Using the ESSNDP mathematical model and the generated data set, the optimal baseline fleet composition was established by removing the hull count constraint. Then, to this baseline fleet composition, from one to ten additional candidate aircraft were added and the optimal solution was re-computed. Finally, from these forty independent cases, the effect of adding these candidate aircraft to the baseline fleet was compared based on the objective function value, fleet composition and operating cost.

We found that, in all but one case, the addition of the 747-8F to the baseline fleet most significantly reduces the objective function value. It accomplishes this by reducing the fleet size more effectively than any other aircraft. When the 747-8F is added to the baseline fleet, it primarily replaces either a 747-400C, or it replaces multiple smaller aircraft that flew the same routes. The addition of the 747-8F also provides operating cost savings, but not to the same degree as the 787-9F and the 777F.

In terms of the operating cost, the 787-9F is, in all but one case, the superior aircraft. It achieves this by having superior fuel efficiency and weight savings which makes it less expensive to fly than the other aircraft, and adding additional diversity in the fleet in terms of capacity. Additionally, the addition of two or more 787-9Fs to the fleet also results in a net reduction in the fleet size, though not to the same degree as the addition of 747-8Fs. Overall, its fleet reduction and superior operating cost reductions give it an objective function curve similar to the 747-8F, which it actually surpasses at ten aircraft.

The 777F was the second-best aircraft in terms of the reducing the operating cost, but its addition failed to reduce the over all fleet size which resulted in an objective function curve that was not as steep as that of the 747-8F or 787-9F. Like the 787-9F, the 777F reduced the operating cost by introducing more diversity in the fleet capacity since it filled the niche between the 767-300F and the 747-400F.

Overall, the addition of the 737-700C did very little to improve the fleet on any of the metrics we studied, and it primarily makes a one-for-one replacement with its older counterpart in the baseline fleet. The result is not particularly surprising since the 737-700C is not very different from the 737-300SF.

This study is a small example of the analyses that are possible with this research approach. For example, new studies could be run using different objective functions. We chose to focus on minimizing the total operating cost and the fleet size, but other studies could focus on environmental impacts, the aircraft load factor, fleet commonality (more aircraft of the same type), etc. This would provide a different view of the needs of an express shipment carrier, and, as we did with total operating cost and fleet size, multiple objectives could be considered, thus making it into a multi-objective optimization problem.

Another potential expansion of this work would be to increase the level of detail in the ESSNDP. Due to runtime considerations, we excluded crew scheduling and maintenance scheduling within the mathematical formulation. However, both of these schedules have a direct impact on express shipment operations. For example, some routes proposed in the current ESSNDP may be infeasible from a crew scheduling point of view, or some aircraft may be flying too often from a maintenance point of view. Adding these additional features would increase the reality of the mathematical model.

The level of reality could be increased by studying a longer period of operations than a single day. For this study, we assumed that the airline only operates during the week and that every weekday was equivalent. In reality, express shipment airlines operate on the weekends, albeit at a lower volume, and each day of operations is different depending on the demand. A more sophisticated study would consider the entire week of operations rather than a single day. This would give a more realistic view of the airline operations since weeks repeat more closely to each other than days.

A final potential next step would be to design a dedicated cargo aircraft with the ESSNDP operations model in the loop. This would be similar to the work by Taylor and de Weck.[11] Potential aircraft designs would be evaluated based on their performance in daily operations. Current freighter aircraft designs are variants of passenger aircraft but with the growth of the express shipment industry, a more detailed consideration of cargo airline needs may be warranted in the future. The use of tactical-level models such as the ESSNDP would enable that cargo-specific consideration.

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