ABSTRACT

Title: **ANALYSIS OF ROUTING STRATEGIES IN AIR TRANSPORTATION NETWORKS FOR EXPRESS PACKAGE DELIVERY SERVICES**

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The package delivery industry plays a dominant role in our economy by providing consistent and reliable delivery of a wide range of goods. Shipment Service Providers (SSP) offer a wide range of service levels characterized by varying time windows and modes of operation and follow different network configurations and strategies for their operations. SSP operate vast systems of aircraft, trucks, sorting facilities, equipment and personnel to move packages between customer locations. Due to the high values of the assets involved in terms of aircraft and huge operational cost implications, any small percentage savings could result in the order of savings of millions of dollars for the company. The current research focuses on the Express Package Delivery Problem and the optimization of the air transportation network. SSP must determine which routes to fly, which fleets to assign to those routes and how to assign packages to those aircraft, all in response to demand projections and operational restrictions. The objective is to find the cost minimizing movement of packages from their origins to their destinations given the very tight service windows, and limited aircraft capacity.

In the current research, we formulate the air transportation network as a mixed integer program which minimizes the total operating costs subject to the demand, capacity, time, aircraft and airport constraints. We use this model to study of various operational strategies and their potential cost implications. We consider two main operational strategies: one involving no intermediate stops on pick-up and delivery sides and the other involving one intermediate stop between origin and hub on pick-up side and between hub and destination on delivery side. Under each strategy, we analyze the cost implications under a single hub network configuration and regional hub network configuration. We study the impact of various routing scenarios, various variants and logical combinations of these scenarios which gives a clear understanding of the network structure. We perform an extensive sensitivity analysis to understand the implications of variation in demand, fixed cost of operation, variable cost of operation and bounds on the number of aircraft taking off and landing in the airports.

ANALYSIS OF ROUTING STRATEGIES IN AIR TRANSPORTATION NETWORKS FOR EXPRESS PACKAGE DELIVERY SERVICES

By

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Professor Ali Haghani, Chair
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Professor G.L. Chang

Dedication

To Baba, Bou, Bapa, Maa, Meghana, Kity and Litu

Acknowledgements

First and foremost, I would like to thank my advisor Dr. Ali Haghani for his valuable guidance and patience all these years. This thesis was a learning experience and offered me an insight about research. I had always been interested in bridging the gap between academic research and real world industrial applications. I believe that academic research should not be confined to be a theoretical pursuit of ‘unknown waters’; it should also be oriented towards subjectivity and real world applicability. A research should shed light on aspects hidden to the obvious both in the philosophic and practical level. And this research has been a honest endeavor along these lines. It aims to answers certain questions that come up in a rational mind. Some of the results may sound obvious at sight; nevertheless, they offer deeper insights about the system. It would be a great reward if this work aids in some minuscule way towards some real world implementation.

I would like to take this opportunity to thank my parents, grandparents, brother, sister, family, friends and relatives who have believed in me and stood by my side all these years. It has not been an easy journey, but with all the blessings and good wishes, I have come through a long way. Thanks to Meghana for being such a great emotional support. It would be unfair if I did not mention how much my brother Siddhartha and sister Sushree cared about my pursuits. I would also like to thank Dr. Schonfeld and Dr. Chang for being in my committee. Last but not the least, I am grateful to Dr. Mahmassani and my friends in the Transportation group for their comments and suggestions for this work.

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Chapter 1

Introduction

1.1 Background

The package delivery industry plays a dominant role in our economy by providing consistent and reliable delivery of a wide range of goods. In the last decade, radical changes have occurred in the goods transported, the geographic scale of the marketplace, customer needs, and the transportation and communications technologies involved. This translates into a highly competitive environment for shipment service providers (SSP). SSP have to rapidly adjust to changing economic and regulatory conditions, offer reliable high quality, low cost services to their customers and simultaneously aim to maximize their profit margin. To capture a larger portion of the market share, SSP offer a wide range of service levels characterized by varying time windows and modes of operation.

Effective design and operating distribution networks to accommodate multi-mode and multiple service levels is a challenging task. The problem becomes even more complex when one considers the integration of these multiple service levels and transportation modes. There are multiple products or service types, defined by the speed of service required. Broadly, these services may be categorized into two types: express services and deferred services, the former one usually necessitating delivery within 24 hours. For example, the Next Day Service provided by UPS requires the pick-up and delivery to occur within 24 hours whereas the Second Day Service and Deferred Service guarantee delivery within 48 hours and 3-5 days respectively. FedEx and other companies provide similar services. Failure to meet service guarantees may lead to penalties like money refunds and loss of business to competitors.

Different SSP follow different network configurations and strategies for their operations. For example, UPS, the world's largest package delivery company adopts an integrated air and ground network. With an integrated delivery network, UPS achieves higher utilization of sorting facilities, aircraft and ground vehicles. Priority is naturally given to the express delivery packages for sorting and dispatching. However, as the cost of transporting deferred packages by air is marginal, if excess capacity exists, some deferred delivery orders are also dispatched by air. This operation reduces the load on the ground transportation systems and opens opportunity for more orders and / or reduced fleet. According to company literature, UPS's integrated air and ground network enhances pick-up and delivery density and provides with the flexibility to transport packages using the most efficient mode or combination of modes. Federal Express on the other hand believes that integration of operations of the ground and air networks is not feasible as the two networks are too different. It argues that "the optimal way to serve very distinct market segments, such as express and ground is to operate highly efficient, independent networks."

SSP operate vast systems of aircraft, trucks, sorting facilities, equipment and personnel to move packages between customer locations. The SSP must determine which routes to fly, which fleets to assign to those routes and how to assign packages to those aircraft, all in response to demand projections and operational restrictions *[Armacost et al. (2002)]*. The objective is to find the cost minimizing movement of packages from their origins to their destinations, given the very tight service windows, limited package sort capacity and a finite number of ground vehicles and aircraft *[Kim et al. (1999)]*. The problem faced by a SSP is combinatorial in nature and involves the simultaneous solution of the capacitated network flow problem with strict time windows, aircraft routing, fleet scheduling and package allocation problem.

The shipment service process begins with a request from a customer with specifications of location of origin and destination, type of service required (Next Day Service / Second Day Service / Deferred Service), size and weight of the package (s) and a time window for the pick-up. A fleet of ground vehicles responds to these requests and consolidates all the packages to the sorting facility in the nearest airport. This calls for the optimization of the vehicle routing problem associated with the ground transportation from various pick-up points in a zone to the nearest airport. As there are strict time windows associated with the Next Day Delivery Services and the package sizes are relatively small compared to the truck sizes, this routing problem basically becomes a less than truck (LTL) routing problem with strict time windows.

The packages are sorted by their destinations and service type. Since, air transport is expensive; there is an attempt to deliver packages to some destinations by ground transportation if possible. But due to the strict time constraints and associated penalties for not meeting service guarantees in case of Express Services, ground transportation can cater only to the destinations which are in geographic proximity to the origin. The Deferred Services are usually catered by ground transportation as the time constraints are relaxed. Some companies like UPS do use the air route for some Deferred Service orders, if excess capacity exists in the aircraft after satisfying the capacity required for express services. The packages are assigned to aircraft destined to concerned airports. The air service may be dedicated or commercial; the former being performed using company's fleet of aircraft, while the latter involves the use of commercial airlines. Express shipment services stick to a direct flight delivery strategy or a hub-and-spoke network arrangement or a combination of both for shipping the packages from origin airport to the destination airport. In the direct flight delivery option, the shipments are directly shipped from the origin airport to the destination airport. The destination airports may be more than one if it satisfies the temporal constraints. The hub and spoke network arrangement necessitates that all the shipments are consolidated at a central facility (hub), sorted and dispatched to the destination airports. Each of the above operational strategies has their advantages and disadvantages depending on the demands. Direct delivery flights may lead to the usage of comparatively more number of flights and each running less than capacity. The hub and spoke arrangement leads to loss of time as it involves a sorting at the hub and the packages reach the destination in a rather roundabout fashion. However, a mixed network can be envisaged as a combination of the direct delivery and hub-and-spoke network configuration, which incorporates the advantages of both. On reaching the destination airport, the packages are assigned to different ground vehicle routes so that it reaches the destination on / before time. There may be a time-window specified in the request with which the carrier should comply.

Conventional network design and routing models cannot sufficiently capture the complexity of multimode, multi-service networks. Network designs and routing decisions must comply with the various time constraints for each service level. Unlike passenger networks, shipments in freight networks can be routed in more circuitous ways to achieve economies of scale and density, provided time constraints are not violated. For deferred service shipments, these cost efficient routings are more likely to occur as the time constraints are more relaxed. However, with the increased number of routing options and service levels, finding an optimum network design and distribution strategy becomes more difficult.

1.2 Literature Review

Express shipment service is an instance of the transportation service network design application. Transportation service network design problems are a variation of the well-studied and well-documented network design problems.

Conventional network design formulations generally involve two types of decision variables: those for the routing decisions and those for the package flow decisions; however these can be applied only to problems of limited size *[Armacost et al. (2002)]*. Comprehensive surveys of network design research are presented by *[Ahuja et al. (1993)]*, *[Minoux (1989)]* and *[Padberg et al. (1985)]*. Research on uncapacitated and capacitated network design is presented by *[Balakrishnan (1989)]*, *[Balakrishnan (1994 a]*, *[Balakrishnan (1994 b]* and *[Bienstock and Gunluk (1995)]*.

Recent research on network design problems has primarily focused on strengthening the LP relaxation *[Padberg et al. (1985)]* and *[Van Roy and Wolsey (1985)]*. Network loading problems have been studied by *[Goeman and Bertsimas (1993)]*, *[Magnanti and Mirchandani (1993)]* and *[Pochet and Wolsey (1995)]*. *[Goeman and Bertsimas (1993)]* and *[Balakrishnan et al. (1989)]* developed approximation algorithms for network design.

However, there are two major difficulties in applying conventional network design problems and approaches to the transportation service network design problem *[Kim et al. (1999)]*. First, the interactions among the decision variables in transportation applications are more complicated. Second, the state-of-the-art network design methods are not suitable for transportation networks which are very huge in size because of their ‘spatio-temporal’ ingredients.

For express shipment service network design, *[Kuby and Gray (1993)]* develop models for the case of Federal Express. *[Hall (1989)]* studies the effects of time zones and overnight service requirements on the configuration of an overnight package network, but the paper does not address the problems of routing and scheduling. *[Barnhart and Schneur (1996)]* develop models for the express package service network design problem and present a column generation approach for its solution. The algorithm finds near optimal air service designs for a fixed aircraft fleet or for a fleet of unspecified size and make-up. However, the problem is simplified as the model assumes only one hub, one ground vehicle feeder service and no transfer of shipments between aircraft at gateways. *[Grunert and Sebastian (2000]* identify planning tasks faced by postal and express shipment companies and define corresponding optimization models. *[Budenbender et al. (2000)]* develop a hybrid tabu search / branch and bound-and-bound solution methodology for direct flight postal delivery. *[Kim et al. (1999)]* develop a model for large scale transportation service network design problems with time windows. Column and row generation optimization techniques and heuristics are implemented to generate solutions to an express package delivery application. Complex cost structures, regulations and policies are taken care of by the use of route-based decision variables. The problem size is greatly reduced by exploiting the problem structure using a specialized network representation and applying a series of problem reduction methods. *[Armacost et al. (2002)]* develop a robust solution methodology for solving the express shipment service network design problem. The conventional formulations are transformed to composite variables and its linear programming relaxation is shown to provide stronger lower bounds than conventional approaches. By removing the flow decisions as explicit decisions, this extended formulation is cast purely in terms of the design elements.

[Grunert and Sebastian (2000)] have not considered the existence of intermediate airports explicitly in their formulations. The aircraft starts from the origin and reaches the hub directly on the pick-up side and similarly, on the delivery side, the aircraft starts from the hub and reaches the destination without making any intermediate stops. *[Armacost et al. (2002)], [Barnhart and Schneur (1996)]* and *[Kim et al. (1999)]* have considered a maximum of one intermediate stop on the pick-up and delivery routes. *[Smilowitz (2001)]* discusses routing in air networks and asymmetric routing strategies. It is quite possible that an aircraft can make two intermediate stops on its pick-up route or two intermediate stops on its delivery route

depending on both the temporal and capacity constraints. *[Smilowitz (2001)]* discusses the aspects of 2:2, 2:1,1:2 and 1:1 zoning and minimum pair-wise matching of 2:1 to 1:2 zoning to reduce the fleet size. However, the formulations are not of mixed integer type.

1.3 Scope of Research

The current study focuses on the air transportation network design for the shipment service providers (SSP). We formulate this network as a mixed integer problem. In our study, we assume that ground vehicles respond to the pick-up orders on time and all the packages are consolidated at the sorting facility. Packages are sorted by destination and service type. Optimizing the ground transportation for pick-up is out of the present scope of this research. We study various formulations under the scenarios described below.

As has been extensively studied and practiced successfully in the industry, hub and spoke networks have a significant advantage over “point to point” or directly connected networks. Researchers have analyzed the air transportation network splitting it into two parts: the pick-up side and the delivery side. The inferences drawn from the study of either side is equally applicable to the other side. In the current study, we focus on the various aspects of the air transportation network typically faced by a shipment service provider particularly in geographic areas the size of the continental USA. However, the inferences drawn are equally applicable to small areas of interest as well. One of the major factors when we are dealing with countries like the size of USA is the time zones, which severely restrict the available options and aggravate the already strict time window conditions.

In the current study, we focus on a combination of various operational strategies and their potential cost implications. We start our analysis with the assumption of a single hub and spoke network configuration for the air network with the location of the hub known a priori. In this case, all origin airports are connected to the hub by (a) flight(s) with no intermediate stops. Similarly, all destination airports are connected to the hub by (a) flight(s) with no intermediate stops. We further our analysis assuming a regional hub and spoke configuration i.e pick-up from origin airports are consolidated at their regional hubs, dispatched to the destination regional hub from where it is transported to the destination airport. Again, the regional hub locations are assumed to be known a priori. In the next analysis, we study the cost effects if we assume a strategy in which the demands could either be routed directly from the origin city to the main hub or through the regional hub. The strategy implications are further analyzed when the demands from origins are routed either directly to the regional destination hub or through the regional origin hub (i.e there is no main hub). Another logical extension is to study the implications of a strategy in which demands are routed from the origin city to the destination hub. Assuming similar strategies on the delivery side, we analyze the various combinations of strategies and their cost impacts.

All the above studies are based on the fact that there is no intermediate stop of the demands from the origin city until it reaches a hub (either the main hub / regional hub). Subject to the temporal and capacity constraints, it is possible to make intermediate stops at airports on pick-up / delivery routes. Earlier researchers *[Barnhart and Schneur (1996)], [Kim et al.(1999)], [Armacost et al. (2002)]* have considered the presence of one intermediate stop on the pick-up and delivery routes in their formulations. We formulate the above problems as mixed integer programs which optimize the total operating costs subject to the demand, capacity, time, aircraft and airport constraints.

1.4 Organization of Thesis

Chapter 2 gives a system overview and discusses the various concepts and definitions involved in the design of air networks for shipment service companies. In Chapter 3, we develop mixed integer formulations for studying the implications of various feasible strategies as described in the previous section. Chapter 4 describes the methodology used to create the various datasets that we have used for evaluation of the models. In Chapter 5, we analyze various scenarios of model performance where we allow no intermediate stops on the pick-up and delivery routes. We extend our research to study implications of scenarios where pick-up and delivery routes have one intermediate stops in Chapter 6. Chapter 5 and Chapter 6 results are based on one sample dataset. In Chapter 7, we conduct a sensitivity analysis of various parameters like demand, fixed and variable costs on the total cost of operation under various scenarios. We summarize our findings of this research and discuss future scope of study in Chapter 8.

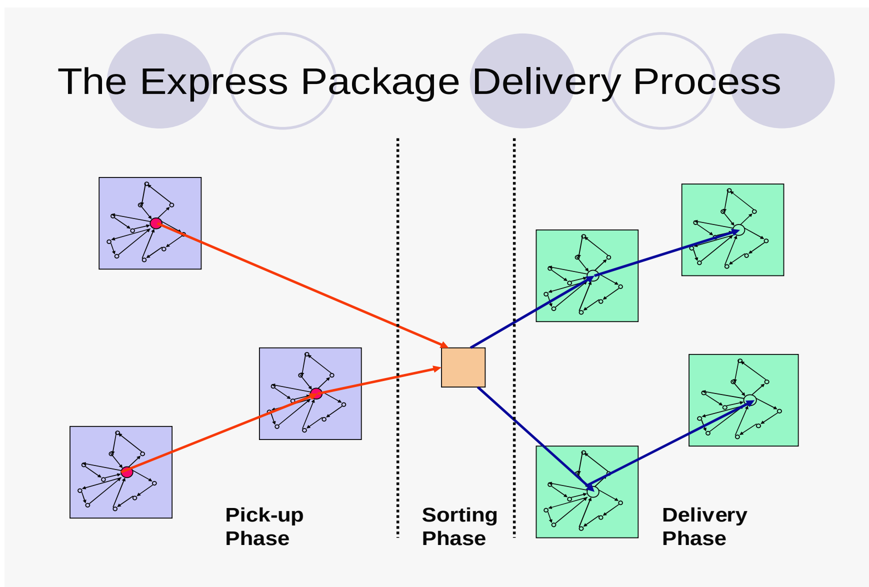
Chapter 2

System Overview: Concepts and Definitions

2.1 Introduction

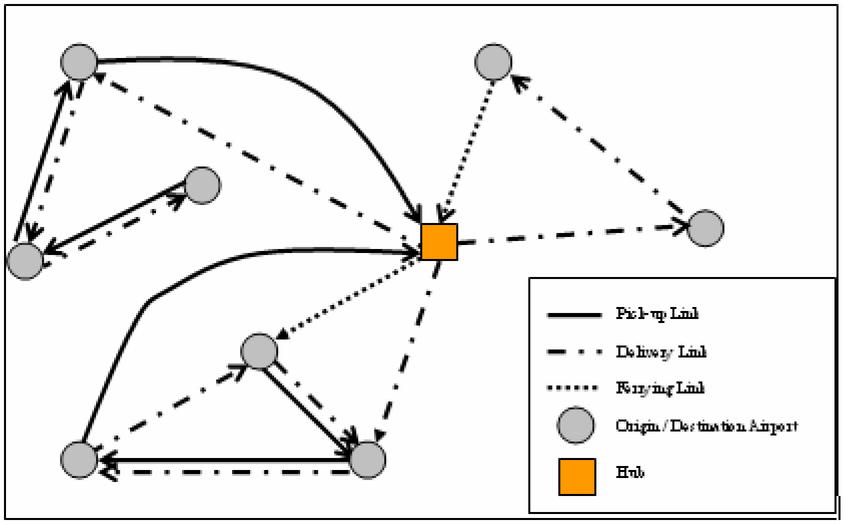
Express Shipment Service problems come under the class of transportation service network design problems. The network design calls for combinatorial optimization at all stages of the process starting from the call for service to the delivery of the package at the destination. The objective is to find the cost minimizing movement of packages from their origins to their destinations, given the very tight service windows, limited package sort capacity and a finite number of ground vehicles and aircraft.

An aircraft route beginning at an airport, typically visits a set of delivery stops followed by an idle period, and then visits a set of pick-up stops before returning to the origin airport. Associated with each airport are earliest pick-up times (EPT_O) and latest delivery times (LDT_D). EPT_O denote the times at which packages will be available for pick-up at an airport. The EPT_O of each airport is scheduled as late as possible to allow customers sufficient time to prepare their shipments. LDT_D denote the times by which all packages must be delivered to satisfy delivery standards.



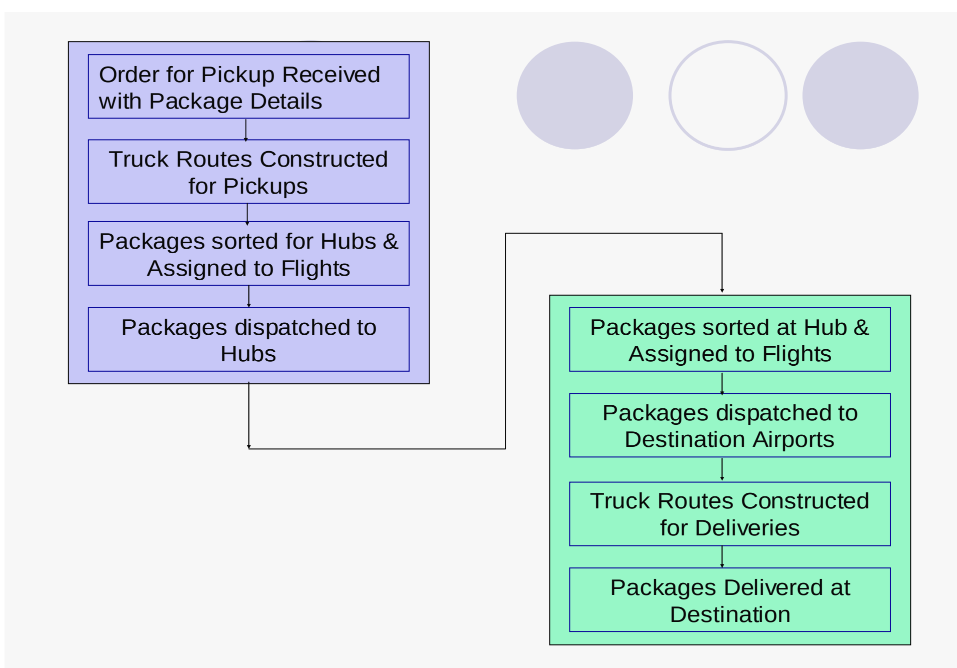
[Figure 2.1: Express Package Delivery Process]

The airports are associated with time windows designating the start and end sort times. An aircraft route can be decomposed into two distinct components – a pick-up route and a delivery route. A pick-up route typically starts from an airport in the early evening, covers a set of airports before ending at a destination airport (in case of direct flight network) or hub (in case of a hub-and-spoke network). A delivery route begins at any airport (in case of direct flight network) or hub (in case of hub-and-spoke network) typically in the early morning and delivers packages at some destination airports. The aircraft may be ferried to some other airport if it optimizes the pick-up process.



[Figure 2.2: Express Package Delivery Network]

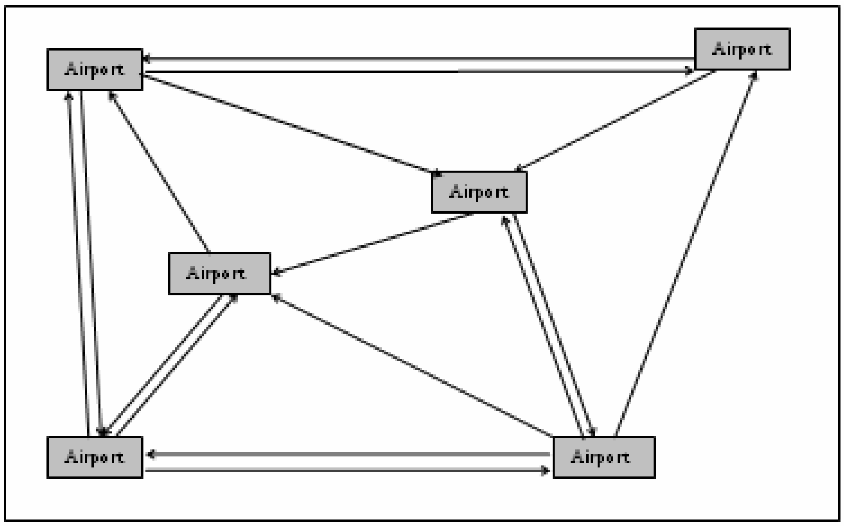
Figures 2.1and 2.2 show a typical network with a few pick-up, delivery and ferrying routes for instances of direct flight delivery and the hub-and-spoke configuration. Figure 2.3 shows the flow diagram of package delivery services.



[Figure 2.3: Express Package Delivery Process Flow Figure]

2.1.1 Direct Flight Delivery Networks

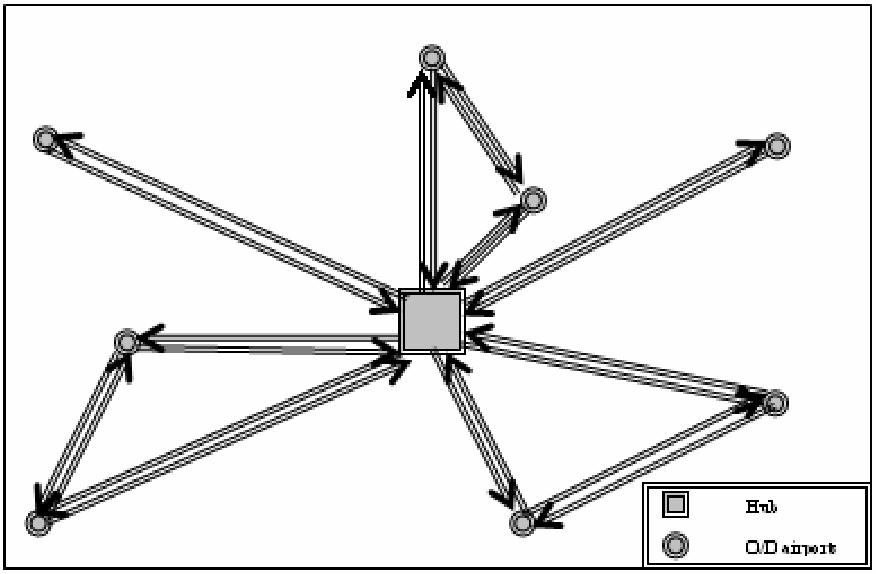
We need to find a cost-minimizing flight schedule and an assignment of requests to the flights subject to the temporal and capacity constraints so that all the shipments are transported from origins to their destinations. Figure 2.4 shows a typical direct network.



[Figure 2.4: Direct Flight Delivery Network]

2.1.2 Hub and Spoke Networks

The problem is to find a cost-minimizing flight schedule from a number of airports to one or several hubs and back again and an assignment of requests to those flights. The flights must satisfy temporal constraints, the capacity constraints taking care of the sort times at the hub(s) and other operational considerations. Figure 2.5 shows a typical one single hub and spoke network.

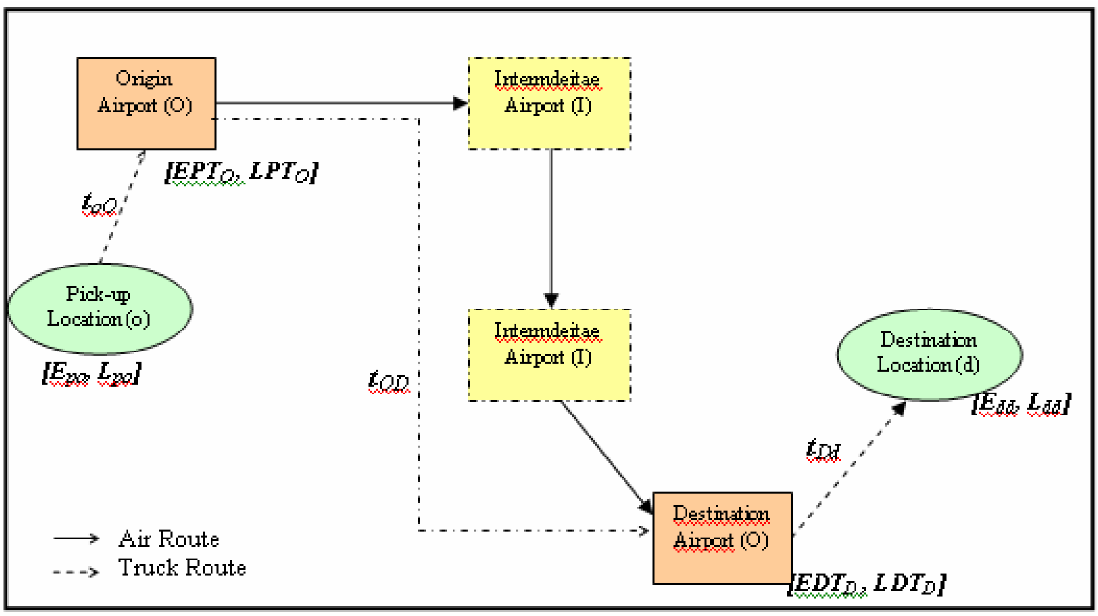


[Figure 2.5: Hub and Spoke Networks]

The airside problems faced by the express shipment services differ greatly from the groundside problem. These differences primarily arise from federal requirements mandating that air routes and schedules be set in advance. Hence, while the schedules may experience changes (due to weather, air traffic control failures etc.), the established air routes may not be updated in real time. Thus, this becomes a problem of strategic routing and scheduling of air fleet and allocation of packages to different routes.

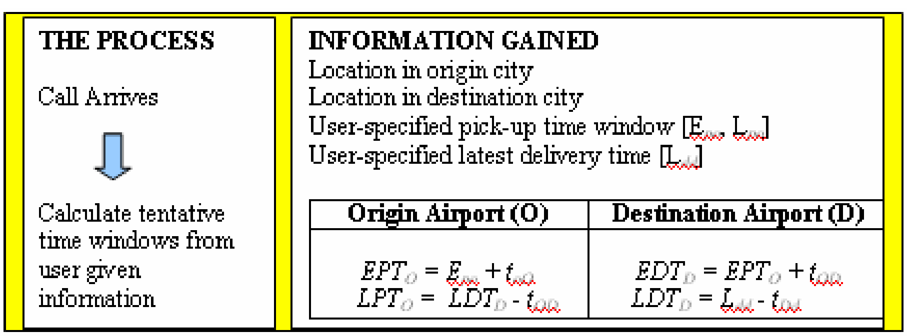
2.2 Time Windows

The shipment service process begins with a request from a customer with specifications of origin and destination locations, type of service required (next day service / 48 hour service / deferred service), size and weight of the package (s) and generally a time window for the pick-up. A fleet of ground vehicles responds to these requests and consolidates all the packages at the sorting facility in the nearest airport. The following information emerges as a result of user specifications (see Figure 2.6):



[Figure 2.6: Time Windows]

Earliest Pick-up Time at Origin Location ***[E$_{po}$]***, Latest Pick-up Time at Origin Location ***[L$_{po}$]*** and the Latest Delivery Time at the destination location ***[L$_{dd}$]***. Alternatively speaking, ***[E$_{po}$, L$_{po}$]*** is the time window in which the package needs to be collected by the ground transportation unit from the customer requesting pick-up. Depending on the ground travel time for transporting the package from the origin location to the sorting facility at the airport and the package sort time, we can associate an Earliest Pick-up Time for the package ***[EPI*** t_{Dd} e origin airport. ***[EPT$_O$]*** is calculated by adding the package sorting times and the ground travel time from the pick-up location to the origin airport ***[t_{oO}]*** to the user-specified earliest pick-up time ***[E_{po}]***. The latest pick-up time at the origin airport ***[LPT_O]*** is specified by the latest plane departure (specified by an exogenously established flight schedule) such that a direct delivery from the destination airport (D) to the destination location (d) does not exceed the user-specified latest delivery time at the destination location ***[L_{dd}]***. The Latest Start Time at origin airport ***[LPT_O]*** could be derived by deducting the sum of air travel time from origin airport ***[O]*** to the destination airport ***[D]*** and the package sorting time at the destination airport from the Latest Delivery Time [***LDT_D*]. *[LDT_D]*** could be derived by deducting the travel time from destination airport ***[D]*** to the destination location ***[d]*** from the user specified latest delivery time ***[L_{dd}]***. We assume that the loading, unloading and package handling times are incorporated in the ground transportation travel times. Similarly, we can associate an earliest delivery time with the destination airport ***[EDT_D],*** which could be obtained by summing up the earliest pick-up time ***[EPT_O]*** at the origin airport, the air travel time from origin airport ***[O]*** to the destination airport ***[D]*** and the package sorting time at destination airport ***[D]***. Similarly, we could associate an Earlier Delivery Time at the destination location ***[E_{dd}]*** as the sum of the ***[EDT_D]*** and the ground travel time from destination airport to the destination location ***[t_{Dd}]***. Figure 2.7 gives the summarized representation of the above.



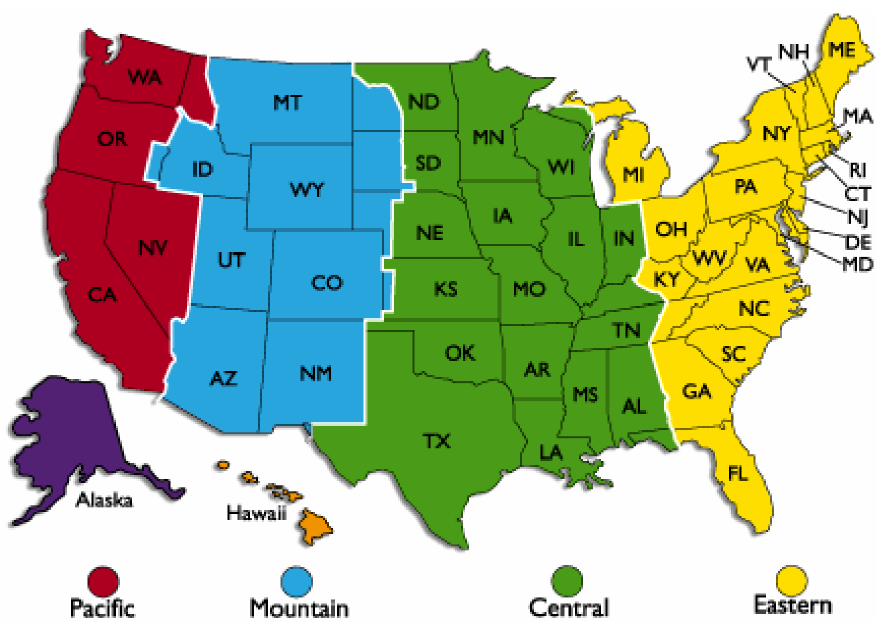
[Figure 2.7: Summary Representation of Time Windows]

2.3 Effect of Time Zones

A lower bound on the time window is defined as the maximum time between any city pair, accounting for all time zone changes. A flight satisfying this lower bound condition is most likely supposed to originate on the western end of a service region (for example the United States) and terminate on the eastern end *[Hall (1989)]*. Let us assume that the city pairs are distributed between two ends of a line segment oriented west to east, over which Z numbers of time zones are crossed. In the northern hemisphere, east bound wind velocity is 100 mph larger than the west bound velocity.

Let us base all our calculations with the easternmost end as our reference. We assume that the cut-off time is same in all cities and represent the identical time that aircraft departs the originating city in the local time zone. Let t =0 be the cut-off time for planes that depart from the easternmost time zone, t =1 be the cutoff time for the second most eastern time zone and t = Z-1 be the cutoff time for the western most time zone. The last plane to arrive at the hub depends on the hub location, but usually, it would arrive from one of the ends of the region. The latest arrival time at the hub is the maximum of western and eastern arrival times and is represented by t(x) where x is the location of the hub.

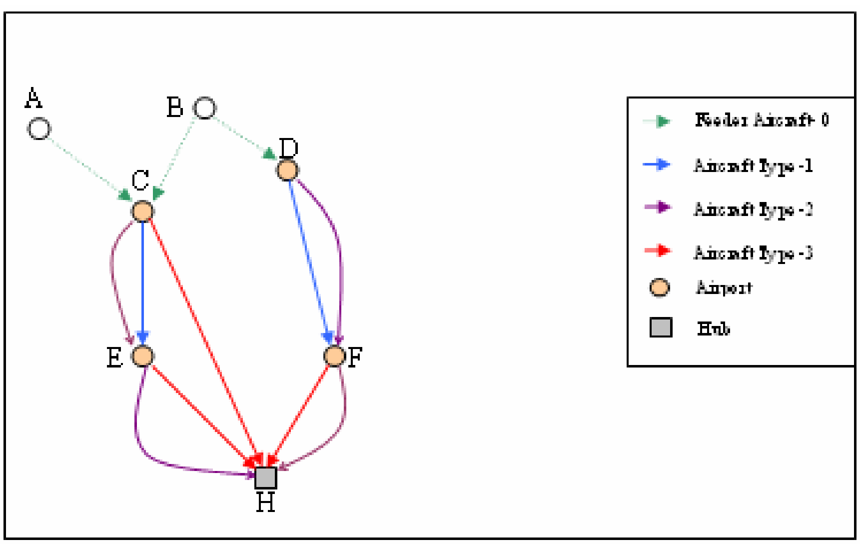
No plane can depart the hub for delivery until every pick-up plane has arrived and requests sorted. The earliest time that a plane can arrive at a destination is t(x) plus the flight time from hub to the destination, adjusted to the local time at the destination. Eastbound shipments from the hub to the destination cities are time critical. So, ideally, the first shipments from the hub should be the one which has the maximum flight time to the eastbound destination. If $t_e^{\max}$ is the maximum flight time for an eastbound destination from the hub, LAD is the latest arrival time at the destination (local time) and the hub is n time zones behind the destination, then the shipment should be dispatched from the hub no later than [LAD - $t_e^{\max}$ - n] (local time at hub) i.e [LAD - $t_e^{\max}$] eastern time. Similarly, if the farthest west bound shipment from the hub is (Z-n) time zones behind the time zone at the hub and the flight time is $t_w^{\max}$, the latest arrival time at the destination is LAD (local time), then the shipment should be dispatched from the hub no later than [LAD - $t_w^{\max}$ + (Z- n)] i.e [LAD - $t_w^{\max}$ + (Z- n) + Z] eastern time. Figure 2.8 shows the various time zones in US. Appendix- 1 shows a sample calculation for time windows with reference to a service region comparable to US.



[Figure 2.8: Time Zone Map of USA]

2.4 Arc, Path and Route Incidence Matrices

We define the terminology for arc, path and route *[Kuby and Gray (1993)]* below and subsequently develop three incidence matrices for our problem formulation. An arc is a single airport to airport connection using a particular aircraft type. There may be a restriction on the type of aircraft that can be flown to and from an airport. Also volume of requests may only require smaller aircraft. In the network shown in Figure 2.9, AC0, CE1, EH2, EH3 etc. are instances of arcs; 0,1,2,3 representing the type of aircraft available. Path is a sequence of arcs used to deliver packages from an origin airport to a destination airport. Each path that is routed through the hub is basically a union of two disjoint paths viz: path from the origin airport to the hub and path from hub to the destination airport. In Fig-2.9, AC0CE1EH2, BC0CEH2, BD0DF2H3, CE2H3, DF2H3 etc. are instances of paths from an origin airport to the hub. Similar paths can be developed for the delivery side, i.e from the hub to the destination airport. Route is a sequence of arcs used to deliver packages from the origin airport to the destination airport by the same aircraft. CE2, CEH3, DFH2 are instances of routes in the network shown in Figure 2.9.



[Figure 2.9: Arcs, Routes and Paths in Air Transportation Network]

We develop three incidence matrices that define the spatial relation between the origin and destination airports, aircraft, arc, path and route variables. The path-route incidence matrix *(I_{pr})* relates each path *p* to all routes *r* in that path. We define the path-route variable I_{pr} as follows:

$$I_{pr} = \begin{cases} 1, \text{ if route r is in path p} \\ 0, \text{ otherwise} \end{cases}$$

Table 2.1 shows a sample of the path-route incidence matrix for the network shown in Figure 2.9.

	AC0	CE1	CEH2	EH3	CH3
AC0CE1EH2	1	1	0	0	0
AC0CEH2	1	0	1	0	0
AC0CH3	1	0	0	0	1

[Table 2.1: Path-Route Incidence Matrix I_{pr}]

The path-airport incidence matrix *(I_{pw})* shows the linkage between a path and the airports that are covered in that path. We define the path-airport variable as follows:

$$I_{pw} = \begin{cases} 1, \text{ if airport w is in path p} \\ 0, \text{ otherwise} \end{cases}$$

Table 2.2 shows a sample of the path-airport incidence matrix for the network shown in Figure 2.9.

	A	B	C	D	E	F	H
AC0CE1EH2	1	0	1	0	1	0	1
BC0CEH2	0	1	1	0	1	0	1
BD0DFH2	0	1	0	1	0	1	1

[Table 2.2: Path-Airport Incidence Matrix I_{pw}]

We define the route-aircraft incidence matrix *(I_{rk})* that captures the use of a particular aircraft type *k* in a route *r*. We define the route-aircraft variable as follows:

$$I_{rk} = \begin{cases} 1, \text{ if aircraft type k is used in path p} \\ 0, \text{ otherwise} \end{cases}$$

Table 2.3 shows a sample of the path-airport incidence matrix for the network shown in Figure 2.9.

	Aircraft Type -0	Aircraft Type -1	Aircraft Type -2	Aircraft Type -3
AC0	1	0	0	0
CE1	0	1	0	0
CEH2	0	0	1	0
CH3	0	0	0	1
DF2	1	0	1	0

[Table 2.3: Route –Aircraft Type Incidence Matrix I_{rk}]

The above incidence matrices are instrumental in our model formulations in Chapter 3.

Chapter 3

System Design and Formulations

3.1 Introduction

In this chapter, we formulate the air transportation network design problem as a mixed integer problem. In our study, we assume that ground vehicles respond to the pick-up orders on time and all the packages are consolidated at the sorting facility. Packages are sorted by destination and service type. Optimizing the ground transportation for pick-up is beyond the present scope of this research. We develop formulations for the following scenarios. As described in Section 1.3, we start our analysis with the assumption of a single hub and spoke network configuration for the air network with the location of the hub known a priori. We further our analysis assuming a regional hub and spoke configuration. Subject to the temporal and capacity constraints, it is possible to cover one / more airports on pick-up / delivery routes. Due to time zone differences, flights that have flexibility on the pick-up route may not have the flexibility on the delivery route (and vice versa). We formulate the above problems as mixed integer programs which optimize the total operating costs subject to the demand, capacity, time, aircraft and airport constraints. The following model is utilized for analysis of different scenarios in the subsequent chapters of this research.

3.2 Assumptions

- We consider that the locations of hub(s) are known a priori. Generally, the requests are routed through the hub as it facilitates better consolidation of the requests by destination, thereby increasing use of capacity. However, some direct flights may also be needed depending on the volume of requests, time constraints and economy.
- We have deterministic requests for service with known volumes between each Origin-Destination (OD) airport pairs.
- The latest pick-up time and latest delivery time is the same at all cities.
- Aircraft routings and schedules are assumed not to vary on a day-to-day basis.
- Line haul costs are assumed not to be a function of the volume of requests.
- We assume that there are no transfers, i.e if there is a flight from an airport to a hub on the pick-up route and requests (packages) are loaded on that flight, they stay on it until it reaches the hub. However, if the flight terminates before the hub on one of the intermediate airports owing to capacity / temporal restrictions, the packages may be transferred.
- There are no intermediate stops between hub to hub flights wherever it is applicable.

3.3 Terminology

We define the following terms for our problem formulation.

X : set of all requests
X_H: set of requests that are routed through hubs
X_D: set of requests that are routed to destinations by direct flights
Clearly, $X = X_H \cup X_D$
W : set of all airports, $w \in W$
O : set of all origin airports, $o \in O$ $, O \subseteq W$
D : set of all destination airports, $d \in D$, $D \subseteq W$
H : set of hubs, $h \in H$
P : set of all feasible paths from origin airport to destination airport via hubs, $p \in P$
P^p : set of all feasible paths from origin airport to hub, $p^p \in P^p$ (pick-up paths)
P^d : set of all feasible paths from hub to destination airport, $p^d \in P^d$ (delivery paths)
P^h : set of all inter-hub feasible paths, $p^h \in P^h$
Clearly, $P = P^p \cup P^d \cup P^h$
q_{od} : amount of request from origin airport o to destination airport d
K : set of all aircraft types, $k \in K$
Q^k : capacity of aircraft type $k \in K$
C : set of commercial aircraft, $c \in C$
*c^{kp^p} : cost of flight from origin o to hub h_i along path p^p using aircraft type k
*$c^k_{h_i h_j}$: cost of flight from hub h_i to hub h_j using aircraft type k

*c^{kp^d} : cost of flight from hub h_j to destination d to along path p^d using aircraft type k

c^c : unit cost of transportation per nautical mile by a commercial aircraft
[: cost includes the sum of fixed and variable costs for the flight]*
n_k : number of aircraft of type $k \in K$

z^{p}_{kw}: maximum number of aircraft of type $k \in K$ that are permitted in airport $w_i, \in O$ on pick-up paths $p^p \in P^p$

z^{d}_{kw}: maximum number of aircraft of type $k \in K$ that are permitted in airport $w_i, \in D$ on delivery paths $p^d \in P^d$

$$I_{w}^{p^p} = \begin{cases} 1, \text{ if airport } w_i, \in O \text{ is present along pick-up path } p^p \in P^p \\ 0, \text{ otherwise} \end{cases}$$

$$I_{w}^{p^d} = \begin{cases} 1, \text{ if airport } w_i, \in O \text{ is present along delivery path } p^d \in P^d \\ 0, \text{ otherwise} \end{cases}$$

Decision Variables

$I_{oh_i}^{kp^p}$: Number of flights from origin o to hub h_i along path p^p using aircraft type k

$I_{h_jd}^{kp^d}$: Number of flights from hub h_j to destination d along path p^d using aircraft type k

$I_{h_ih_j}^{k}$: Number of aircraft of type k from hub h_i to hub h_j, $h_i, h_j \in H$

$x_{oh_i}^{p^p}$: Amount of request that is transported from origin o to hub h_i along path p^p

$x_{h_id}^{p^d}$: Amount of request that is transported from hub h_j to destination d along path p^d

$x_{oh_i}^{c}$: Amount of request transported from origin o to hub h_i by commercial aircraft $c \in C$

$x_{h_id}^{c}$: Amount of request transported from hub h_j to destination d by commercial aircraft $c \in C$

$x_{h_ih_j}$: Amount of request that is transported from hub h_i to hub h_j, $h_i, h_j \in H$

$x_{h_ih_j}^{c}$: Amount of request transported from hub h_i to hub h_j, commercial aircraft $c \in C$

3.4 Problem Formulation

The mixed integer program can be formulated as follows:

$$\textit{Minimize} \quad \sum_{o\in O}\sum_{h_i\in H}\sum_{p^p\in P^p} I_{oh_i}^{kp^p} c^{kp^p} + \sum_{d\in D}\sum_{h_j\in H}\sum_{p^d\in P^d} I_{h_jd}^{kp^d} c^{kp^d} + \sum_{h_i\in H}\sum_{h_j\in H} I_{h_ih_j}^{k} c_{h_ih_j}^{k}$$

$$+ c^c \left(\sum_{h_i\in H}\sum_{o\in O} x_{oh_i}^{c} + \sum_{h_i\in H}\sum_{d\in D} x_{h_id}^{c} + \sum_{h_i\in H}\sum_{h_j\in H} x_{h_ih_j}^{c} \right) \tag{0}$$

subject to

$$\sum_{h_i\in H}\sum_{p^p\in P^p} x_{oh_i}^{p^p} + \sum_{h_i\in H} x_{oh_i}^{c} - \sum_{d\in D} q_{od} \geq 0 \quad ,\forall \quad o\in O \tag{1}$$

$$\sum_{h_j\in H}\sum_{p^d\in P^d} x_{h_jd}^{p^d} + \sum_{h_j\in H} x_{h_jd}^{c} - \sum_{o\in O_o} q_{od} \geq 0 \quad ,\forall \quad d\in D \tag{2}$$

$$\sum_{o_i\in O}\sum_{p^p\in P^p} x_{oh}^{p^p} - \sum_{h_j\in H} x_{h_ih_j} - \sum_{d\in D}\sum_{p^d\in P^d} x_{h_jd}^{p^d} - \sum_{h_i\in H} x_{oh}^{c} - \sum_{h_i\in H} x_{hd}^{c} - \sum_{h_j\in H} x_{h_ih_j}^{c} \leq 0 \quad \forall h_i, h_j \in H \tag{3}$$

$$\sum_{w_i\in O} I_w^{p^p} x_{oh_i}^{p^p} - I_{oh_i}^{kp^p} Q^k \leq 0 \quad ,\forall \quad p^p \in P^p, k\in K \tag{4}$$

$$\sum_{w_i\in D} I_w^{p^d} x_{h_id}^{p^d} - I_{h_jd}^{kp^d} Q^k \leq 0 \quad ,\forall \quad p^d \in P^d, k\in K \tag{5}$$

$$\sum_{p^p\in P^p} I_{oh_i}^{kp^p} + \sum_{h_i\in H}\sum_{h_j\in H} I_{h_ih_j}^{k} \leq n_k \quad ,\forall \; k\in K \tag{6}$$

$$\sum_{p^d\in P^d} I_{h_jd}^{kp^d} \leq n_k \quad ,\forall \; k\in K \tag{7}$$

$$\sum_{p^p\in P^p} I_w^{p^p} \leq z_{kw}^{p} \quad \forall \quad w_i\in O, k\in K \tag{8}$$

$$\sum_{p^d\in P^d} I_w^{p^d} \leq z_{kw}^{d} \quad \forall \quad w_i\in D, k\in K \tag{9}$$

$$I_{oh_i}^{kp^p}, I_{h_jd}^{kp^d}, I_{h_ih_j}^{k} \geq 0 \; and \quad \text{int} \tag{10}$$

$$x_{oh_i}^{p^p}, x_{h_id}^{p^d}, x_{oh_i}^{c}, x_{h_ih_j}, x_{h_ih_j}^{c} \geq 0 \tag{11}$$

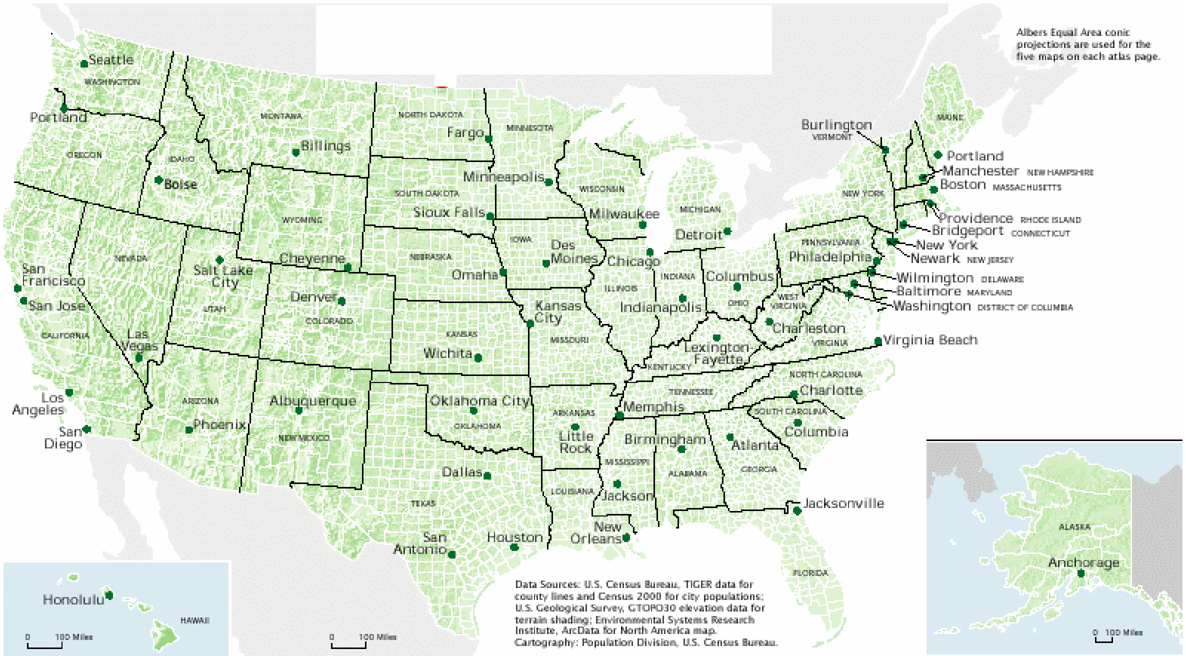
The objective function is to minimize the total cost of operation for requests for service. The first three terms in equation (0) represent the cost components on the pick-up, delivery and inter-hub paths respectively by use of company owned aircraft in the operations. These cost components capture the fixed and variable cost for each origin-hub hub-destination and hub-hub pair for each aircraft type. Fixed costs are attributed to the aircraft, crew, airport take-off and landing fees etc. and the variable cost being the fuel cost The fourth, fifth and sixth terms in the objective function reflect the cost components attributed to the use of commercial aircraft in the pick-up, delivery and inter-hub paths respectively. Constraints (1) and (2) show that all requests are satisfied for the pick-up and delivery sides respectively. Constraint (3) ensures that the hubs are transshipment points and the amount of requests entering a hub is same as the amount leaving. Constraints (4) and (5) are the aircraft capacity constraints or the bundle constraints on the pick-up and delivery side respectively which capture the fact that amount of request that can flow along a path cannot exceed the capacity of the aircraft. Constraints (6) and (7) are the aircraft availability constraints i.e the number of aircraft of a certain type used in the pick-up and delivery phases cannot exceed the numbers available. Constraints (8) and (9) represent the bounds on the number of flights of a certain type of aircraft that are allowed in the pick-up and delivery phases respectively. Constraint (10) ensures the integrality and non-negativity of the flights and Constraint (11) represents the non-negativity constraints of the other variables.

Chapter 4

Datasets

4.1 Test Problem Data

We use the continental USA as our area of study. We create an air network in line with the United Parcel Service (UPS) network with 90 cities as shown in Figure 4.1. Appendix 2A lists the airports that we have considered in our sample air network. We assume that Louisville is the main hub and Ontario, Rockford, Dallas, Louisville, Philadelphia and Columbia are the regional hubs when and where applicable as shown in Figure 4.2. Appendix 2B shows the assignment of airports to the nearest regional hubs. When we are dealing with multiple hub scenarios, we define the hub nearest to the origin and destinations as “Origin-Regional Hub” and “Destination Regional Hub” respectively.



[Figure 4.1: Map showing Cities in Sample Air Network]

[Figure 4.2: Map showing Location of Hubs in Sample Air Network]

For demand data, we use the 1997 Commodity Flow Survey (CFS) data of courier flows originating /destined from / to the Metropolitan Statistical Areas (MSA) and other states.

Chan and Ponder (1979) list service industries and hi-tech dominated light industries as the major users of express package shipping. O'hUallachain and Reid (1990) link businesses and professional services with technological development and information access. In order to calculate the express package volumes from various MSAs, we adopt an approach similar to *[Kuby and Gray (1993)]* to estimate the air package supply volumes. Census 2000 population data for all states and Metropolitan Statistical Area (MSA) is used for our calculations.

Besides population, there are other economic factors like employment type that would be expected to affect the volume of packages shipped from / to a city through express mode (air). In an effort to more accurately estimate volumes, we have considered the 2001 Metro Business Patterns as per North American Industry Classification System (NAICS). We have assumed that employment in the Information (NAICS Code 51), Insurance and Finance (NAICS Code 52), Technical, Professional and Scientific Services (NAICS Code 54) and Management of Companies and Enterprises (NAICS Code 55) sectors are a good indicator of express package volumes. We define a Location Quotient measuring regional variation in employment in the above sectors as follows:

Location Quotient (LQ): **[(e 2001 / E 2001) / (n 2001 / N 2001)]**

Where e2001: 2001 MSA or, CMSA employment under NAICS 51, 52, 54 & 55

E2001:2001 MSA or, CMSA total employment in US (NAICS 11 through 99)

n2001:2001 total employment in US under NAICS 51, 52, 54 & 55

N2001: 2001 total employment in US (NAICS 11 through 99)

From the CFS data, we take the volume of packages routed by Parcel, USPS or, Courier from the MSAs to all other MSAs and states. We derive the package volume per capita per day for all the MSAs and states. For our sample network, we take the airports under the UPS Cargo Network. Next, we try to allocate different airports to population (markets). Allocating an airport for a city / geographical area is by itself a combinatorial problem and not the present focus of our research. It's reasonable to assume that an airport would serve the demands generated in the nearest city. For simplicity, we allocate the demands generated in a state to the airports present in the state. Even though, a portion of the demand could be better served by allocating it to an airport of another state, we have not focused on this aspect. For states which do not have any airport in the network, we divide the demands generated to the nearest airport(s) in neighboring state(s). By undergoing the above exercise, we obtain the population served by all the airports in our network. We calculate the total courier volume generated for all the airports based on this population and the demand/capita/day obtained before. Basically, the total volume of courier generated in an airport can be found out by the following expression:

Total Courier Volume Out = C LQ*[MSA Volume/ Capita/Day]*[MSA Population] +*

∑[Geographical Area 'g' Volume / Capita / Day][Geographical Area 'g' Population]*

Source: The Colography Group Inc., Package Market Trend Analysis, Dec 28, 2001

[Figure 4.3: Package Market Volume Distribution 2001]

where 'g' is the set of geographical areas allotted to the airport. C is a factor ($0 \leq C \leq 1$) corresponding to the fraction of total courier volumes which are to be served by aircraft. We have taken C as 0.25 as an upper bound of 16% as shown in Figure 4.3. LQ is the location quotient of the airport city under consideration. This is incorporated in the formula to capture the fact that a city with a high LQ is supposed to generate higher demands for the air network.

Table 4.1 shows the market share of the major players in the Courier industry.

Company	Overnight		2/3 Day		Ground Parcel	
	(’000)	%	(’000)	%	(’000)	%
USPS	66.4	5	1117.8	59	1538.8	18
FedEx	558.2	43	330.1	17	1457.9	18
UPS	393.8	30	330.3	17	4644.9	57
Airborne	236.3	18	103.8	6	345.7	4
Others	46.2	4	5.4	1	212.7	3
Total	1300.9	16	1887.4	23	8200.0	61

[Table 4.1: Market Share of Major Players in Courier Industry]

The courier demand is a fluctuating variable with respect to time and space.We created our demand file for one such realization. Origin-Destination matrix generation for courier flows is a subject of research by itself, which is beyond the current scope. The above process was aimed to obtain a practical Origin-Destination demand set that we could utilize to run our model.

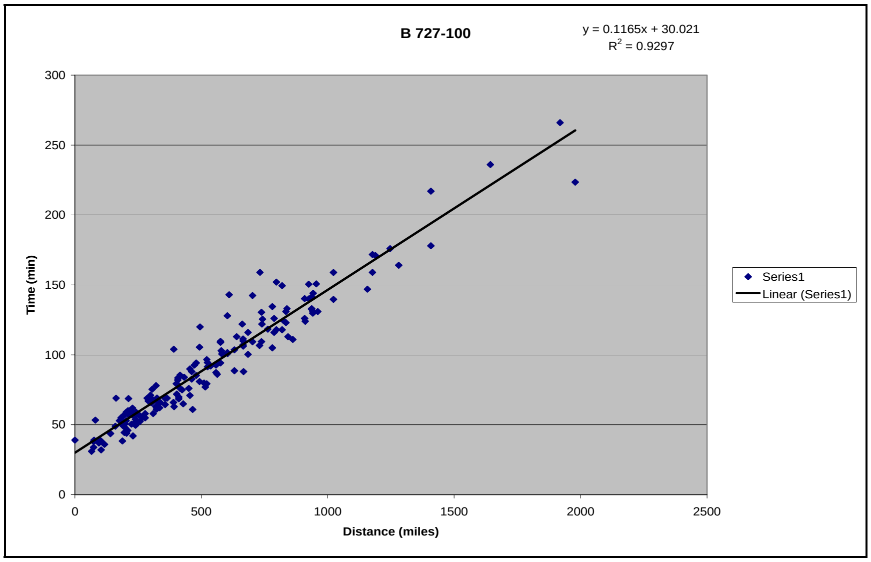
In our model, we assume that we operate two kinds of aircraft Type-A and Type-B. These aircraft are in line with the Boeing 727-100 and Boeing 757-200 specifications and are chosen because of their widespread use in the express package delivery industry. Company literature shows that these two aircraft types are dominant in air cargo delivery operations. For aircraft related data like cost and maximum payload data, we refer to the Annual Reports (SEC 1OK Form) of FedEx and UPS. For our analysis, we would consider that the Shipment Service Provider (SSP) operates only aircraft of the following types as shown in Table 4.2.

Sl.No.	Air Craft Type	Maximum Payload (lbs)	Avg. Fixed Cost (in dollars)	Fuel usage per nautical mile (kg)
1	Type-A (Boeing 727 -100)	46,000	5000*	9.0*
2	Type- B (Boeing 757 -200)	88,000	7500*	12.50*

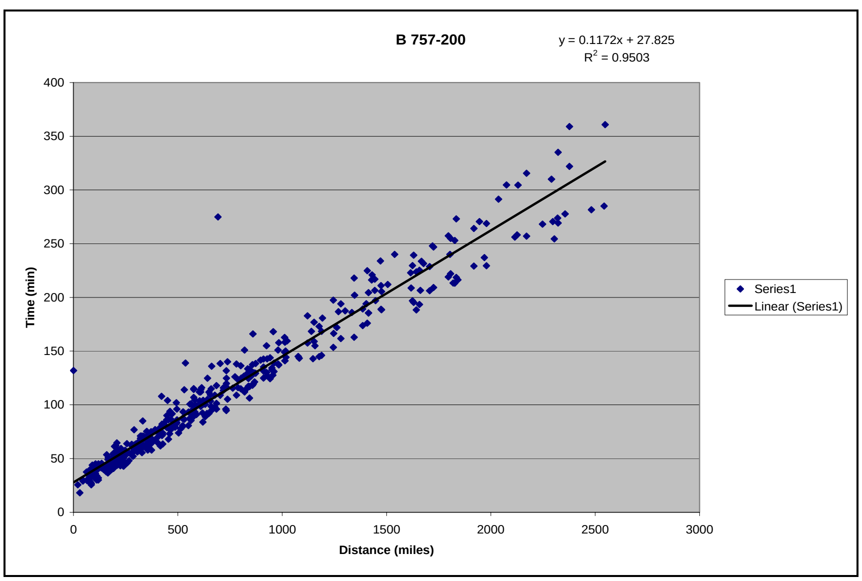
Approximate Values (actual values may vary)

[Table 4.2: Aircraft Characteristics]

The average fixed costs assumed are approximate values as the actual fixed costs incurred would vary on an aircraft to aircraft basis and would depend on factors like age of aircraft, miles flown etc. Similarly, the fuel usage per nautical mile is also an average value. Actual fuel usage would depend on many factors like origin-destination, wind direction, percent full etc. These approximations are practical and could easily provide sufficient insight to the problem context from a planning perspective. And these approximate values could easily be replaced by actual data or functions if it’s available. For calculation of travel time incurred by a particular aircraft from one city to another, we performed a regression analysis. The two major factors determining the travel time between two cities is the distance and speed. Great Circle Distances for each origin-destination pair of cities based on their latitudes and longitudes. We calculated the mean travel times (ramp to ramp) from airline data available from BTS Aviation databases and Air Carrier Statistics. We plotted the mean travel times against the distances for all the flights using a particular aircraft to find the line of best-fit. The best fit graphs are shown in Figures 4.4a and 4.4b.



[Figure 4.4a: Regression Analysis for Type-A (B727-100) aircraft travel time]



[Figure 4.4b: Regression Analysis for Type-B (B757-200) aircraft travel time]

The accuracy of the travel time equations for all the aircraft are shown by the high coefficients of determination (R-Squared > 0.9). The regression equations for the two types of aircraft are shown in Table 4.3, with T denoting the travel time (in minutes) and D denoting the distance (in nautical miles). The constant in the equation accounts for the taxi-in and taxi-out times and the added times the aircraft takes to ascend to cruising altitude and attain cruising speed and then descend to land. The coefficient of the distance variable is the time in minutes that an aircraft takes to travel one mile at cruising speed and altitude. Travel times for each origin-destination city pair are derived for each of the above aircraft.

Sl.No.	**Air Craft Type**	**Travel Time Equation**	**R-Squared**
1	Type-A (Boeing 727 -100)	T = 0.1165D + 30.021	0.9297
2	Type-B (Boeing 757 -200)	T = 0.1172D + 27.825	0.9503

[Table 4.3: Travel Time Equations]

We make use of the air network, demand data, aircraft data described in this chapter for analysis of various operational scenarios in the following chapters.

Chapter 5

No Intermediate Stops on Pick-up & Delivery Routes

5.1 Introduction

In this chapter, we evaluate the model performance under various operational strategies. We apply the mixed integer formulations described in Chapter 3 to the datasets of Chapter 4 and obtain various scenarios. These scenarios are developed both on the pick-up and delivery sides of the problem and all logical combinations of pick-up and delivery strategies are evaluated.

We start our analysis with the assumption of a single hub and spoke network configuration for the air network. In this case, all origin airports are connected to the hub by flight(s) with no intermediate stops. Similarly, all destination airports are connected to the hub by flight(s) with no intermediate stops. We further extend our analysis assuming a regional hub and spoke configuration *i.e* pick-up from origin airports are consolidated at their regional hubs, dispatched to the destination regional hub from where it is transported to the destination airport. In the next analysis, we study the cost effects if we assume a strategy in which the demands could either be routed directly from the origin city to the main hub or through the regional hub. The strategy implications are further analyzed when the demands from origins are routed either directly to the regional destination hub or through the regional origin hub (i.e there is no main hub). Another logical extension is to study the implications of a strategy in which demands are routed from the origin city to the destination hub. Assuming similar strategies on the delivery side, we analyze the various combinations of strategies and their cost impacts.

All the above studies are based on the fact that there is no intermediate stop of the demands from the origin city until it reaches a hub (either the main hub / regional hub). Subject to the temporal and capacity constraints, it is possible to cover one or more airports on pick-up / delivery routes. The following sections describe the results obtained for various operational strategies:

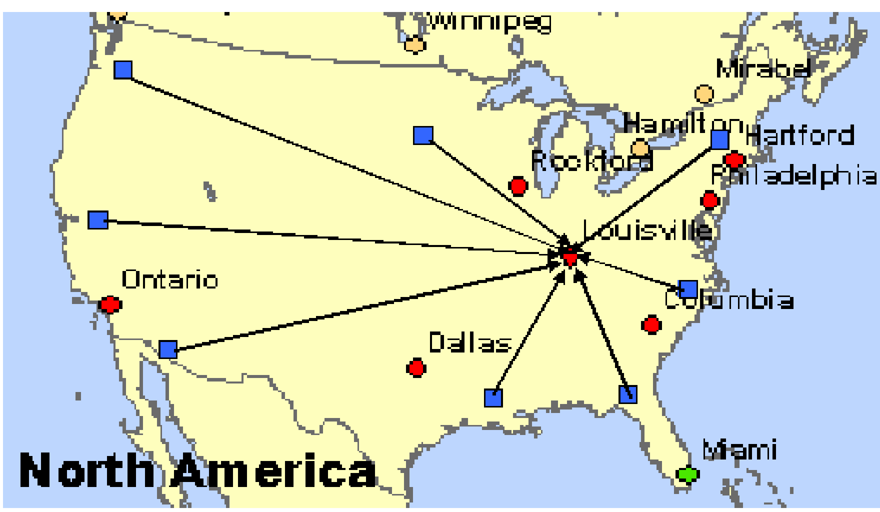
5.2 Scenario-1:

No Intermediate Stops with <u>only one</u> Origin-Hub pair allowed on pick-up and <u>only one</u> Hub-Destination pair allowed on delivery side

In this case, we assume that on the pick-up route, there is no intermediate stop between the origin cities to the hub. And the demands are routed from origin to destination such that there is only one Origin-Hub pair on the pick-up side and only one Hub-Destination pair on the delivery side. Similarly, there is no intermediate stop between the hub and the destination cities on the delivery route. In other words, demands are restricted on certain flight legs and we assume that there is only one flight leg from origin to hub and hub to delivery. The hub may be a single main hub or a regional hub, the location of which is known a priori. Depending on the number of hubs and operational strategies, we come up with the following cases:

5.2.1 Case-A: Single Hub

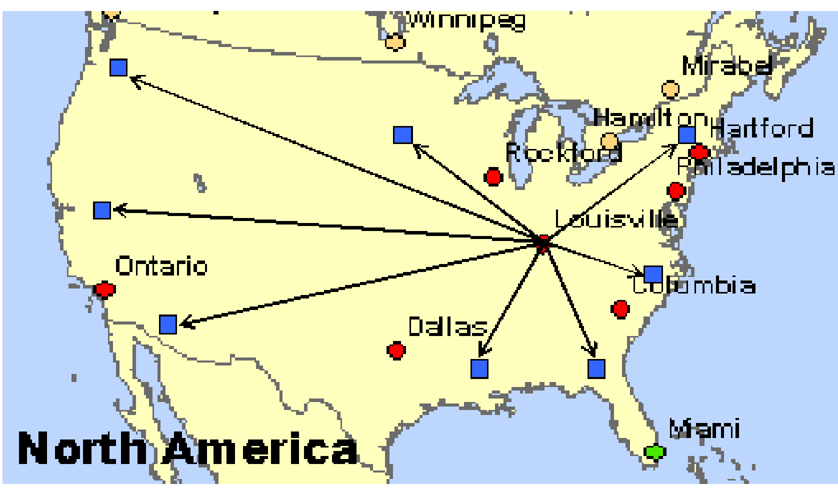
(i) Pick-up Side



[Figure 5.1: No Intermediate Stops- Single Hub Case (Pick-up Side)]

In this case, we assume that there is only one hub in the network and demands are routed from the origin cities through this hub (see Figure 5.1). In our dataset, we have conducted our analysis taking Louisville as our single hub. We assume that demands can be routed to the hub by three means *viz:* Boeing 727 -100, Boeing 757 -200 or a commercial / third party aircraft. These are referred to as Type-A, Type-B and Type-C aircraft in our analysis. Naturally, we expect to use commercial aircraft when the demands to be routed are very small and it's not cost effective to assign a single aircraft for that operation. We have assumed in our cost structure that a commercial aircraft would charge 3 times the actual cost incurred by a company owned aircraft. Appendix 2A gives the list of cities and codes assigned for the MIP formulation. Time windows are not a factor here in this formulation as this is the base case and unless we go for a direct delivery option from origin to destination, we cannot do any better. Since we are dealing with flights with no intermediate stops, we have not put bounds on the number of aircraft originating from an origin to the hub.

(ii) Delivery Side



[[Figure 5.2: No Intermediate Stops- Single Hub Case (Delivery Side)]

We analyze the delivery side along the same lines assuming that there is only one hub in the network and demands are routed from this hub to destination city with no intermediate stops (see Figure 5.2). Table 5.1 summarizes the results for the single hub case.

Single Hub at Louisville	**Cost**
	$(000)
Pick-up Cost	**4800**
Delivery Cost	**4953**
GRAND TOTAL	**9753**

[Table 5.1: Results for No Intermediate Stops- Single Hub Case]

We refer to this scenario as our base scenario through the subsequent sections and compare results of other scenarios with respect to this.

5.2.2 Case-B: Demands routed through Regional Hubs

In this strategy, we assume that all demands are routed through the nearest regional hubs. The 90 cities taken in our dataset have been assigned to six regional hubs at Ontario, Rockford, Louisville, Dallas/ Fort Worth, Philadelphia and Columbia depending on their proximity. These hub-city assignments are shown in Appendix-2B. Pick-up demands are consolidated at the origin regional hub (the regional hub nearest to the origin city), sorted and dispatched to the destination regional hubs (the regional hub nearest to the destination city). These demands are subsequently routed to the destinations.

(i) Pick-up Side

The model is similar to Case-A but instead of dealing with 90 cities spanning all over the continental US in one instance, we have the cities assigned to 6 regions. Each zone is a separate single hub network and is connected to the other zones by arcs from hub to hub. Figure 5.3 shows the network for pick-up side.

[Figure 5.3: No Intermediate Stops- Regional Hubs Case (Pick-up Side)]

Table-5.2 shows the results for the pick-up side of this scenario.

Hubs	Scenario 1 -Case B Pick-up $(000)
ONTARIO	423
ROCKFORD	720
LOUISVILLE*	303
DALLAS/FT.WORTH	360
PHILADELPHIA	636
COLUMBIA	478
TOTAL	2918

[Table 5.2: Results for No Intermediate Stops- Regional Hubs Case (Pick-up Side)]

(ii) Delivery Side

The delivery side analysis is similar to the single hub network. Figure 5.4 shows the delivery network.

[Figure 5.4: No Intermediate Stops- Regional Hubs Case (Delivery Side)]

Table 5.3 shows the results for the delivery side of this scenario.

Hubs	**Scenario 1 -Case B Delivery** $(000)
ONTARIO	**572**
ROCKFORD	**484**
LOUISVILLE*	**295**
DALLAS/FT.WORTH	**428**
PHILADELPHIA	**662**
COLUMBIA	**488**
TOTAL	**2929**

[Table 5.3: Results for No Intermediate Stops- Regional Hubs Case (Delivery Side)]

(iii) Interhub Component

The third cost component is the major one and it deals with the inter hub flights between the six regional hubs.

Table 5.4 shows the summary of results obtained from above MIP runs.

Hubs	Pick-up $(000)	Interhub $(000)	Delivery $(000)
ONTARIO	423	4915	572
ROCKFORD	720		484
LOUISVILLE*	303		295
DALLAS/FT.WORTH	360		428
PHILADELPHIA	636		662
COLUMBIA	478		488
TOTAL	2918	4915	2929
GRAND TOTAL	10762		

[Table 5.4: Results for No Intermediate Stops- Regional Hubs Case (Total Cost)]

]

We find that the total cost of this scenario is 10.3% more than the base case. This is probably due to the fact that all demands are forced to go through the origin and destination regional hubs on the pick-up and delivery sides respectively. If there is a demand comparable to a full flight load between an origin airport and destination regional hub, it is practical to dispatch the demands directly to the destination regional hubs (instead of routing it through the origin regional hub). We analyze the implications of these kinds of strategies in our subsequent sections.

5.2.3 Case C: Demands routed through Origin Regional Hub and directly dispatched to destination

Since the cost of routing from a regional hub to other regional hubs is a big proportion of the total cost and there is already a consolidation at the regional hubs, we analyzed the scenario where the demands after reaching the origin regional hub would be sorted and consolidated with respect to their destination cities (instead of sorting them with respect to destination regional hub as we did in 5.2.2. Case B). By this strategy, we undo the costs incurred for pick-up and delivery between regional hubs and delivery from the destination regional hub to the destination cities.

[Figure 5.5: Demands routed through Origin Regional Hubs and directly dispatched to Destination]

(i) Pick-up Side

Pick-up is the same as Scenario 1 Case-B (Table 5.2).

(ii) Delivery Side

This would be the cost of dispatching the demands from origin regional hubs to destinations by direct flights.

Table 5.5 summarizes the results of this analysis.

Hubs	Pick-up Cost $(000)	Delivery Cost $(000)
ONTARIO	423	1872
ROCKFORD	720	1590
LOUISVILLE*	303	1009
DALLAS/FT.WORTH	360	1320
PHILADELPHIA	636	1771
COLUMBIA	478	1325
Total	2918	8887
GRAND TOTAL	11805	

[Table 5.5: Results for Scenario 1 Case C]

Clearly, this strategy is not a good one as the cost implications are 21% higher than the base case (Scenario 1 Case A).

5.2.4 Case D: Demands routed to destination regional hub

This scenario was not pursued further as the strategy itself by its structure has huge cost implications. Instead of a consolidation at the early stages (*i.e* at origin regional hubs), if the demands are carried directly to destination hubs, it essentially means less than capacity flights flying much longer distances.

Table 5.6 summarizes the results obtained from our analysis for Scenario-1.

Cases	Pick-up Cost $(000)	Delivery Cost $(000)	Total Cost $(000)	Percent with Case A as base
Case-A: Single Hub	4800	4953	9753	
Case-B: Demands routed through Regional Hubs	7833	2929	10762	10.3%
Case C: Demands routed through Origin Regional Hub and dispatched to destination	2918	8887	11805	21.0%

[Table 5.6: Summary of Results for Scenario 1]

It can be observed that for the scenarios where we do not allow any intermediate stops between origin and hub (likewise hub to destination) and we follow a strategy that demands could be routed through only one origin-hub pair (likewise only one hub-destination pair), we find that the single hub case performs the best. The other two scenarios have higher cost implications compared to the single hub case. This can be inferred from the strict "only one origin-hub pair and only one hub-destination pair" strategy which kind of forces demands to take a circuitous path in Case-B and Case C.

5.3 Scenario-2:

No Intermediate Stops with demands routed from Origin through multiple hubs on pick-up and multiple hubs to Destination on delivery

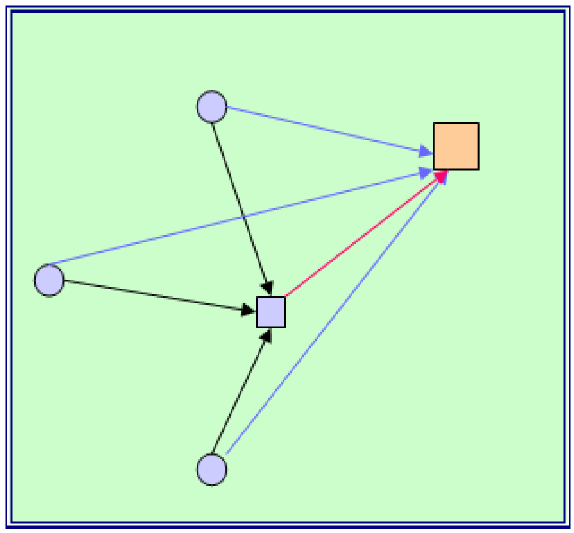
In Scenario-1, we studied instances where the demand was routed between only one origin-hub pair on pick-up side. Similarly, on the delivery side, we routed the demands from only one hub to a destination. This restriction naturally led to inefficient use of capacity, thereby increasing cost. Under the present scenario, we study the implications of the strategy when the demands could be routed to the destination through more than one hub on both pick-up and delivery sides. For example, for the case where there are regional hubs, on the pick-up side, the demands could be split into two routes: one route going from the origin to the destination regional hub and the second going in a more circuitous way from origin to origin regional hub to destination regional hub. This split builds upon the idea that if there is a demand from origin to destination regional hub which is slightly more than an aircraft capacity, then it makes sense to send an aircraft from origin to destination regional hub and route the balance demand through the local regional hub; where there is a likelihood that it gets consolidated with demands from other origins to the same destination hub. This strategy promises with its structure to make better use of aircraft capacity and available fleet. As before, we assume no intermediate stops.

We start with a case where there are regional hubs and one main hub. All the demands are routed through the main hub. On the pick-up side, the demands could be routed directly to the main hub or through the origin regional hub to the main hub. Similarly, on the delivery side, the demands could either be directly dispatched from main hub to destination or through the destination regional hub.

5.3.1 Case A: Demands routed either through Origin Regional Hub or directly to main hub on pick-up side and routed either through destination regional hub or directly to destination on delivery side

(i) Pick-up Side

Following are the results obtained from MIP runs on a CPLEX 9.0 Solver. Louisville was assumed to be the main hub and all demands were routed from origins and origin regional hubs (Ontario, Rockford, Dallas/ Fort Worth, Philadelphia and Columbia) to the destinations or destination regional hubs through this main hub. Figures 5.6a and 5.6b show the network diagram for pick-up side.



[Figure 5.6a: Demands routed through Origin Regional Hub or directly to main hub (Pick-up)]

[Figure 5.6b: Demands routed through Origin Regional Hub or directly to main hub (Pick-up)]

The results are shown in Table 5.7a.

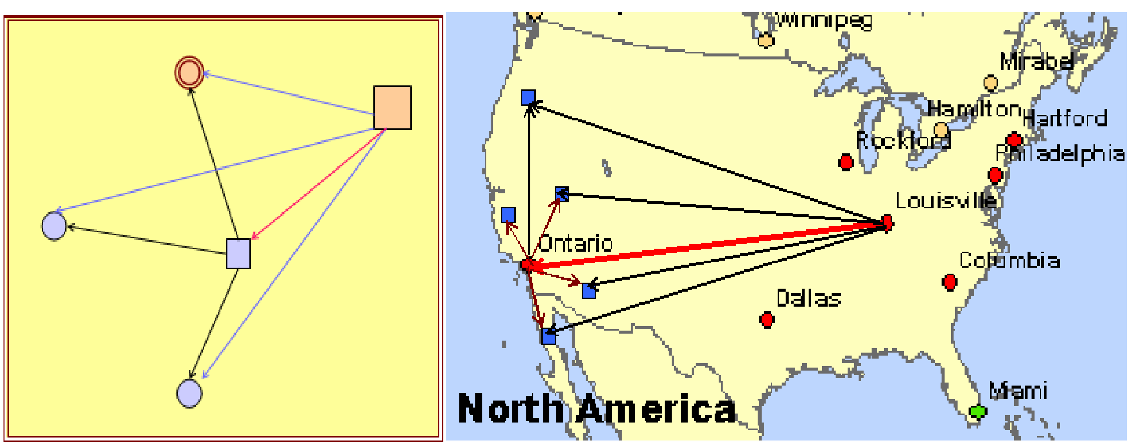
REGIONAL HUBS	COST
	$(000)
ONTARIO	**1011**
ROCKFORD	**848**
LOUISVILLE *	**303**
DALLAS/FT.WORTH	**671**
PHILADELPHIA	**969**
COLUMBIA	**604**
TOTAL	**4405**

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 5.7a: Results of Scenario 2 Pick-up Side]

(ii) Delivery Side

We adopt a similar methodology for the delivery side (see Figures 5.7) and come up with the following costs as shown in Table 5.7b.



[Figure 5.7: Demands routed destination regional hub or directly to destination (Delivery)]

REGIONAL HUBS	Cost
	$(000)
ONTARIO	**1433**
ROCKFORD	**566**
LOUISVILLE*	**295**
DALLAS/FT.WORTH	**740**
PHILADELPHIA	**1021**
COLUMBIA	**606**
TOTAL	**4661**

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 5.7b: Results of Scenario 2 Delivery Side]

REGIONAL HUBS	Pick-up Cost	Delivery Cost	Total Cost
	$(000)	$(000)	$(000)
ONTARIO	**1011**	**1433**	**2444**
ROCKFORD	**848**	**566**	**1414**
LOUISVILLE*	**303**	**295**	**598**
DALLAS/FT.WORTH	**671**	**740**	**1411**
PHILADELPHIA	**969**	**1021**	**1990**
COLUMBIA	**604**	**606**	**1210**
TOTAL	**4405**	**4661**	**9066**

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 5.8: Results of Scenario 2 (Total Cost)]

Comparing this value with Scenario 1 Case A, we find that there is a significant saving of 7.0% by opting for this strategy.

5.3.2 Case B: Combining Scenario 1 results with Scenario 2 results

We further our analysis to see the implications of the results obtained under Scenario 1. It makes sense to see the effects of a strategy if we combine the delivery side of Scenario 1 Case A to the pick-up side of Scenario 2 Case A. Along the same lines, we could combine the pick-up side of Scenario 1 Case A to delivery side of Scenario 2 Case A. The results are shown in Tables 5.9a and 5.9b respectively.

<table>
<tr><th>REGIONAL HUBS</th><th>Scenario 2 Case A (Delivery)</th><th>Scenario1 Case A (Pick-up)</th></tr>
<tr><td></td><td>$000</td><td>$000</td></tr>
<tr><td>ONTARIO</td><td>1433</td><td rowspan="6">4800</td></tr>
<tr><td>ROCKFORD</td><td>566</td></tr>
<tr><td>LOUISVILLE*</td><td>295</td></tr>
<tr><td>DALLAS/FT.WORTH</td><td>740</td></tr>
<tr><td>PHILADELPHIA</td><td>1021</td></tr>
<tr><td>COLUMBIA</td><td>606</td></tr>
<tr><td>TOTAL</td><td colspan="2">9461</td></tr>
</table>

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 5.9a: Scenario 1 Case A Pick-up with Scenario2 Case A Delivery]

<table>
<tr><th>REGIONAL HUBS</th><th>Scenario 2
Case A (Pick-up)</th><th>Scenario1 Case A
(Delivery)</th></tr>
<tr><td></td><td>$000</td><td>$000</td></tr>
<tr><td>ONTARIO</td><td>1011</td><td rowspan="6">4953</td></tr>
<tr><td>ROCKFORD</td><td>848</td></tr>
<tr><td>LOUISVILLE*</td><td>303</td></tr>
<tr><td>DALLAS/FT.WORTH</td><td>671</td></tr>
<tr><td>PHILADELPHIA</td><td>969</td></tr>
<tr><td>COLUMBIA</td><td>604</td></tr>
<tr><td>TOTAL</td><td colspan="2">9358</td></tr>
</table>

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 5.9b: Scenario 2 Case A Pick-up with Scenario1 Case A Delivery]

We see that "Scenario 2 Case A Delivery with Scenario 1 Case A Pick-up" and "Scenario 2 Case A Pick-up with Scenario 1 Case A Delivery" lead to savings of 3.0% and 4.1% respectively compared to the base case. Thus, we can conclude that even if we do not allow intermediate stops, simply opting for a strategy in which demands could be routed through either hub as applicable, we end up saving in the order of 7.0%.

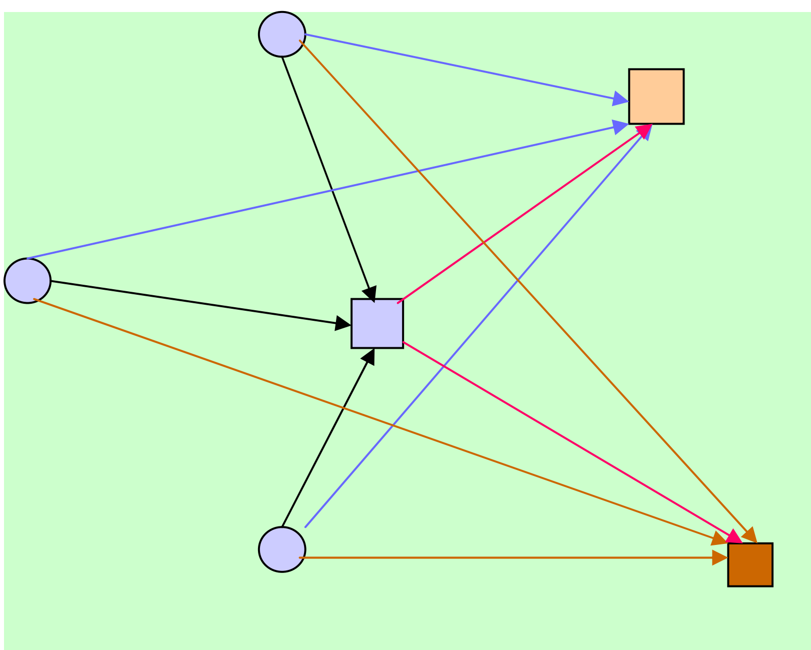
5.4 Scenario 3:

No Main Hubs, Demands routed through Regional Hubs only

In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only.

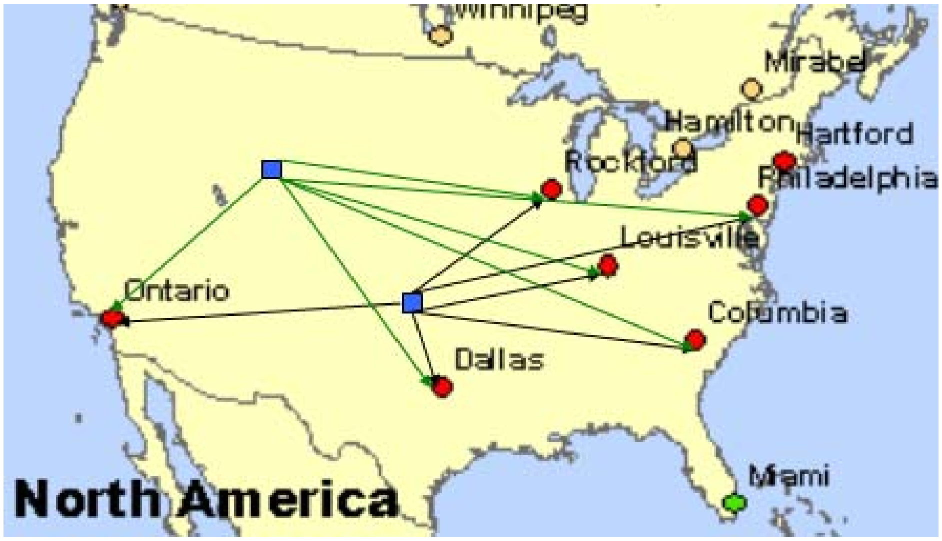
5.4.1 Case A: Demands routed either through Origin Regional Hub or directly to Destination Regional Hub on pick-up side

On the pick-up side, the demands would be routed either directly from the origin to destination regional hub or through the origin regional hub (see Figures 8a and 8b).



[Figure 5.8a: Demands routed through Origin Regional Hub or directly to Destination Regional Hub]

The delivery side naturally becomes a case where the demands need to be routed from the delivery destination hub to the destination (as studied in Scenario1 Case B).



[Figure 5.8b: Demands routed through Origin Regional Hub or directly to Destination Regional Hub]
]

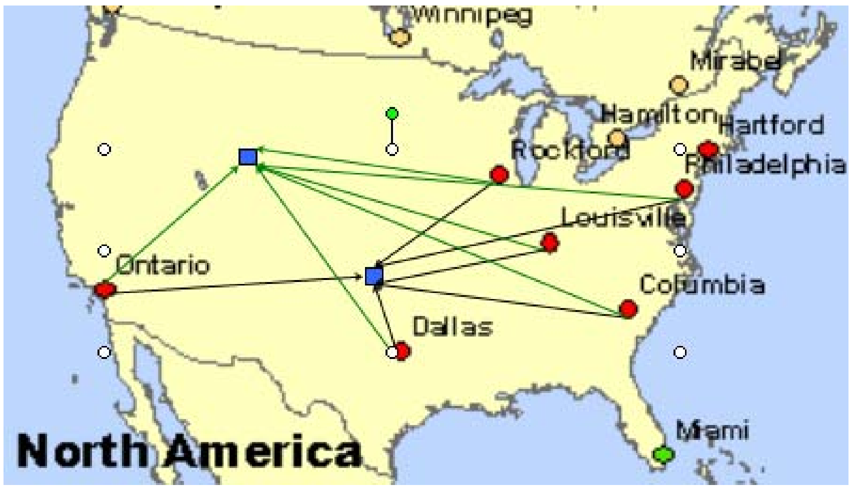
The results of the MIP runs are shown in Table 5.10.

REGIONAL HUBS	Pick-up	Delivery
	$(000)	$(000)
ONTARIO	**849**	**572**
ROCKFORD	**1158**	**484**
LOUISVILLE*	**726**	**295**
DALLAS/FT.WORTH	**763**	**428**
PHILADELPHIA	**1160**	**662**
COLUMBIA	**752**	**488**
TOTAL	**5408**	**2929**
GRAND TOTAL	**8337**	

[Table 5.10: Results of Scenario 3 Case A (Pick-up)]

5.4.2 Case B: Demands routed either through Destination Regional Hub or directly to destination on delivery side

On the delivery side, the demands would be routed either directly to the destination or through the destination regional hub (see Figure 5.9). We assume that the demands are routed from the origins to the original regional hub in the same manner as studied in Scenario1 Case B.



[Figure 5.9: Demands routed through Destination Regional Hub or directly to destination (Delivery)]

The results of the MIP runs are shown in Table 5.11.

REGIONAL HUBS	Pick-up	Delivery
	$(000)	$(000)
ONTARIO	**423**	**1112**
ROCKFORD	**720**	**769**
LOUISVILLE*	**303**	**490**
DALLAS/FT.WORTH	**360**	**821**
PHILADELPHIA	**636**	**1128**
COLUMBIA	**478**	**703**
TOTAL	**2918**	**5023**
GRAND TOTAL	**7941**	

[Table 5.11: Results of Scenario 3 Case B (Delivery)]

From the results shown in Table 5.10 and Table 5.11, we find that for the strategy in which demands are routed either through origin regional hub or directly to destination regional hub on pick-up side has 5.0% more cost implications than the strategy in which demands are routed either through destination regional hub or directly to destination on delivery side.

All the above analysis conducted in Scenario 1 through 3 are based on the strategy that there are no intermediate stops from the origin to the hub on the pick-up route and from the hub to the destination on the delivery route. We summarize out results in Table 5.12. And we see that ***'Scenario 3 No Main Hubs, Demands routed through Regional Hubs only Case-B'*** appears to be the best strategy as we obtain savings in the order of 14.5% and 18.7% on the pick-up (Case A) and delivery side (Case B) strategies respectively. However, it may be noted that the inferences drawn may vary if there are major changes in demands. Nevertheless, this analysis gives a "comparative feel" of the various scenarios. We undertake a more in-depth sensitivity analysis in Chapter 7 to make generalized inferences of impacts of various strategies on our problem.

Scenarios	Pick-up Cost	Delivery Cost	Total Cost	Percent with Case A as base
Scenario 1:No Intermediate Stops with <u>only one</u> Origin-Hub pair allowed on pick-up and <u>only one</u> Hub-Destination pair allowed on delivery side				
Case-A: Single Hub	4800	4953	9753	
Case-B: Demands routed through Regional Hubs	7833	2929	10762	10.3%
Case C: Demands routed through Origin Regional Hub and dispatched to destination	2918	8888	11806	21.0%
Scenario 2: No Intermediate Stops with demands routed from Origin through multiple hubs on pick-up and multiple hubs to Destination on delivery side				
Case A: Demands routed either through Origin Regional Hub or directly to main hub on pick-up side and routed either through destination regional hub or directly to destination on delivery side	4405	4661	9066	-7.0%
Case B: Combining Scenario 1 results with Scenario 2 results				
a] Scenario1 Case A (Pick-up) + Sub Case a (Delivery)	4800	4661	9461	-3.0%
b] Sub Case a (Pick-up) + Scenario1 Case A (Delivery)	4405	4953	9358	-4.0%
Scenario 3: No Main Hubs, Demands routed through Regional Hubs only				
Case-A: Demands routed either through Origin Regional Hub or directly to Destination Regional Hub on pick-up side	5408	2929	8337	-14.5%
Case-B: Demands routed either through Destination Regional Hub or directly to destination on delivery side	2918	5023	7941	-18.7%

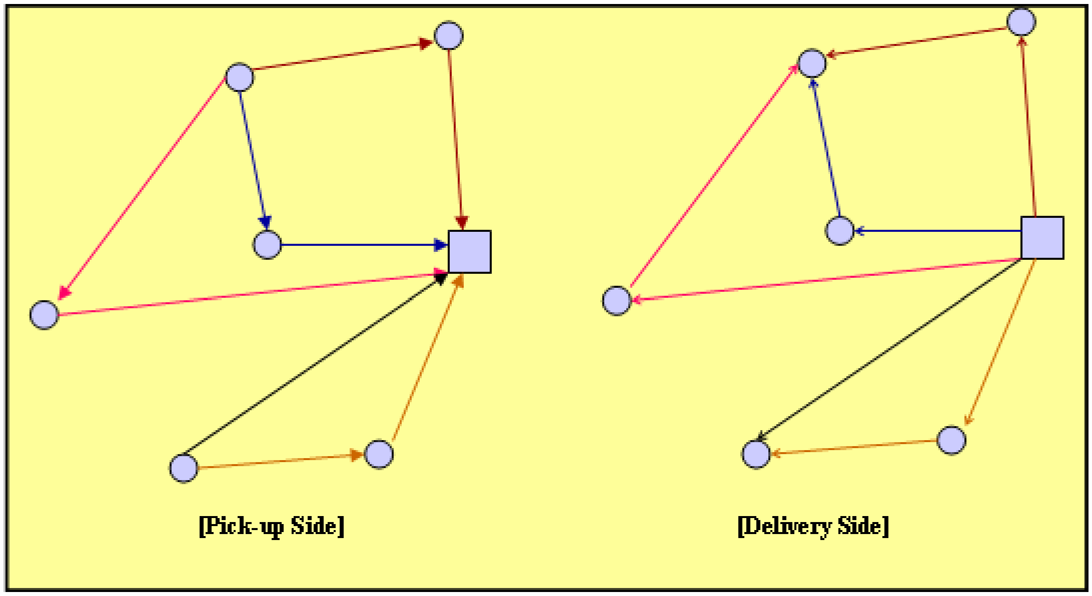
[Table – 5.12]

Chapter 6

Intermediate Stops on Pick-up & Delivery Routes

6.1 Introduction

All analysis conducted in Chapter 5 by Scenarios 1 through 3 are based on the model that there are no intermediate stops from the origin to the hub on the pick-up route and from the hub to the destination on the delivery route. This strategy by its structure leads to less than capacity flight legs. Subject to the temporal and capacity constraints, it is possible to cover one / more airports on pick-up / delivery routes. Introducing intermediate stops leads to reduced fleet size required for the operations thereby opening the opportunity to reduce total costs of operation. Again, there may be several strategies one could envisage to dispatch the demands on pick-up and delivery routes. In this chapter, we introduce the concept of intermediate stops and study the implications of a strategy in which we allow one intermediate stop on the pick-up route and similarly, one intermediate stop on the delivery route (see Figure 6.1).



[Figure 6.1: One Stop Routes on Pick-up and Delivery Sides]

In the subsequent sections, we study various possible configurations, logical combinations and their extensions for the one intermediate stop case.

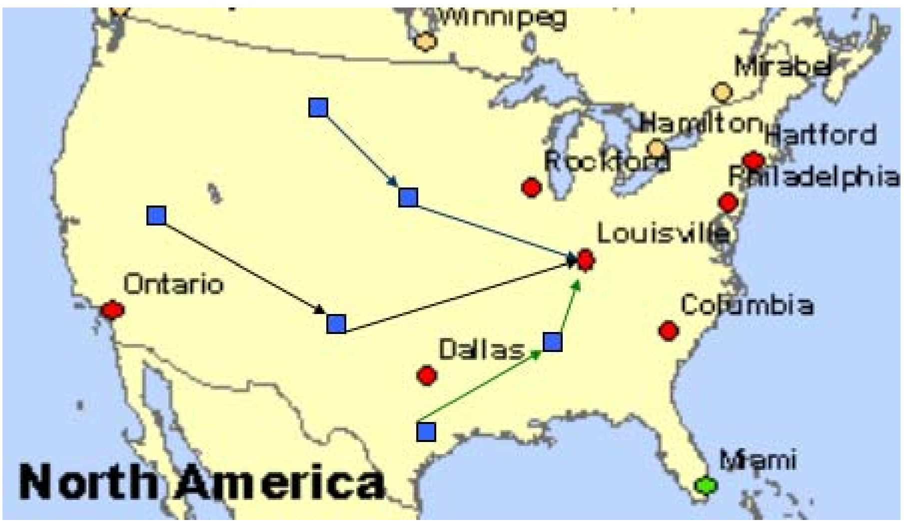
6.2 Scenario 1: Presence of One Intermediate Stop on Pick-up and Delivery Routes – Single Hub Case

We make use of the travel time matrices that we derived from the statistical analysis of the two aircraft types. As described in Chapter 3, we build a set of feasible paths on the city network on both the pick-up and delivery sides with an intermediate stop on each path. Corresponding to each path and depending on the aircraft type, we have total travel time from an origin to the hub (or, hub to destination) which is equal to the sum of the actual air travel time and take-off and landing times and loading time at the intermediate stop. These travel times are further adjusted by taking the time zones into account. The take-off and landing times of an aircraft are the constants of the regression analysis performed on the aircraft travel times as shown in Chapter 4. We assume that the loading time at the intermediate stop on a pick-up route and the unloading time at an intermediate stop on a delivery route are 45 minutes each. We assume a constant cut-off time at all cities by which all the demands reach the origin airports. Similarly, we assume a constant cut-off time by which all the demands should reach the hub. The effect of time zones and the time windows are described in Chapter 2. Based on the above cut-off times, we eliminate the one stop paths obtained above that do not satisfy the temporal constraints. This prescreening helps in reducing the number of path variables that we pass on to the MIP formulation, thereby reducing the problem size. Obviously, we still add the paths corresponding to the direct flights from the origins to the hub (hub to the destinations) on pick-up (delivery) routes. These paths are envisaged to be used by the optimal solution if there are no one-stop paths from an origin to hub (hub to destination) that satisfies the temporal constraints. These paths may also be used in the optimal solution if the demand from an origin (to a destination) is more than aircraft capacity.

In that case, it makes sense to have a direct flight to hub instead of routing it through an intermediate stop. We apply the MIP model described in Chapter 3 to obtain optimal / near-optimal solutions. The model captures the demand constraints, aircraft availability constraints, aircraft balance and volume balance constraints, airport constraints like the maximum number of take-off and landing permitted etc.

(i) Pick-up side

As described in the previous section, we took the set of all feasible paths from all origin cities to the hub with one intermediate stop and applied the MIP formulation. Louisville was again taken as our hub (see Figure 6.2).



[Figure 6.2: One Stop Routes for Single Hub Case (Pick-up)]

(ii) Delivery side

Similar analysis was performed on the delivery side (see Figure 6.3).

[Figure 6.3: One Stop Routes for Single Hub Case (Delivery)]

Table 6.1 summarizes the results obtained from the CPLEX runs.

Single Hub at Louisville	One Stop	No Stop	Savings
	$000	$000	%
Pick-up Side	**4556**	**4800**	**5.4%**
Delivery Side	**4781**	**4953**	**3.6%**
GRAND TOTAL	**9337**	**9753**	**4.5%**

[Table 6.1: Results of One Stop Scenario for Single Hub Case]

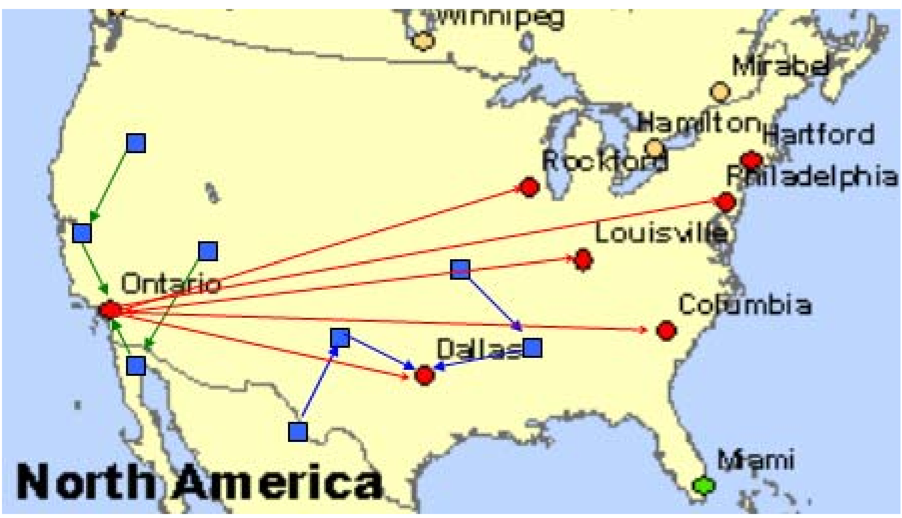
Thus, with the introduction of one intermediate stop on the pick-up and delivery routes in the single hub case leads to a total savings of 4.5%.

6.3 Scenario 2: Presence of One Intermediate Stop on Pick-up and Delivery Routes – Regional Hubs Present

In this section, we further our analysis with the scenario where we have six regional hubs in our network; the hubs being located at Ontario, Rockford, Louisville, Dallas / Ft. Worth, Philadelphia and Columbia. The origin airports are assigned to the hub which is at a minimum distance; so we have six zones with each zone having a regional hub and some airports. For each zone, on the pick-up side, we construct paths from each origin to the regional hub having one intermediate stop. Similarly, we construct paths from the hub to the destination with one intermediate stop. We eliminate paths from the set of paths obtained above depending on the temporal constraints to obtain a set of feasible paths for the network. We apply the MIP formulation to each regional hub on both the pick-up and delivery sides. As described in Chapter 5, we assume that the demands would be flown from the regional hubs to other regional hubs by direct flights.

(i) Pick-up side

Figure 6.4 shows a sample network on the pick-up side under this strategy.



[Figure 6.4: One Stop Cases with Regional Hubs Present (Pickup Side)]

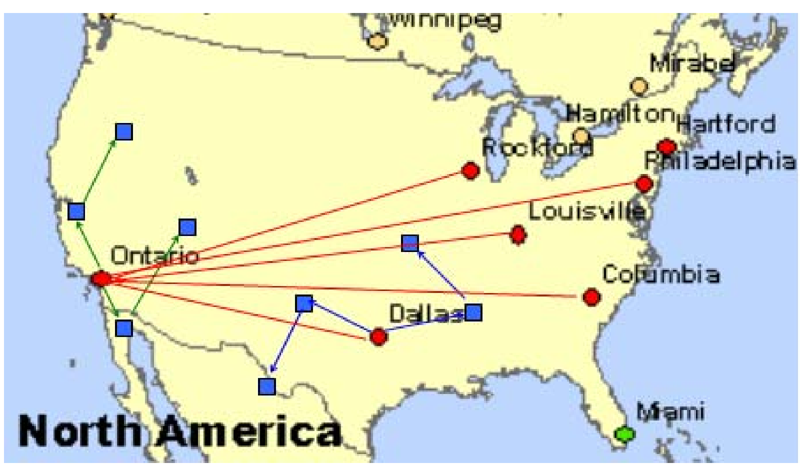
Table 6.2 shows the results obtained from the model runs for the pick-up side for one intermediate stop case and its comparison to the no intermediate stop case. From the results, we find that the cost implications in the one-intermediate stop case are about 4.4 % lesser than the no intermediate hub case. This may be attributed to the effective use of capacity.

REGIONAL HUBS	Pick-up		% Savings
	One Intermediate Stop	No Intermediate Stop	
	$(000)	$(000)	
ONTARIO	**391**	**423**	**7.5%**
ROCKFORD	**715**	**720**	**0.7%**
LOUISVILLE *	**293**	**303**	**3.5%**
DALLAS/FT.WORTH	**325**	**360**	**9.6%**
PHILADELPHIA	**606**	**636**	**4.8%**
COLUMBIA	**459**	**478**	**3.9%**
TOTAL	**2789**	**2918**	**4.4%**

[Table 6.2: Comparison of Pick-up Costs for Regional Hubs Case]

(ii) Delivery side

Fig-6.5 shows a sample network on the delivery side under this strategy.



[Figure 6.5: One Stop Cases with Regional Hubs Present (Delivery Side)]

Similarly, on the delivery side, we show the results obtained in the one intermediate stop and compare with the fleet size requirements for the no intermediate stop case. As shown in Table 6.3, we find that there is a savings of 3.9 % in total cost.

REGIONAL HUBS	Delivery		% Savings
	One Intermediate Stop	No Intermediate Stop	
	$(000)	$(000)	
ONTARIO	**554**	**572**	**3.1%**
ROCKFORD	**481**	**484**	**0.6%**
LOUISVILLE	**283**	**295**	**4.0%**
DALLAS/FT.WORTH	**405**	**428**	**5.4%**
PHILADELPHIA	**632**	**662**	**4.5%**
COLUMBIA	**459**	**488**	**5.9%**
TOTAL	**2814**	**2929**	**3.9%**

[Table 6.3: Comparison of Delivery Costs for Regional Hubs Case]

Total cost incurred would be 10518 [$(000)] the sum of the pick-up side, delivery side and interhub transportation costs. This total cost is 2.3% lower and 12.6% higher compared to the Single Hub-No Stop (Section 5.2) and Single Hub-One Stop (Section 6.2) respectively. We see that even when there are savings of around 4% in both the pick-up and delivery phases, the total cost is higher. This is because of the high interhub transportation cost component. We have assumed that there won't be any intermediate stops on the flights from to hub to hub. This is a realistic assumption owing to the fact that there is considerable consolidation at hubs. And we don't have much leeway as we are dealing with tight time windows.

6.4 Scenario 3: Presence of One Intermediate Stop on Pick-up and Delivery Routes when demands directly dispatched to Destination Regional Hubs

Interhub transportation cost is a big component as we have seen in previous sections (Sections 5.2.2 and 6.3) in which demands were consolidated at origin regional hubs and dispatched to destination regional hubs by interhub flights. In this section, we study the strategy where demands are directly dispatched to the destination regional hubs on the pick-up side and dispatched from origin regional hubs to the destinations on the delivery side. As before, we generate one stop flights on both pick-up and delivery routes subject to temporal constraints. In the pick-up case, the flight would start from an origin city, make a stop in an intermediate city and finally reach the destination regional hub. On the delivery side, the flight would start from the origin regional hub, make an intermediate stop and finally reach the destination city.

Case-A: One Stop Routes From Origin Cities to Destination Regional Hubs

Figure 6.6 shows a sample network on the pick-up side under this strategy.

[Figure 6.6: One Stop Routes from Origin Cities to Destination Regional Hubs]

As shown in Figure 6.6, on the pick-up side, demands are routed from the origin city to the destination regional hubs. These are subsequently delivered to the destinations by one stop paths from the destination regional hub. Table 6.4 shows the results of the MIP runs.

REGIONAL HUBS	Pick-up Cost $(000)	Delivery Cost $(000)	TOTAL COST $(000)
ONTARIO	1576	554	2130
ROCKFORD	1073	481	1554
LOUISVILLE	750	283	1033
DALLAS/FT.WORTH	1016	405	1421
PHILADELPHIA	1787	632	2419
COLUMBIA	1077	459	1536
TOTAL	7279	2814	10093

[Table 6.4: Results of Scenario 3 - One Stop Case A]

The total cost under this strategy is 3.5% and 8.1% higher compared to the Single Hub-No Stop (Section 5.2) and Single Hub-One Stop (Section 6.2) respectively.

Case-B: One Stop Routes From Origin Regional Hubs To Destination Cities

As shown in Figure 6.7, on the delivery side, demands are routed from the origin regional hub to the destination city. Table 6.5 shows the result of the MIP runs.

[Figure 6.7: One Stop Routes From Origin Regional Hubs To Destination Cities]

REGIONAL HUBS	Pick-up Cost $(000)	Delivery Cost $(000)	TOTAL COST $(000)
ONTARIO	391	1117	1508
ROCKFORD	715	1485	2200
LOUISVILLE	293	870	1163
DALLAS/FT.WORTH	325	1727	2052
PHILADELPHIA	606	1729	2335
COLUMBIA	459	1122	1581
TOTAL	2789	8050	10839

[Table 6.5: Results of Scenario 3 - One Stop Case B]

The total cost under this strategy is 11.1% and 16.1% higher compared to the Single Hub-No Stop (Section 5.2) and Single Hub-One Stop (Section 6.2) respectively. One of the reasons that the total cost under the above scenarios is higher than the single hub cases (either with no intermediate stops / one stop) could be attributed to the fact that there is not sufficient amount of consolidation. This results in less than capacity flights. Under Case-A, most likely, it happens that the one stop paths from origin cities to destination regional hub fly less than payload capacity. Similarly, under Case-B, there is not sufficient amount of consolidation which results in less than flight loads from origin regional hub to destination.

6.5 Scenario 4: Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up

and

Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery

On the pick-up side, demands are routed from the origin either through one-stop routes to the destination regional hubs or through no stop routes through the origin regional hub (see Figure 6.8). The delivery side becomes the case where we allow one-stop routes to the destination. Similarly on the delivery side, demands are routed from origin regional hubs either through one-stop routes to destinations or through no stop routes through destination regional hub on delivery (see Figure 6.9). The pick-up side is the case where we allow one-stop routes from origin to origin regional hub..

[Figure 6.8: Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up]

[Figure 6.9: Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery]

Table 6.6 shows the results of the MIP runs for this scenario.

	Pick-up Side	Delivery Side	TOTAL
	$000	$000	$000
Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up	**4210**	**2814**	**7024**
Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery	**2789**	**4025**	**6814**

[Table 6.6: Results of Scenario 4]

Table 6.7 summarizes the results of all one-stop scenarios.

SCENARIOS	**Pick-up Cost** $(000)	**Delivery Cost** $(000)	**TOTAL COST** $(000)	**Savings compared to (1)**
	$(000)	$(000)		
(1) Single Hub Case	**4556**	**4781**	**9337**	
(2)Demand routed through origin regional hubs	**7704**	**2815**	**10519**	**-13%**
(3)Demand routed from origins to destination regional hubs	**7279**	**2814**	**10093**	**-8%**
(4)Demand routed from origin regional hubs to destinations	**2789**	**8050**	**10839**	**-16%**
(5)a Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up	**4210**	**2814**	**7024**	**25%**
(5)b Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery	**2789**	**4025**	**6814**	**27%**

[Table 6.7: Summary of One Stop Scenarios]

From the analysis, we find that the scenario where demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up or, demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery performs the best operational cost wise with average savings of 26%. Clearly, this strategy stands out to be the best of all the scenarios we have discussed in Chapters 5 and 6.

Chapter 7

Sensitivity Analysis

7.1 Introduction

In the previous two chapters, we studied the cost impact of various operational scenarios and we made comparisons of cost savings. It may be noted that the costs obtained from the MIP runs for all the cases in Chapter 5 and 6 are based on one deterministic set of origin-destination demands. Similarly, the unit cost incurred by an aircraft per nautical mile reflects a preset fuel price and fixed cost of the aircraft. Naturally, the observations made in the previous chapter cannot be generalized for all feasible demands and unit cost of transportation. An ideal way of finding the cost savings under various scenarios would be obtaining real demand and cost data from the industry and running the model scenarios.

However, with the absence of real data, we could run some sensitivity analysis and figure out the trends in operational costs across various scenarios. Since demand and unit cost of transportation are the most important factors in the problem, we perform a sensitivity analysis for these two components. For the demand analysis, we take three sets of deterministic demands in addition to the earlier demand taken for the model run. These three demand sets reflect 50%, 150% and 200% of the original demand taken. We run the same scenarios and analyze the cost implications of demand. Similarly, on the unit cost of transportation side, we run some sensitivity analysis to study the effect of fixed costs and fuel price on the total cost of operations. In addition, to the above two components, we conduct some sensitivity analysis on the implications of airport constraints on the model. Chapter 5 and 6 assumed that there was no limitation on the number of flights between a pair of airports. Realistically, there is a restriction on the number of take-offs and landings at a particular airport that depends on factors like gateway availability etc. We analyze the cost implications by providing bounds on the number of flights of a particular type of aircraft between a pair of cities. One could easily incorporate other airport constraints and study the implications.

7.2 Demand Sensitivity

As discussed in the introduction, for the demand analysis, we take three sets of deterministic demands in addition to the earlier demand taken for the model run. These three demand sets reflect 50%, 150% and 200% of the original demand taken. Cost components remain the same as before. We run the scenarios described in Chapters 5 and 6 and analyze the cost implications.

7.2.1 No Intermediate Stop Scenarios

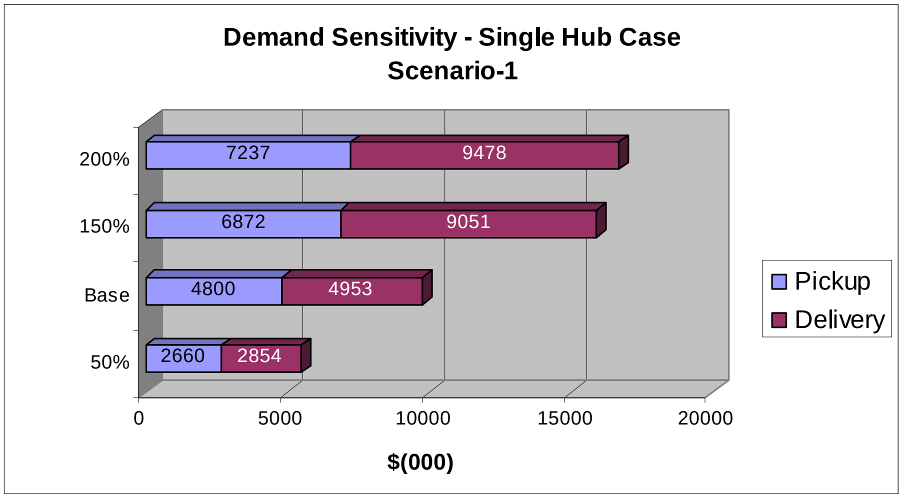
7.2.1.1 Scenario-1: Only one Origin-Hub pair and only one Hub-Destination pair

(i) Single Hub Case

Table 7.1 and Figure 7.1 show the results of the MIP runs.

SINGLE HUB AT LOUISVILLE	50%	Base	150%	200%
	$('000)	$('000)	$('000)	$('000)
PICK-UP	2660	4800	6872	7237
DELIVERY	2854	4953	9051	9478
TOTAL	5514	9753	15923	16715
% Change from Base	-43%		63%	71%

[Table 7.1: No Stop Scenario 1- Single Hub Case Demand Sensitivity Results]



[Figure 7.1: Demand Sensitivity- No Stop Scenario1- Single Hub Case]

It appears that economies of scales are achieved when the demand increases from 150% to 200%.

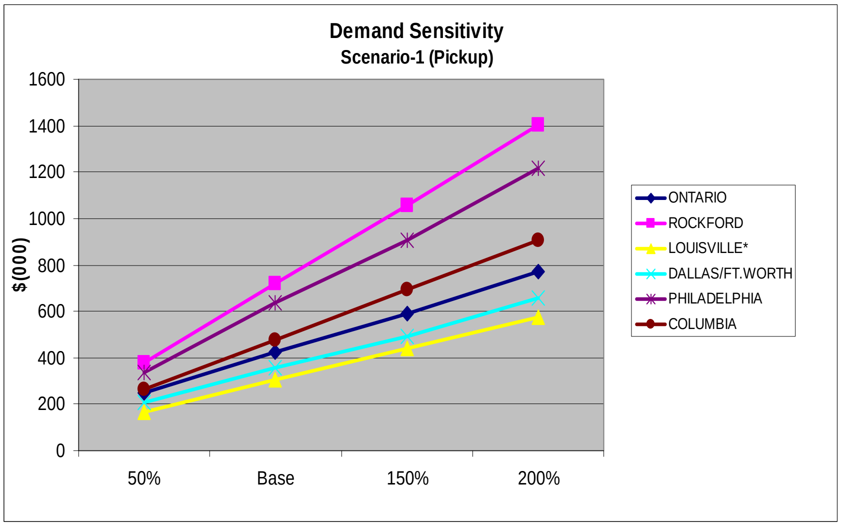
(ii) Regional Hubs Present

Pick-up and Delivery Costs

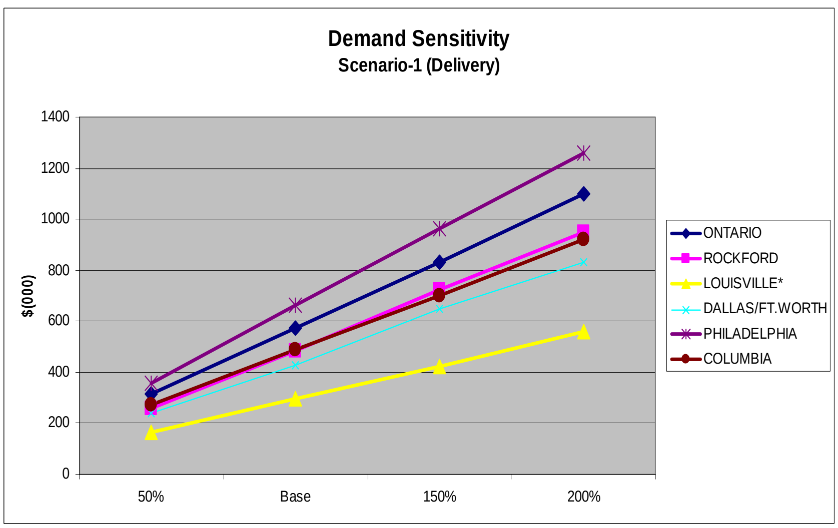
Table 7.2 and Figures 7.2a and 7.2b show the results of MIP runs for the case when demands are routed through origin regional hubs only.

REGIONAL HUBS	Pick-up Side				Delivery Side			
	50%	Base	150%	200%	50%	Base	150%	200%
	('000)	('000)	('000)	('000)	('000)	('000)	('000)	('000)
ONTARIO	247	423	593	771	315	572	829	1098
ROCKFORD	378	720	1055	1403	256	484	724	949
LOUISVILLE*	164	303	442	577	164	295	421	558
DALLAS/FT.WORTH	205	359	493	656	238	428	647	831
PHILADELPHIA	337	636	906	1216	358	662	964	1259
COLUMBIA	265	478	691	906	271	488	698	919
TOTAL	1596	2918	4180	5529	1602	2929	4283	5615

[Table 7.2: No Stop Scenario 1- Regional Hub Case Demand Sensitivity Results]



[Figure-7.2a: Demand Sensitivity- No Stop Scenario1- Regional Hubs Case (Pickup)]



[Figure 7.2b: Demand Sensitivity- No Stop Scenario1- Regional Hubs Case (Delivery)]

The increase in cost due to increase in demand has a linear relation for each regional hub both on the pick-up and delivery sides.

Interhub Transportation Costs

Table 7.3 shows the interhub transportation costs for different demand levels.

Base	50%	150%	200%
('000)	('000)	('000)	('000)
4915	**2549**	**7314**	**9681**

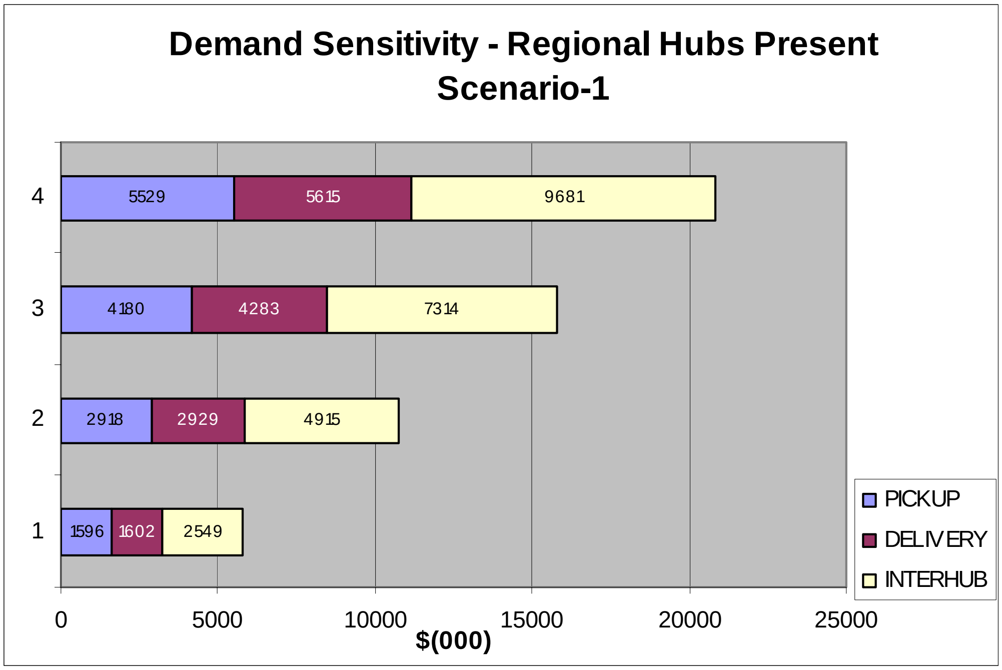
[Table 7.3: Interhub Transportation Costs]

Total Cost

This is the sum of the pick-up side cost, delivery side cost and the interhub transportation costs. Table 7.4 and Figure 7.3 show the results.

TOTAL COST				
REGIONAL HUBS	**50%**	**Base**	**150%**	**200%**
	('000)	('000)	('000)	('000)
ONTARIO	**562**	**995**	**1422**	**1869**
ROCKFORD	**634**	**1204**	**1778**	**2352**
LOUISVILLE*	**328**	**598**	**864**	**1135**
DALLAS/FT.WORTH	**443**	**787**	**1140**	**1487**
PHILADELPHIA	**695**	**1298**	**1869**	**2475**
COLUMBIA	**536**	**966**	**1389**	**1825**
INTERHUB	**2549**	**4915**	**7314**	**9681**
TOTAL	**5747**	**10762**	**15777**	**20824**
% Change from Base	**47%**		**47%**	**93%**

[Table 7.4: Demand Sensitivity of Total Cost for Scenario 1 Regional Hub Case]



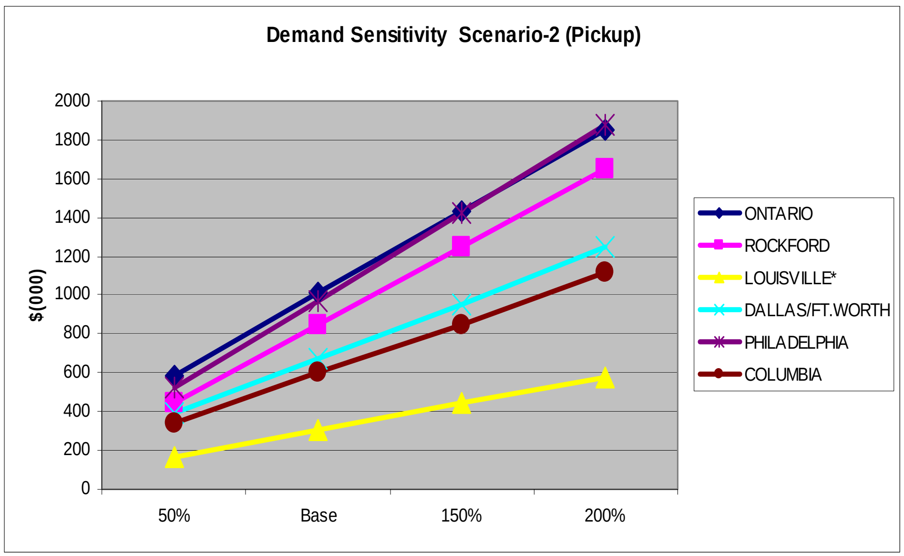
[Figure 7.3: Demand Sensitivity of Total Cost for Scenario 1 Regional Hub Case]

7.2.1.2 Scenario-2: No Intermediate Stops with demands routed through multiple hubs

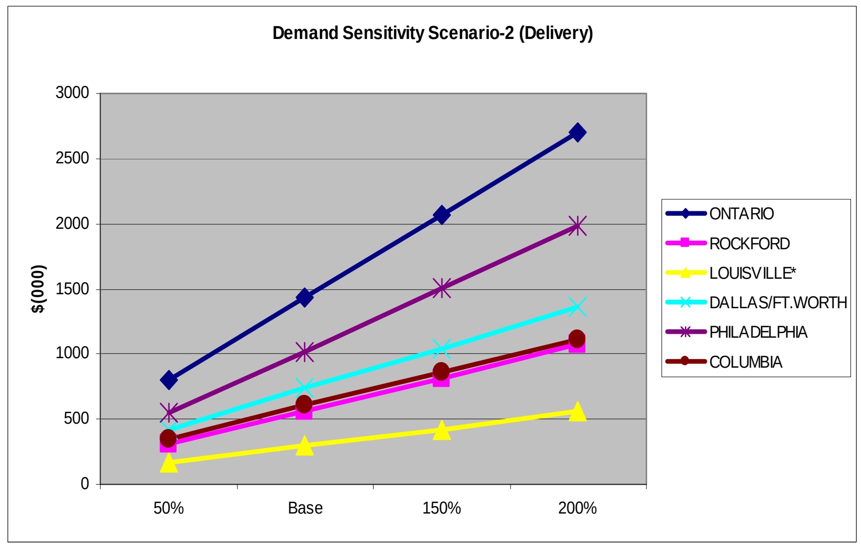
In this case, demands are routed either through Origin Regional Hub or directly to main hub on the pick-up side. On the delivery side, demands are routed either through destination regional hub or to destination Table 7.5 shows the result of MIP runs. Figures 7.4a and 7.4b show the cost impact of the variation in demand on pick-up and delivery sides respectively.

Scenario-2	50%		Base		150%		200%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	585	804	1011	1433	1430	2064	1853	2695
ROCKFORD	447	311	848	566	1252	817	1649	1078
LOUISVILLE*	164	164	303	295	443	421	577	558
DALLAS/FT.WORTH	394	419	671	740	953	1035	1245	1361
PHILADELPHIA	523	554	969	1021	1427	1502	1877	1985
COLUMBIA	343	344	604	606	843	859	1114	1114
TOTAL	5051		9066		13045		17106	
% Increase from Base	-44%				44%		89%	

[Table 7.5: No Stop- Scenario 2 Demand Sensitivity Results]

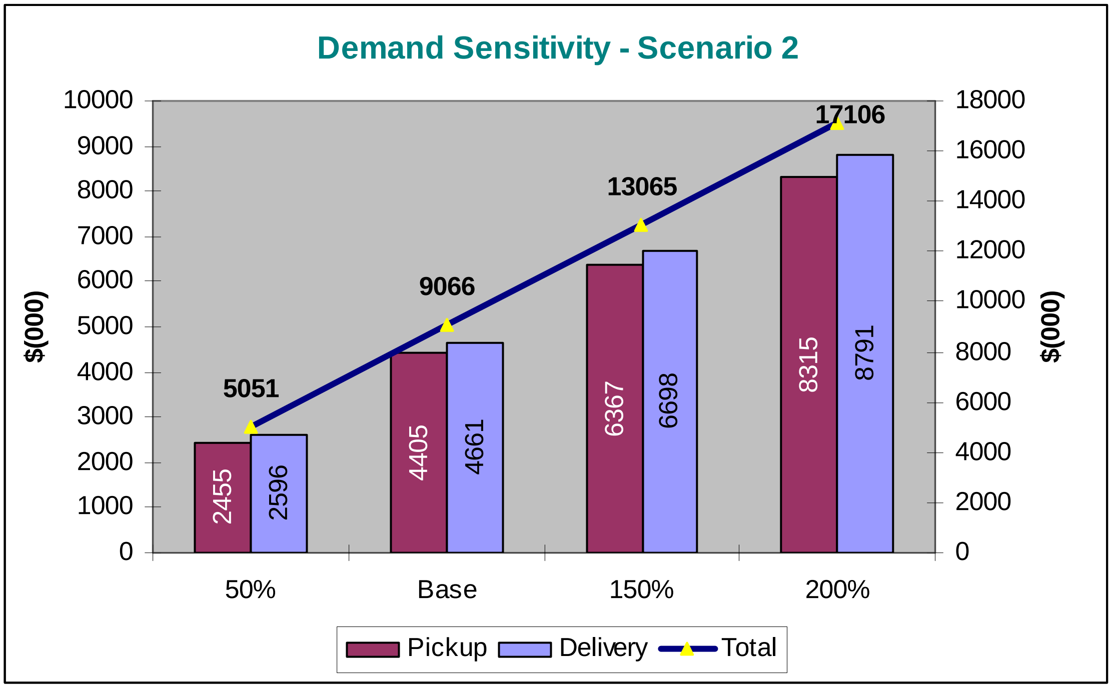


[Figure 7.4a: No Stop- Scenario 2 Demand Sensitivity (Pickup)]



[Figure 7.4b: No Stop- Scenario 2 Demand Sensitivity (Delivery)]

As shown in Figure 7.4a and Figure 7.4b, the cost increases linearly for both pick-up and delivery sides with the increase in demand. Figure 7.5 shows the graphic of total cost.



[Figure 7.5: No Stop- Scenario 2 Demand Sensitivity (Total Cost Variation)]

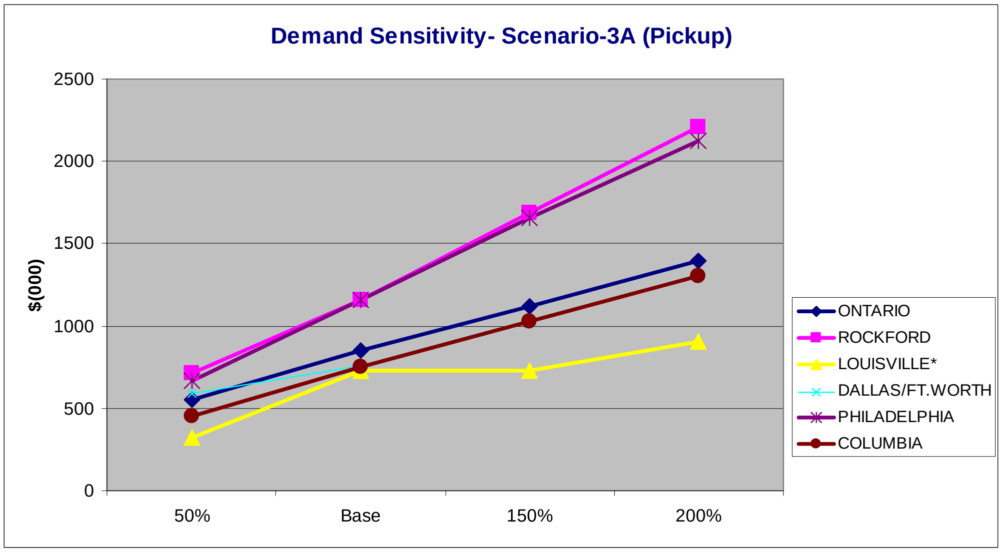
It appears that total cost increases with a slope of nearly one; i.e. total costs increases by almost the same percentage as the increase in demand.

7.2.1.3.1 Scenario 3A: Demands routed either through Origin Regional Hub or Destination Regional Hub on pick-up side

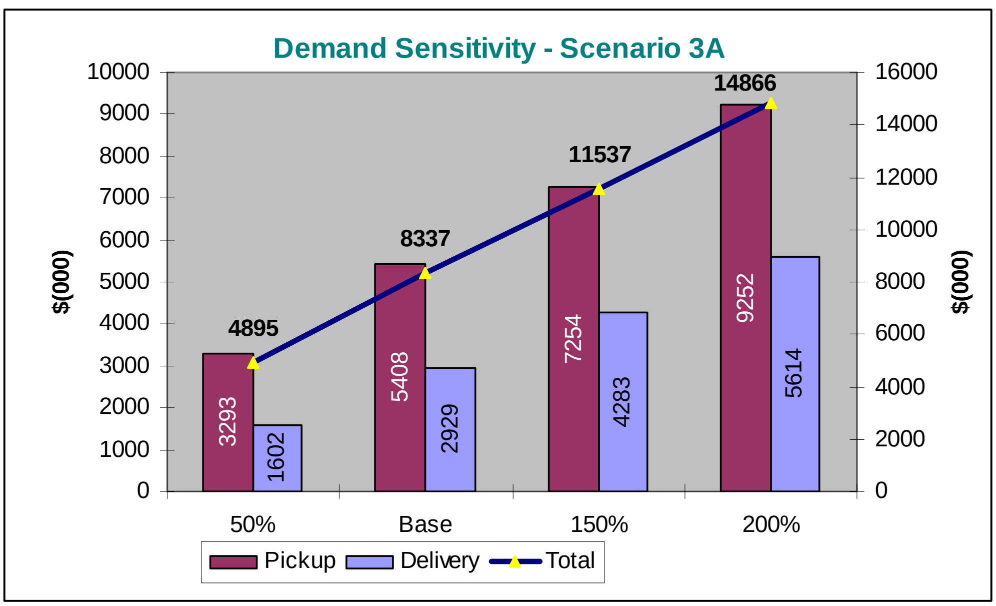
In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only. On the pick-up side, demands are routed either through Origin Regional Hub or directly to Destination Regional Hub. On the delivery side, demands are routed directly to the destination. Table 7.6a shows the results of the MIP runs. Figure 7.6a and Figure 7.6b shows the variation of total costs with respect to demand.

Scenario- 3A	50%		Base		150%		200%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	554	315	849	572	1118	829	1395	1098
ROCKFORD	711	256	1158	484	1686	724	2207	949
LOUISVILLE	323	164	726	295	728	421	903	558
DALLAS/FT.WORTH	588	238	763	428	1033	647	1315	831
PHILADELPHIA	665	358	1160	662	1660	964	2127	1259
COLUMBIA	452	271	752	488	1029	698	1305	919
TOTAL	**3293**	**1602**	**5408**	**2929**	**7254**	**4283**	**9252**	**5614**
GRAND TOTAL	**4895**		**8337**		**11537**		**14866**	
% Increase from Base	**-41%**				**38%**		**78%**	

[Table 7.6a: No Stop- Scenario 3A Demand Sensitivity]



[Figure 7.6a: No Stop- Scenario 3A Demand Sensitivity of Regional Hubs]



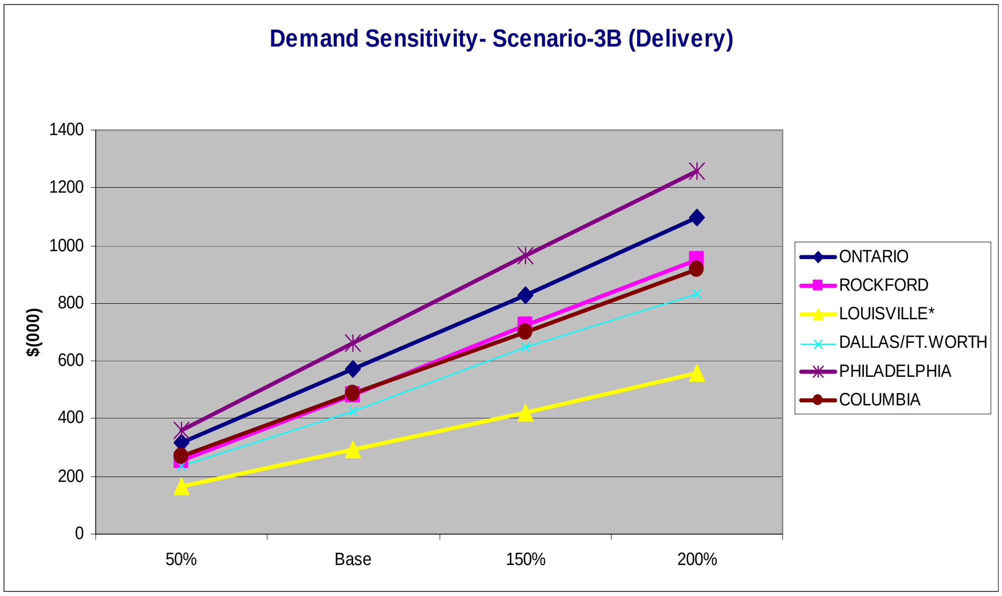
[Figure 7.6b: No Stop- Scenario 3A Demand Sensitivity (Total Cost)]

7.2.1.3.2 Scenario 3B: Demands routed from Origin Regional Hubs to destination or Destination Regional Hub

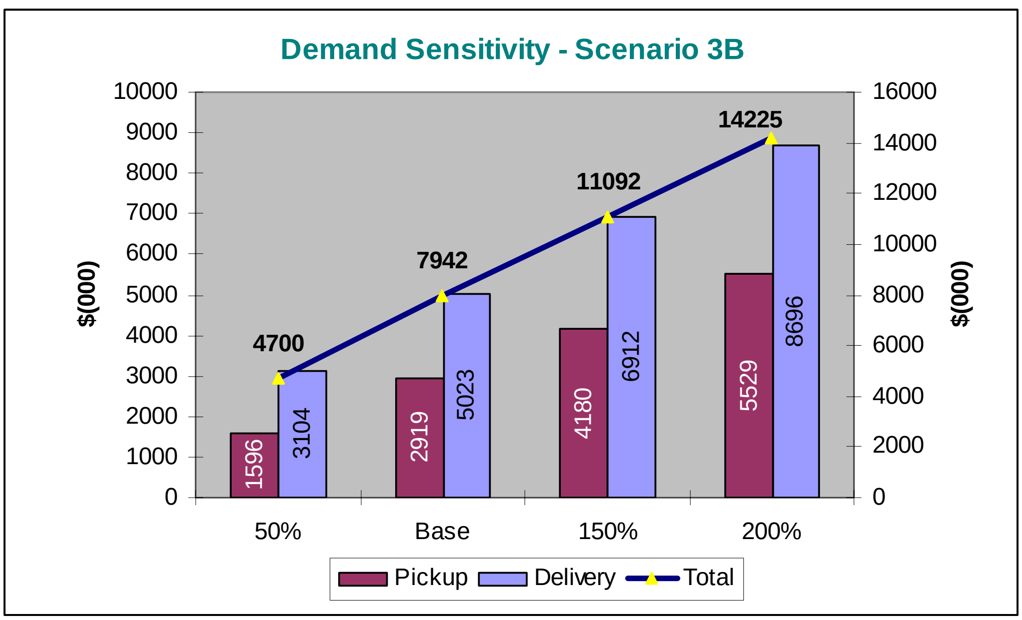
On the pick-up side, demands are routed through the Origin Regional Hub. On the delivery side, demands are routed either through destination regional hub or to directly to the destination. Table 7.6b shows the results of the MIP runs. Figure 7.7a shows the variation of delivery cost with respect to demand. Figure 7.7b shows the variation of total cost with respect to demand.

Scenario- 3B	50%		Base		150%		200%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	247	708	423	1112	593	1472	771	1876
ROCKFORD	378	451	720	769	1055	1088	1403	1403
LOUISVILLE	164	306	303	490	442	645	577	796
DALLAS/FT.WORTH	205	524	359	821	493	1166	656	1345
PHILADELPHIA	337	680	636	1128	906	1593	1216	2068
COLUMBIA	265	435	478	703	691	948	906	1208
TOTAL	**1596**	**3104**	**2919**	**5023**	**4180**	**6912**	**5529**	**8696**
GRAND TOTAL	**4700**		**7942**		**11092**		**14225**	
% Increase from Base	**-41%**				**40%**		**79%**	

[Table 7.6b: No Stop- Scenario 3B Demand Sensitivity]



[Figure 7.7a: No Stop- Scenario 3A Demand Sensitivity of Regional Hubs]



[Figure-7.7b: No Stop Scenario 3A Total Cost versus Demand]

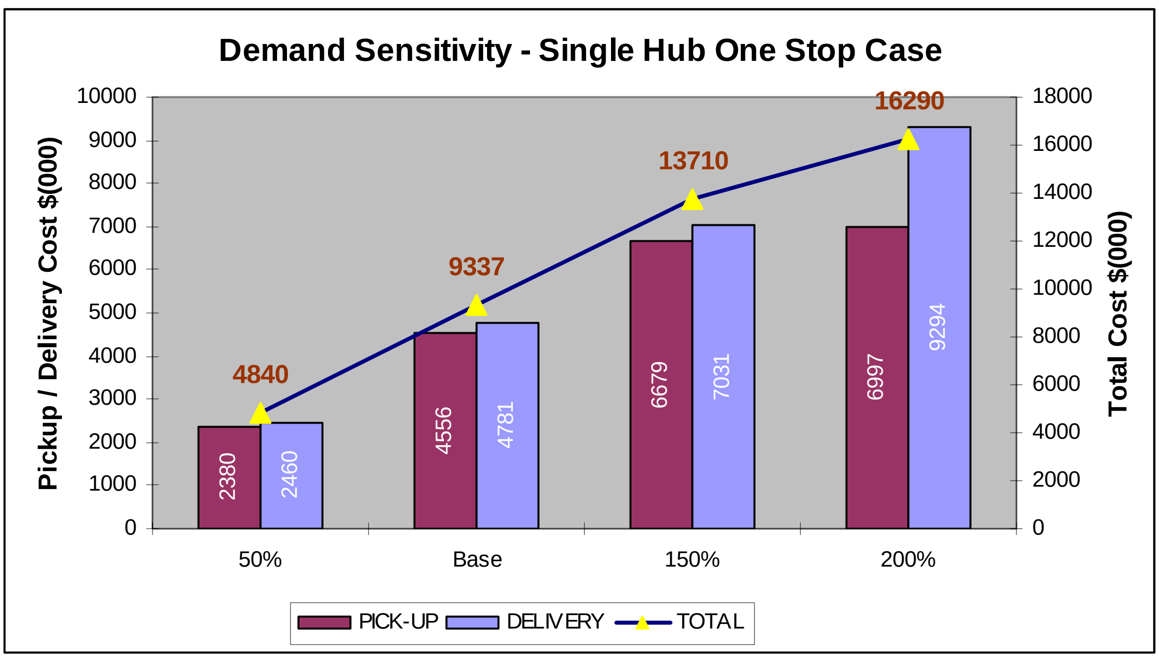
7.2.2 One Intermediate Stop Scenarios

7.2.2.1 Scenario 1: Single Hub Case

As shown in Table 7.7 and Figure 7.8, some economies of scale is observed when the demand doubles, but mostly it cost increases with a slope one with respect to demand.

SINGLE HUB AT LOUISVILLE	50%	Base	150%	200%
	$('000)	$('000)	$('000)	$('000)
PICK-UP	2380	4556	6679	6997
DELIVERY	2460	4781	7031	9294
TOTAL	4840	9337	13710	16290
% Change from Base	-48%		47%	74%

[Table 7.7: One Stop- Single Hub Case Demand Sensitivity Results]



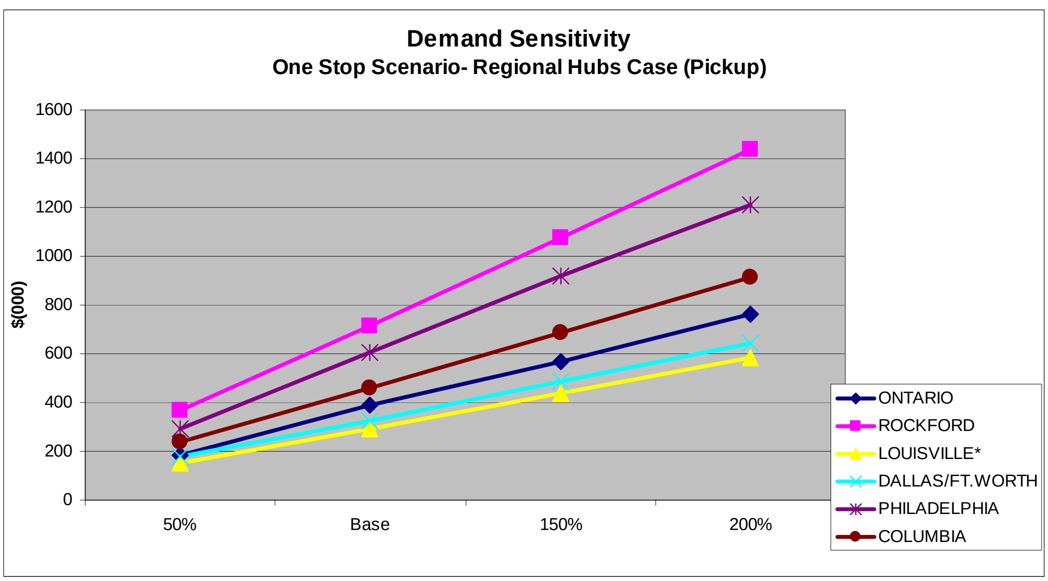
[Figure 7.8: One Stop- Single Hub Case Demand Sensitivity Results]

7.2.2.2 Scenario 2: Regional Hubs Present-All demands dispatched through origin regional hubs

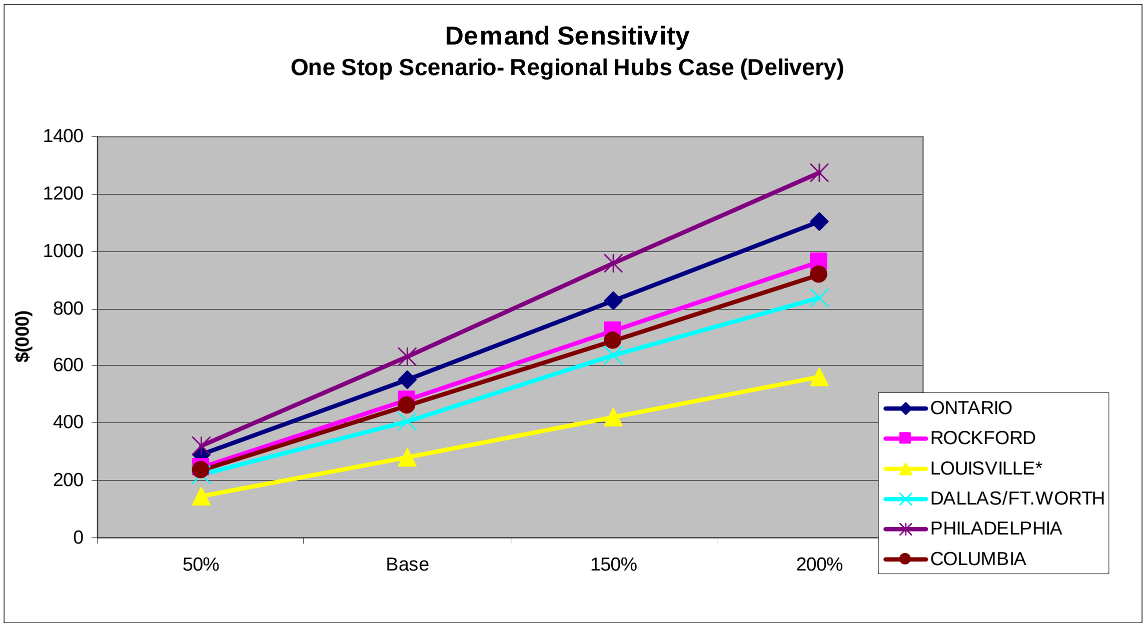
Results for the pick-up and delivery sides are shown in Table 7.8. Figure 7.9a and 7.9b show the variation of cost with respect to demand.

REGIONAL HUBS	Pick-up Side				Delivery Side			
	50%	Base	150%	200%	50%	Base	150%	200%
	\$('000)	\$('000)	\$('000)	\$('000)	\$('000)	\$('000)	\$('000)	\$('000)
ONTARIO	185	391	570	760	289	554	830	1105
ROCKFORD	369	715	1078	1438	247	481	724	965
LOUISVILLE*	152	293	440	583	147	283	422	563
DALLAS/FT.WORTH	178	325	486	643	222	405	636	839
PHILADELPHIA	294	606	917	1211	323	632	958	1274
COLUMBIA	237	459	688	916	238	461	688	917
TOTAL	1415	2789	4179	5551	1468	2817	4258	5664

[Table 7.8: One Stop- Scenario 1 Regional Hubs Case Demand Sensitivity Results]



[Figure 7.9a: One Stop- Scenario 1 Regional Hubs Case Demand Sensitivity (Pickup)]



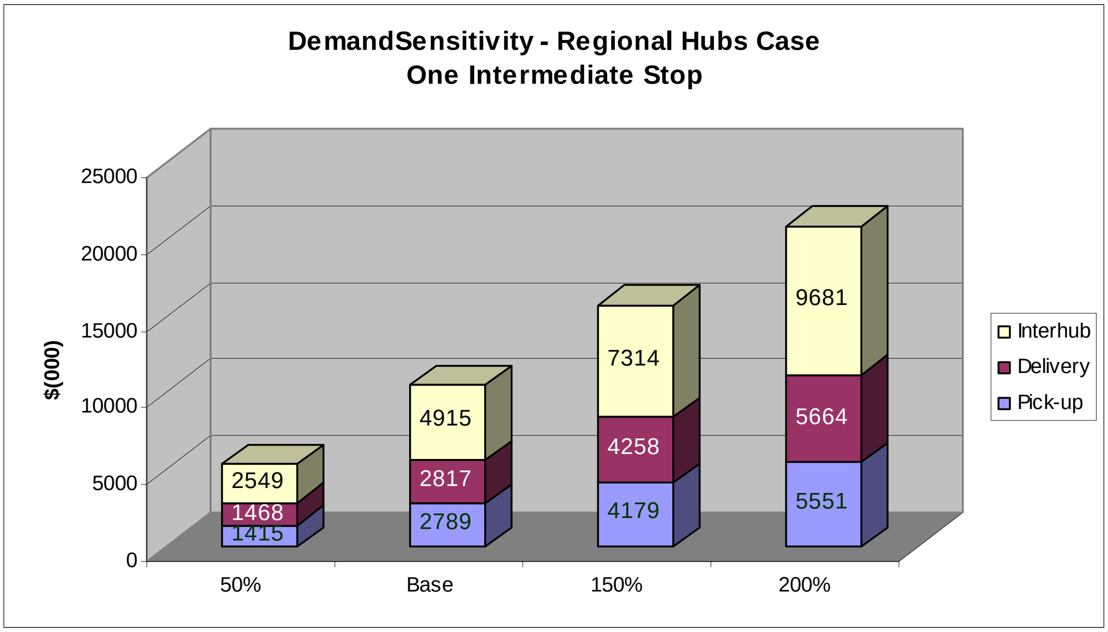
[Figure 7.9b: One Stop- Scenario 1 Regional Hubs Case Demand Sensitivity (Delivery)]

Total Cost of operations is shown in Table 7.9.

TOTAL COST				
REGIONAL HUBS	**50%**	**Base**	**150%**	**200%**
	$('000)	$('000)	$('000)	$('000)
ONTARIO	**475**	**946**	**1400**	**1865**
ROCKFORD	**616**	**1196**	**1803**	**2403**
LOUISVILLE*	**300**	**576**	**862**	**1146**
DALLAS/FT.WORTH	**401**	**730**	**1122**	**1482**
PHILADELPHIA	**617**	**1238**	**1875**	**2485**
COLUMBIA	**475**	**921**	**1376**	**1832**
INTERHUB	**2549**	**4915**	**7314**	**9681**
TOTAL	**5432**	**10521**	**15751**	**20896**
% Change from Base	**-48%**		**50%**	**99%**

[Table 7.9: One Stop- Scenario 1 Regional Hubs Case Demand Sensitivity (Total Cost)]

Figure 7.10 shows the variation of total cost with respect to variation in the demand.



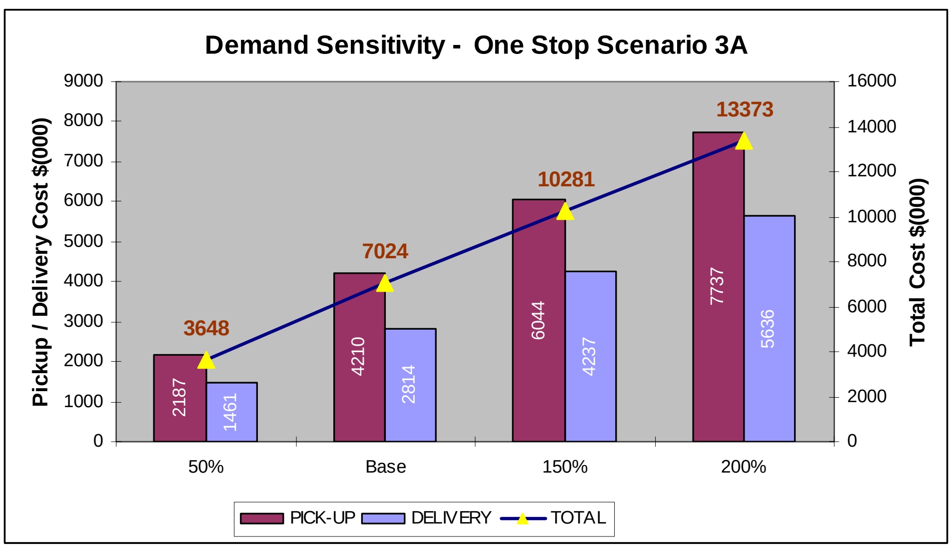
[Figure 7.10: One Stop- Scenario 1 Regional Hubs Case Demand Sensitivity (Total Cost)]

7.2.2.3.1 Scenario 3A: Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up

On the pick-up side, demands are routed from the origin either through one-stop routes to the destination regional hubs or through no stop routes through the origin regional hub (see Figure 6.8). The delivery side becomes the case where we allow one-stop routes to the destination. Table 7.10 and Figure 7.11 show the results of the MIP runs.

Scenario 3A	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
50%	**2187**	**1461**	**3648**	**-48%**
Base	**4210**	**2814**	**7024**	
150%	**6044**	**4237**	**10282**	**46%**
200%	**7737**	**5636**	**13373**	**90%**

[Table 7.10: One Stop- Scenario 3A Demand Sensitivity (Total Cost)]



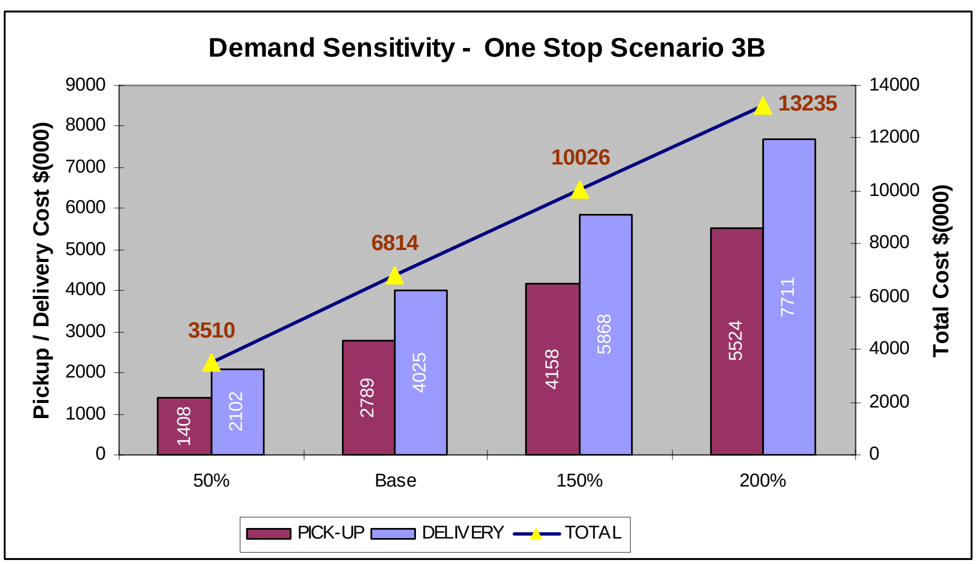
[Figure 7.11: One Stop- Scenario 3A Demand Sensitivity (Total Cost)]

7.2.2.3.2 Scenario 3B: Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery

The pick-up side is the case where we allow one-stop routes from origin to origin regional hub. On the delivery side, demands are routed from origin regional hubs either through one-stop routes to destinations or through no stop routes through destination regional hub on delivery. Table 7.11 and Figure 7.12 show the results of the MIP runs.

Scenario 3B	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
50%	**1408**	**2102**	**3511**	**-48%**
Base	**2789**	**4025**	**6814**	
150%	**4158**	**5868**	**10027**	**47%**
200%	**5524**	**7711**	**13235**	**94%**

[Table 7.11: One Stop- Scenario 3B Demand Sensitivity (Total Cost)]



[Figure 7.12: One Stop- Scenario 3B Demand Sensitivity (Total Cost)]

7.3 Fixed Cost Sensitivity

Unit cost of transportation is the most important factor from the revenue standpoint of the operations. Cost of transportation between an origin-destination pair has two broad components: fixed and operational. Fixed cost of owning or leasing, maintaining the aircraft, personnel, airport fees etc. come under the fixed category. The operational cost component is broadly dependent on the unit cost of fuel, type of aircraft used and nautical distance between the origin and destination. As we can see, the unit cost of transportation between an origin-destination pair could be easily affected by any of the above factors e.g fuel price. In the following sections, we have conducted sensitivity analysis of cost with regard to the fixed cost of operations. In this analysis, we increased the fixed component of the flights to 125%, 150%, 200%, 300% and 500% of the fixed cost assumed in Chapter-5 and Chapter-6. The variable cost component was kept same as before. MIP runs were conducted for the same scenarios as discussed in Chapter 5 and Chapter 6.

7.3.1 No Intermediate Stop Scenarios

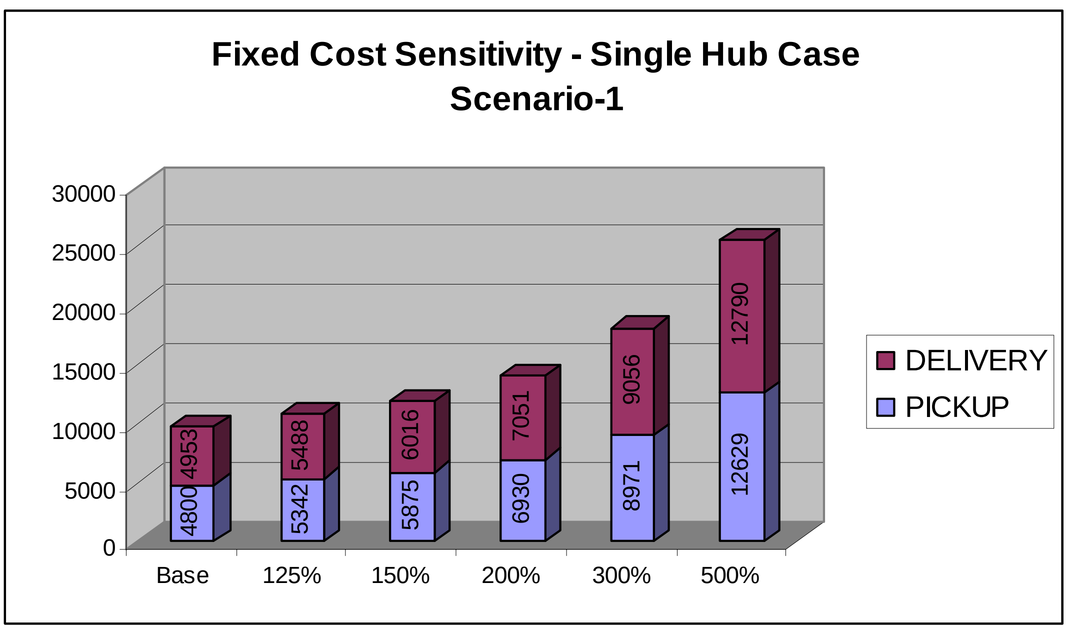
7.3.1.1 Scenario-1: Only one Origin-Hub pair and only one Hub-Destination pair

(i) Single Hub Case

Table-7.12 and Figure-7.13 show the results of the MIP runs.

SINGLE HUB AT LOUISVILLE	Base	125%	150%	200%	300%	500%
	('000)	('000)	('000)	('000)	('000)	('000)
PICK-UP	4800	5342	5875	6930	8971	12629
DELIVERY	4953	5488	6016	7051	9056	12790
TOTAL	9753	10830	11891	13981	18027	25419
% Increase from Base		11%	22%	43%	85%	160%

[Table 7.12: No Stop Scenario 1- Single Hub Case Fixed Cost Sensitivity Results]



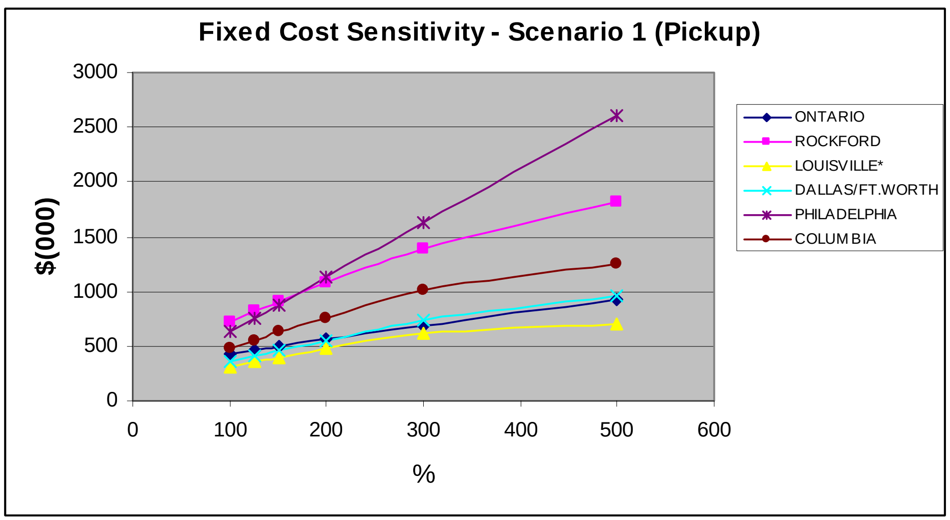
[Figure7.13: Fixed Cost Sensitivity- No Stop Scenario1- Single Hub Case]

(ii) Regional Hubs Present

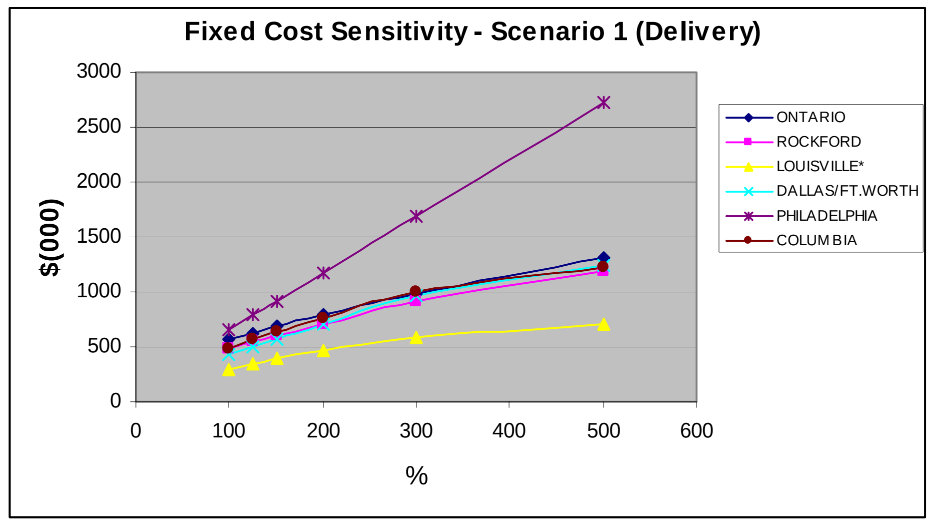
Table 7.13 shows the results of the MIP runs for the case when demands are routed through origin regional hubs only. Figures 7.14a and 7.14b show the variation of total cost with respect to the variation in fixed cost.

	Pick-up Side						Delivery Side					
REGIONAL HUBS	**Base**	**125%**	**150%**	**200%**	**300%**	**500%**	**Base**	**125%**	**150%**	**200%**	**300%**	**500%**
	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)
ONTARIO	423	461	496	562	690	925	572	629	686	788	980	1316
ROCKFORD	720	822	908	1074	1391	1814	484	549	605	712	914	1192
LOUISVILLE*	303	354	402	488	613	707	295	348	393	470	584	707
DALLAS/FT.WORTH	360	410	459	556	736	958	428	497	565	703	960	1241
PHILADELPHIA	636	759	882	1128	1621	2603	662	791	921	1178	1693	2723
COLUMBIA	478	555	627	758	1013	1245	488	563	635	762	997	1226
TOTAL	**2919**	**3361**	**3773**	**4567**	**6064**	**8251**	**2929**	**3377**	**3806**	**4614**	**6129**	**8406**

[Table 7.13: No Stop Scenario 1 Regional Hub Case - Fixed Cost Sensitivity Results]



[Figure 7.14a: Fixed Cost Sensitivity- No Stop Scenario1- Regional Hubs Case (Pickup)]



[Figure 7.14b: Fixed Cost Sensitivity- No Stop Scenario1- Regional Hubs Case (Delivery)]

Interhub Cost

Table 7.14 shows the interhub transportation cost for variation in fixed cost.

Base	125%	150%	200%	300%	500%
('000)	('000)	('000)	('000)	('000)	('000)
4915	**5353**	**5789**	**6660**	**8400**	**11855**

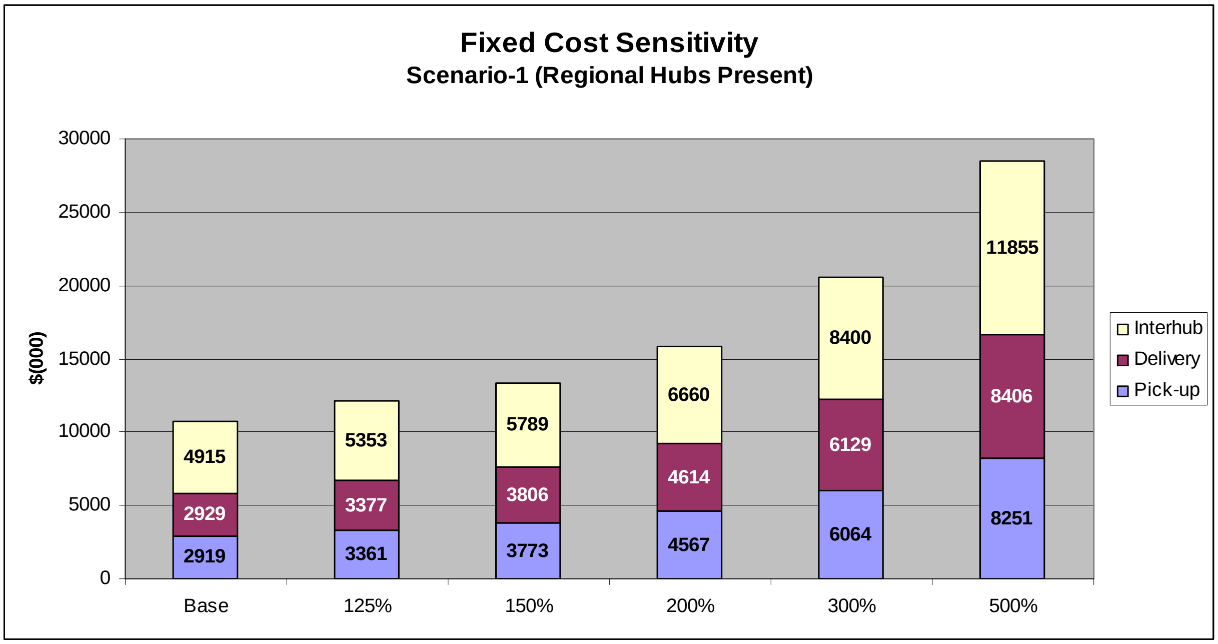
[Table 7.14: Interhub Transportation Costs]

Total Cost

This is sum of the pick-up side cost, delivery side cost and the interhub transportation cost and is shown in Table 7.15 and Figure 7.15.

TOTAL COST						
REGIONAL HUBS	Base	125%	150%	200%	300%	500%
	('000)	('000)	('000)	('000)	('000)	('000)
ONTARIO	995	1090	1182	1351	1671	2241
ROCKFORD	1204	1372	1513	1787	2305	3006
LOUISVILLE*	598	701	795	958	1197	1415
DALLAS/FT.WORTH	788	907	1025	1259	1696	2199
PHILADELPHIA	1298	1550	1803	2307	3314	5326
COLUMBIA	966	1118	1262	1520	2010	2471
INTERHUB	4915	5353	5789	6660	8400	11855
TOTAL	10763	12091	13369	15841	20593	28513
% Increase from Base		12%	24%	47%	91%	165%

[Table 7.15: Fixed Cost Sensitivity of Total Cost for Scenario 1 Regional Hub Case]



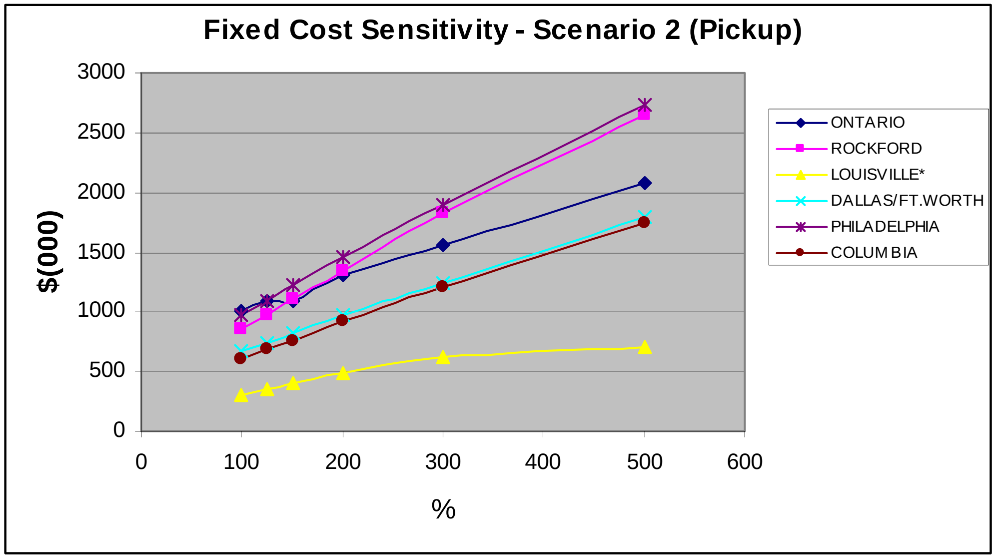
[Figure 7.15: Sensitivity of Total Cost for Scenario 1 Regional Hub Case]

7.3.1.2 Scenario-2: No Intermediate Stops with demands routed through multiple hubs

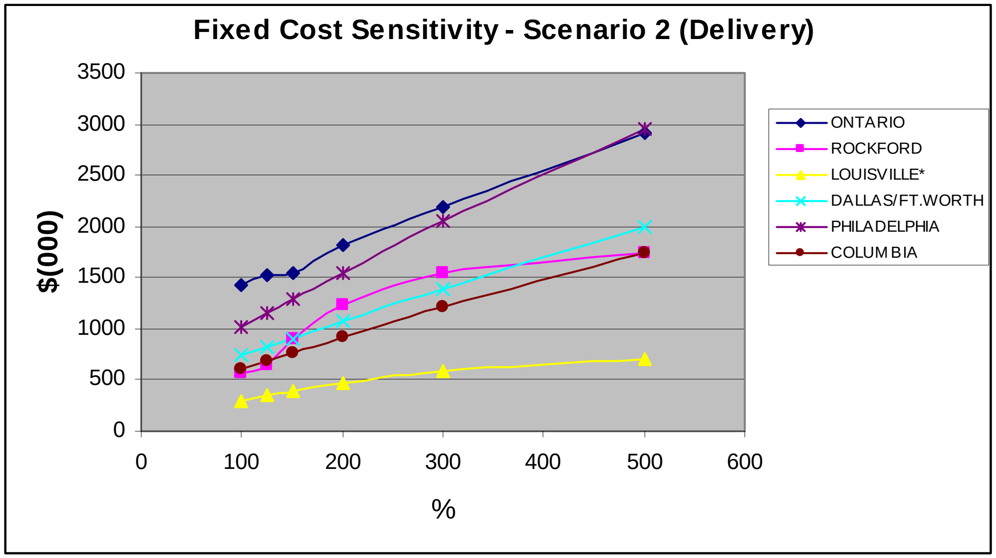
In this case, demands are routed either through Origin Regional Hub or directly to main hub on the pick-up side. On the delivery side, demands are routed either through destination regional hub or to destination Table 7.16 shows the result of MIP runs. Figures 7.16 a and 7.16b show the cost impact of the variation in fixed cost on pick-up and delivery sides respectively.

Scenario-2	Base		125%		150%		200%		300%		500%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	1011	1433	1085	1533	1093	1539	1300	1819	1566	2190	2076	2922
ROCKFORD	848	566	974	653	1100	906	1348	1226	1829	1535	2642	1743
LOUISVILLE*	303	295	354	348	402	393	488	470	613	584	707	707
DALLAS/FT.WORTH	671	740	745	824	820	908	967	1072	1248	1396	1785	2004
PHILADELPHIA	969	1021	1095	1155	1219	1288	1456	1548	1900	2044	2736	2950
COLUMBIA	604	606	684	686	762	766	916	926	1201	1211	1745	1739
TOTAL	**9066**		**10136**		**11197**		**13536**		**17318**		**23756**	
% Increase from Base			**12%**		**24%**		**49%**		**91%**		**162%**	

[Table 7.16: No Stop- Scenario 2 Fixed Cost Sensitivity Results]



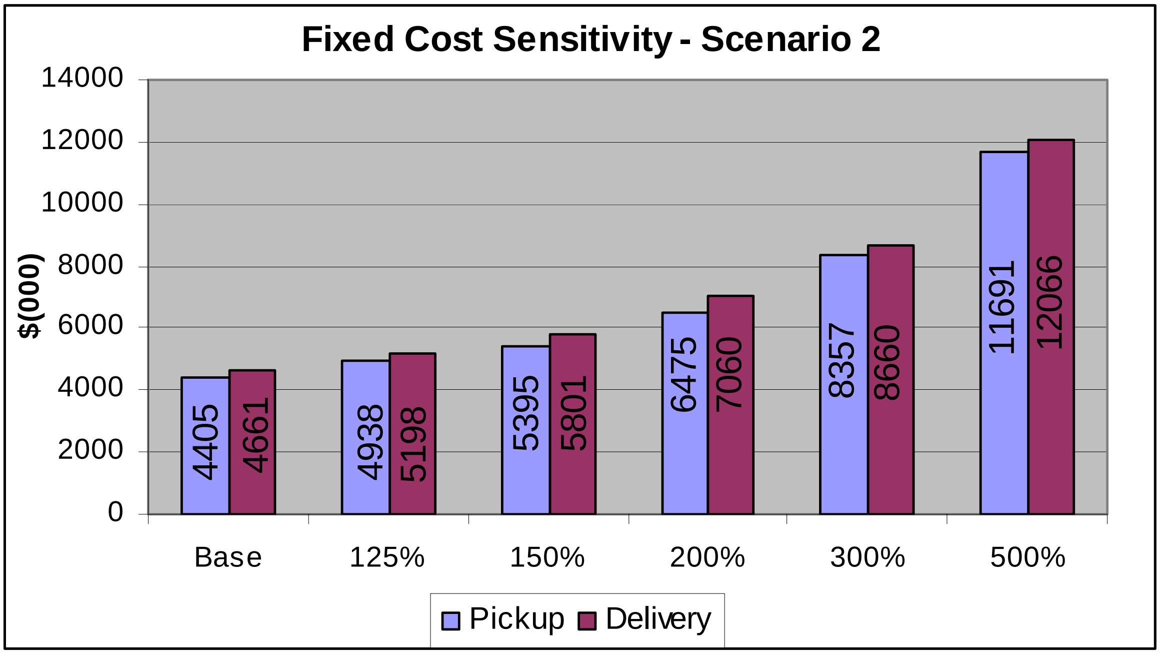
[Figure-7.16a: No Stop- Scenario 2 Fixed Cost Sensitivity (Pickup)]



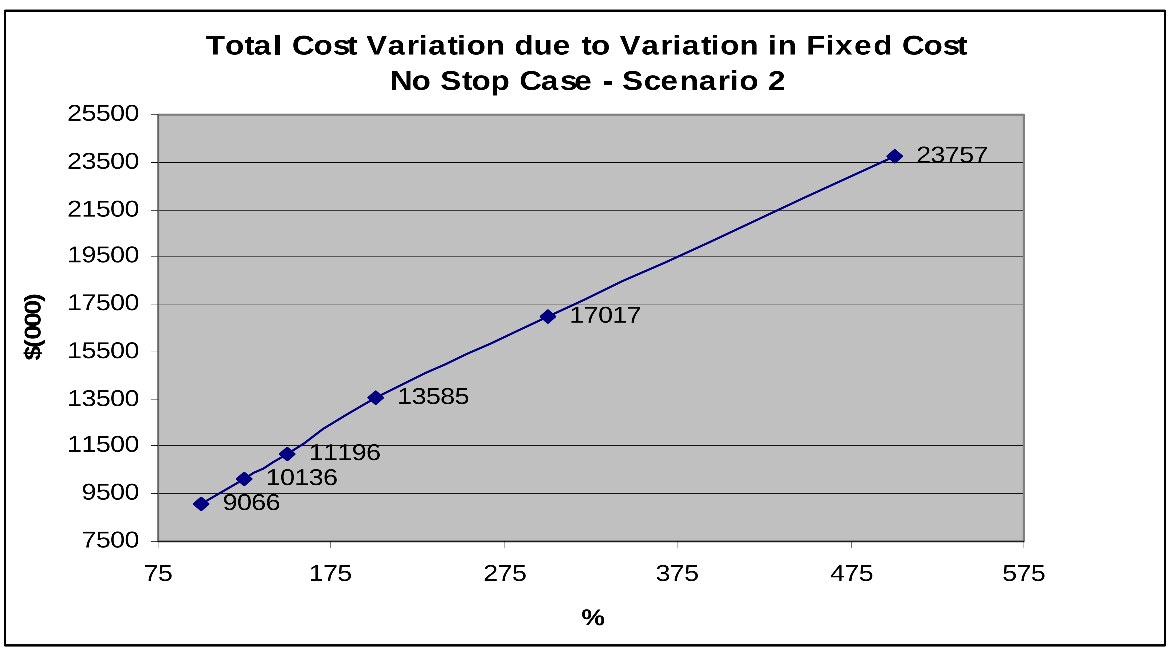
[Figure-7.16b: No Stop- Scenario 2 Fixed Cost Sensitivity (Delivery)]

Total Cost

Figure 7.17a and 7.17b shows the variation of pick-up, delivery and total cost with respect to change in the fixed cost of operations under this strategy.



[Figure 7.17a: No Stop- Scenario 2 Demand Sensitivity (Total Cost Variation)]



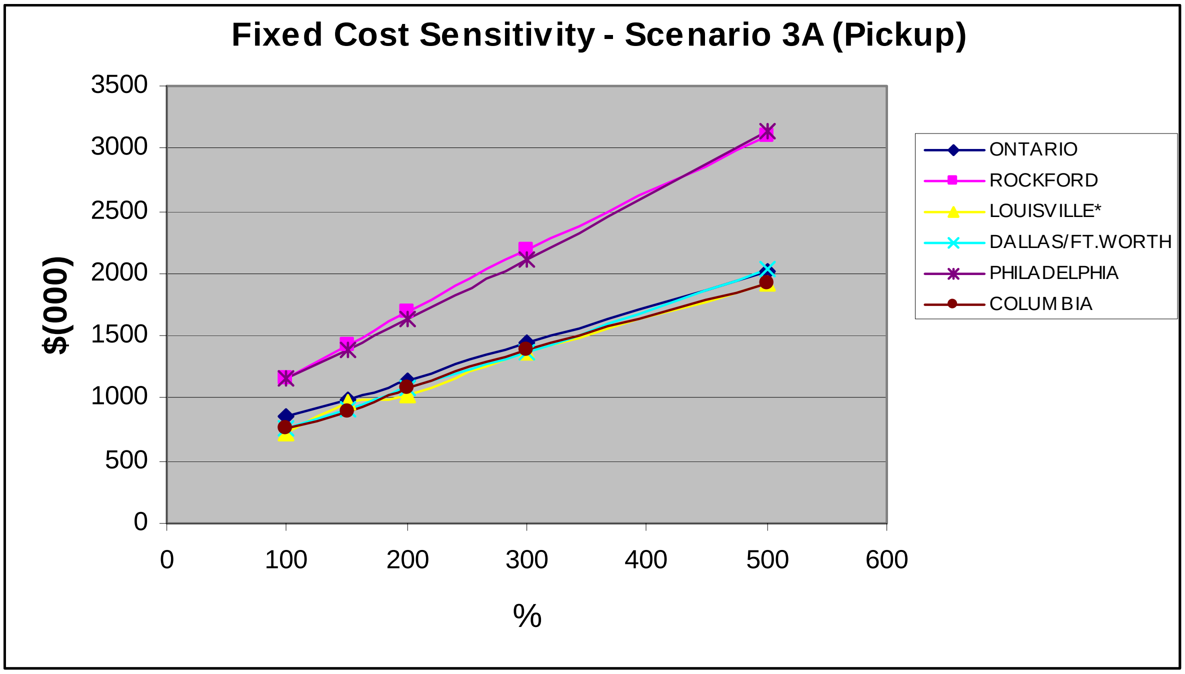
[Figure 7.17b: No Stop- Scenario 2 Demand Sensitivity (Total Cost Variation)]

7.3.1.3.1 Scenario 3A: Demands routed either through Origin Regional Hub or Destination Regional Hub on pick-up side

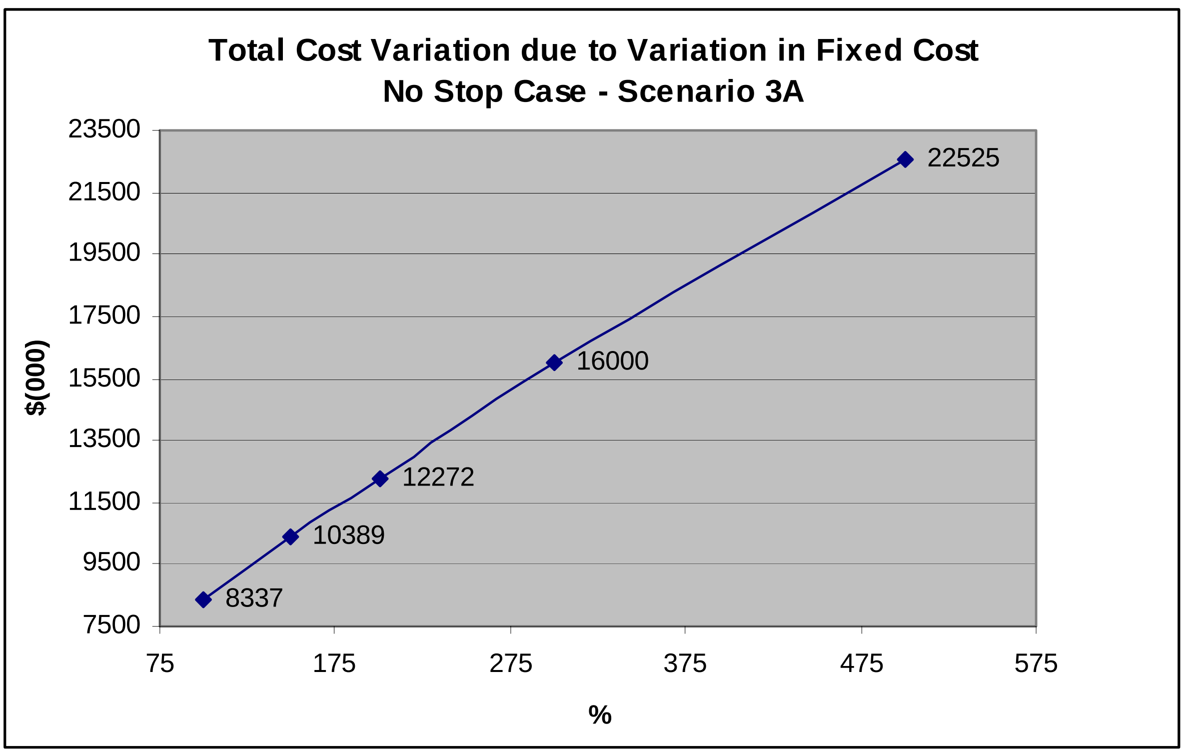
In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only. On the pick-up side, demands are routed either through Origin Regional Hub or directly to Destination Regional Hub. On the delivery side, demands are routed directly to the destination. Table 7.17 shows the results of the MIP runs. Figures 7.18a shows the variation of pick-up cost with respect to change in fixed costs. Figure 7.18b shows the variation of pick-up, delivery and total costs with respect to variation in fixed cost.

Scenario- 3A	Base		150%		200%		300%		500%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	849	572	995	686	1143	788	1452	980	2008	1316
ROCKFORD	1158	484	1426	605	1684	712	2188	914	3094	1192
LOUISVILLE	726	295	964	393	1035	470	1365	584	1926	707
DALLAS/FT.WORTH	763	428	915	565	1084	703	1365	960	2033	1241
PHILADELPHIA	1160	662	1388	921	1636	1178	2116	1693	3138	2723
COLUMBIA	752	488	896	635	1077	762	1386	997	1921	1226
TOTAL	**5408**	**2929**	**6584**	**3805**	**7659**	**4613**	**9872**	**6128**	**14120**	**8405**
GRAND TOTAL	**8337**		**10389**		**12272**		**16000**		**22525**	
% Increase from Base			**25%**		**47%**		**92%**		**170%**	

[Table 7.17: No Stop- Scenario 3A Fixed Cost Sensitivity]



[Figure 7.18a: No Stop- Scenario 3A Fixed Cost Sensitivity of Regional Hubs]



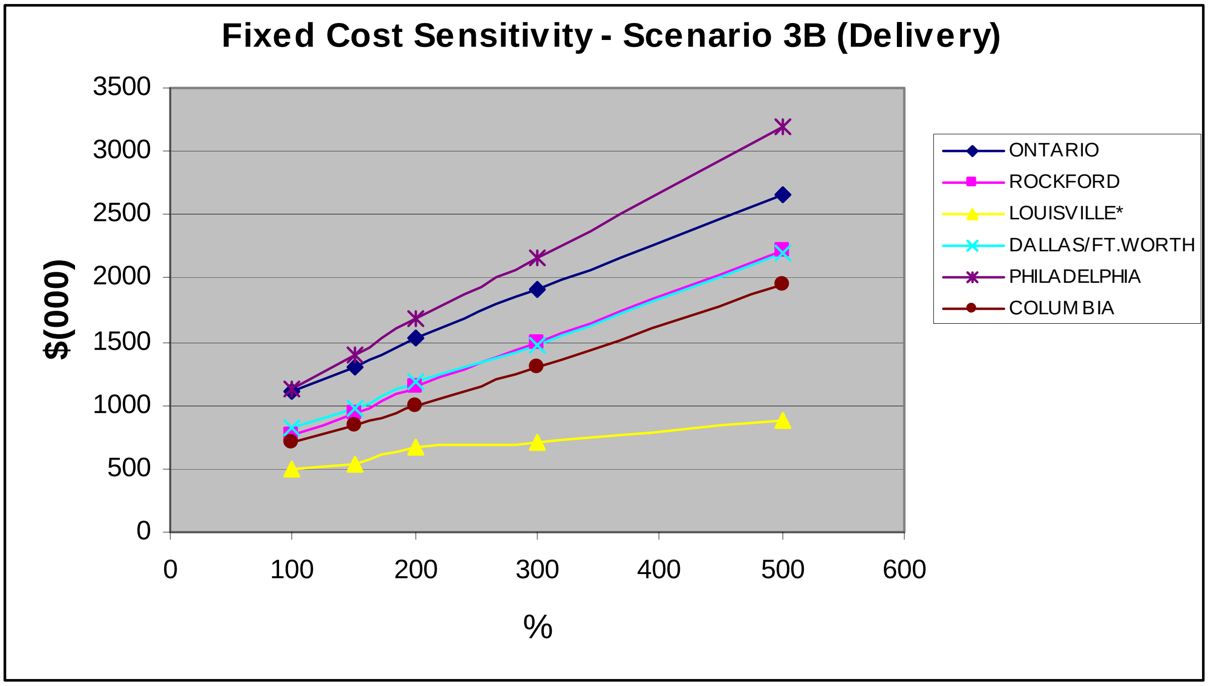
[Figure 7.18b: No Stop- Scenario 3A Fixed Cost Sensitivity (Total Cost)]

7.3.1.3.2 Scenario 3B: Demands routed from Origin Regional Hubs to destination or Destination Regional Hub

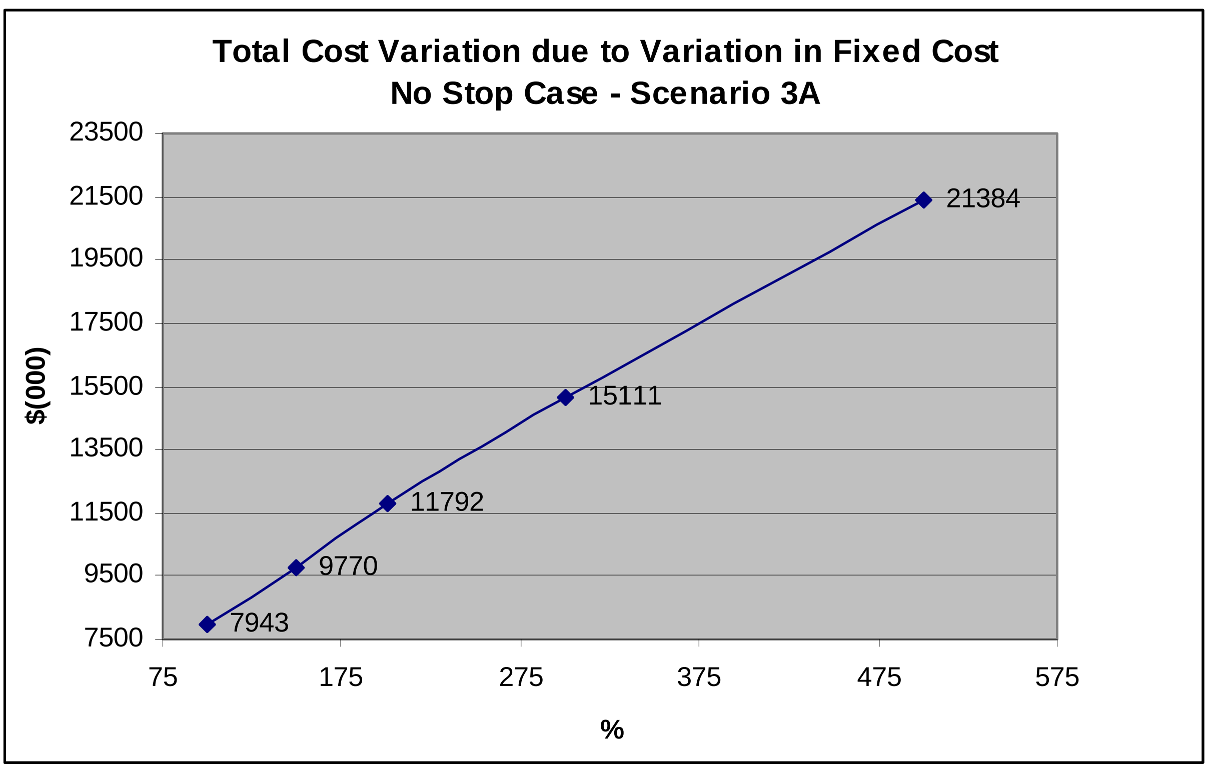
In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only. On the pick-up side, demands are routed to the Origin Regional Hub directly. On the delivery side, demands are routed directly to the destination. Table 7.18 shows the results of the MIP runs. Figures 7.19a show the variation of pick-up cost with respect to change in fixed costs. 7.19b shows the variation of total costs with respect to variation in fixed cost.

Scenario- 3B	Base		150%		200%		300%		500%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	423	1112	496	1301	562	1523	690	1914	925	2659
ROCKFORD	720	769	908	945	1074	1153	1391	1486	1814	2218
LOUISVILLE	303	490	402	535	488	676	613	703	707	887
DALLAS/FT.WORTH	360	821	459	978	556	1184	736	1477	958	2208
PHILADELPHIA	636	1128	882	1389	1128	1686	1621	2165	2603	3203
COLUMBIA	478	703	627	848	758	1004	1013	1302	1245	1957
TOTAL	**2920**	**5023**	**3774**	**5996**	**4566**	**7226**	**6064**	**9047**	**8252**	**13132**
GRAND TOTAL	**7943**		**9770**		**11792**		**15111**		**21384**	
% Increase from Base			**23%**		**48%**		**90%**		**169%**	

[Table 7.18: No Stop- Scenario 3B Fixed Cost Sensitivity]



[Figure 7.19a: No Stop- Scenario 3A Fixed Cost Sensitivity of Regional Hubs]



[Figure 7.19b: No Stop- Scenario 3A Fixed Cost Sensitivity (Total Cost)]

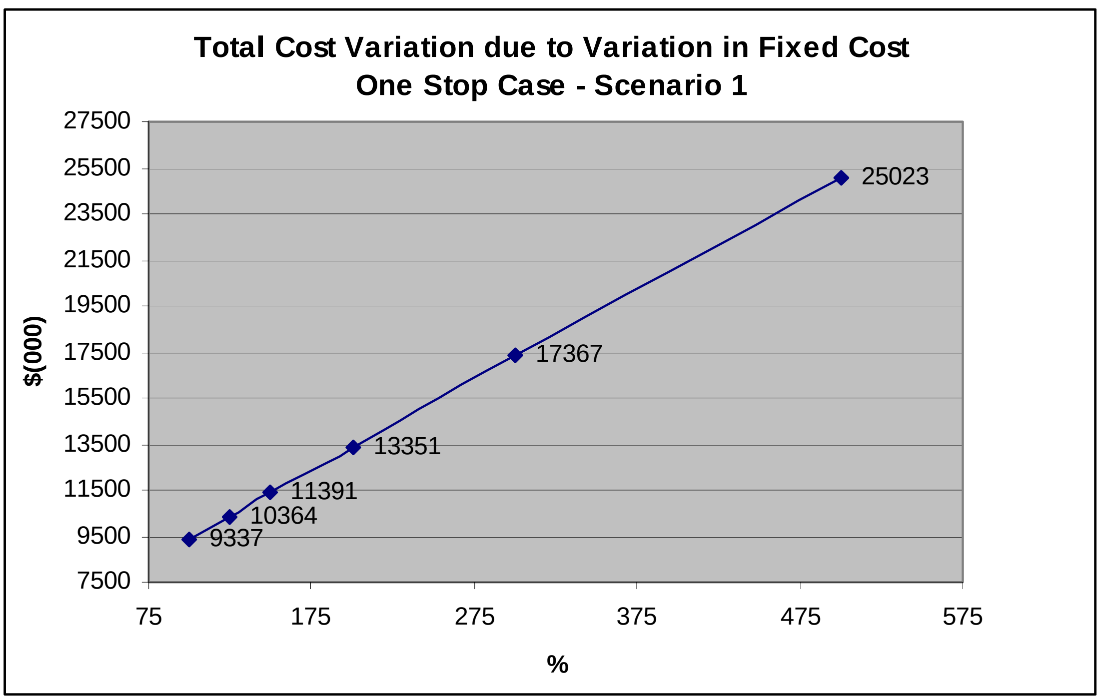
7.3.2 One Intermediate Stop Scenarios

7.3.2.1 Scenario 1: Single Hub Case

Table 7.19 and Figure 7.20 show the result of the MIP runs.

SINGLE HUB AT LOUISVILLE	Base	125%	150%	200%	300%	500%
	('000)	('000)	('000)	('000)	('000)	('000)
PICK-UP	4556	5101	5603	6676	8551	12460
DELIVERY	4781	5263	5788	6675	8816	12563
TOTAL	9337	10364	11391	13352	17367	25023
% Increase from Base		11%	22%	43%	86%	168%

[Table 7.19: One Stop- Single Hub Case Fixed Cost Sensitivity Results]



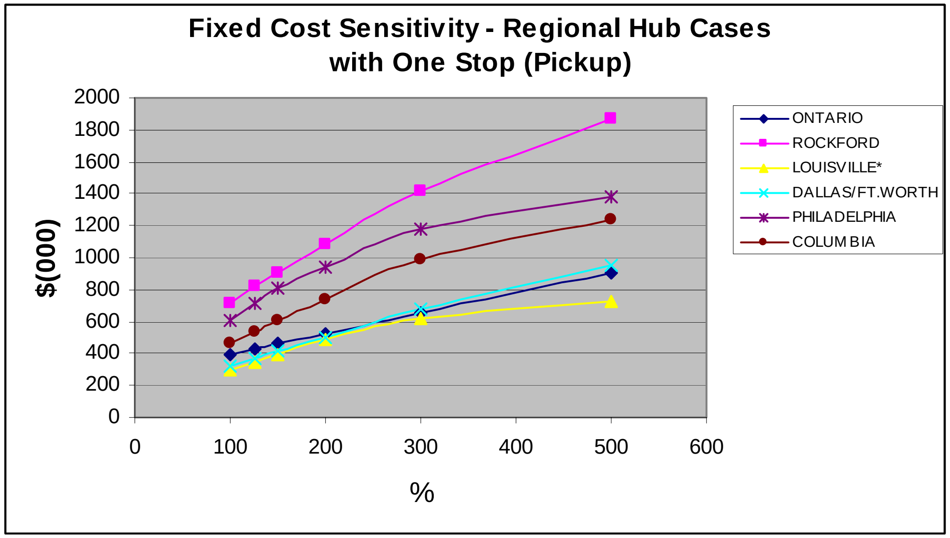
[Figure7.20: One Stop- Single Hub Case Fixed Cost Sensitivity Results]

7.3.2.2 Scenario 2: Regional Hubs Present-All demands dispatched through origin regional hubs

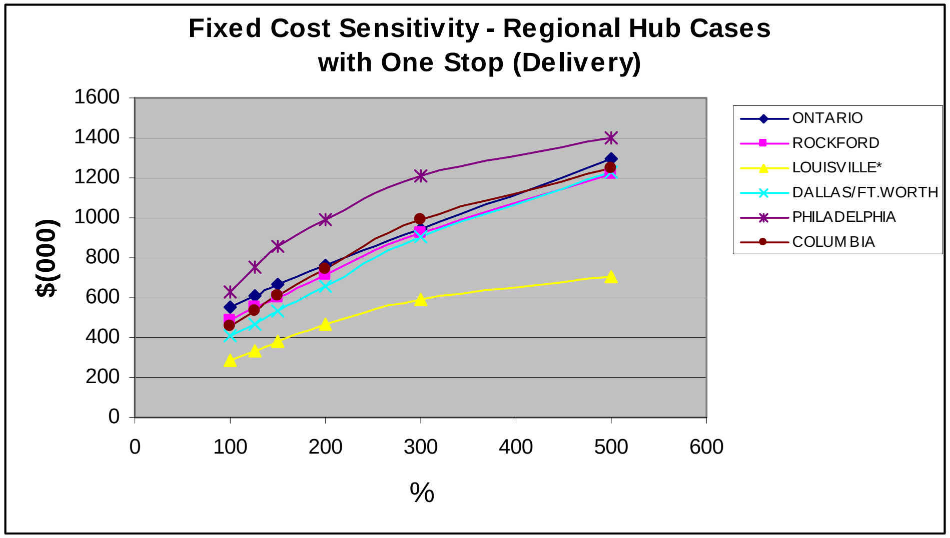
Results for the pick-up and delivery cases are shown in Table 7.20. Figures 7.21a and 7.22b show the variation of total cost with respect to fixed cost.

	Pick-up Side						Delivery Side					
REGIONAL HUBS	**Base**	**125%**	**150%**	**200%**	**300%**	**500%**	**Base**	**125%**	**150%**	**200%**	**300%**	**500%**
	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)
ONTARIO	391	426	459	526	658	907	554	609	663	759	947	1293
ROCKFORD	715	820	908	1083	1416	1868	481	548	604	714	922	1222
LOUISVILLE*	293	346	396	485	617	728	283	334	380	462	588	705
DALLAS/FT.WORTH	325	369	414	505	677	954	405	468	530	654	901	1228
PHILADELPHIA	606	719	811	938	1182	1382	632	754	858	989	1214	1399
COLUMBIA	459	533	603	734	986	1235	459	536	608	741	994	1247
TOTAL	**2789**	**3213**	**3591**	**4271**	**5536**	**7075**	**2814**	**3248**	**3643**	**4319**	**5566**	**7093**

[Table 7.20: One Stop- Scenario 1 Regional Hubs Case Fixed Cost Sensitivity Results]



[Figure 7.21a: One Stop- Scenario 1 Regional Hubs Case Fixed Cost Sensitivity (Pickup)]



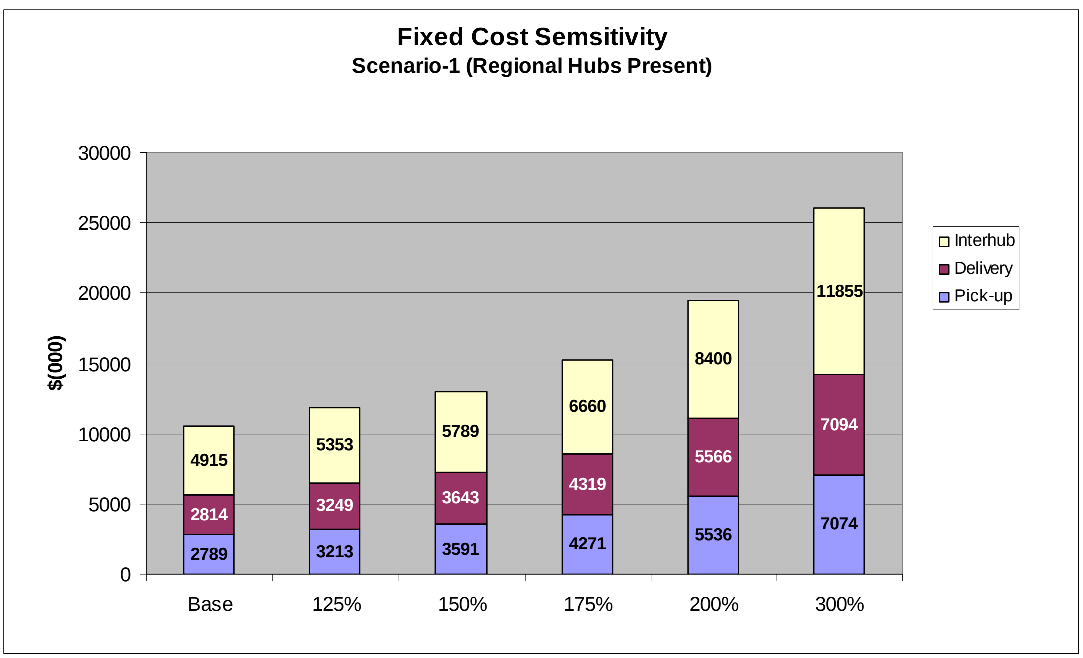
[Figure 7.21b: One Stop- Scenario 1 Regional Hubs Case Fixed Cost Sensitivity (Delivery)]

Total Cost of operations is shown in Table 7.21

TOTAL COST						
REGIONAL HUBS	Base	125%	150%	200%	300%	500%
	('000)	('000)	('000)	('000)	('000)	('000)
ONTARIO	946	1035	1123	1285	1605	2200
ROCKFORD	1196	1368	1512	1796	2338	3090
LOUISVILLE*	576	680	776	948	1205	1433
DALLAS/FT.WORTH	730	836	945	1159	1578	2182
PHILADELPHIA	1238	1473	1669	1927	2397	2781
COLUMBIA	918	1068	1210	1475	1980	2482
INTERHUB	4915	5353	5789	6660	8400	11855
TOTAL	10519	11813	13023	15250	19502	26023
% Increase from Base		12%	24%	45%	85%	147%

[Table 7.21 One Stop- Scenario 1 Regional Hubs Case Fixed Cost Sensitivity (Total Cost)]

Figure 7.22 shows the variation of total cost with respect to changes in the demand.



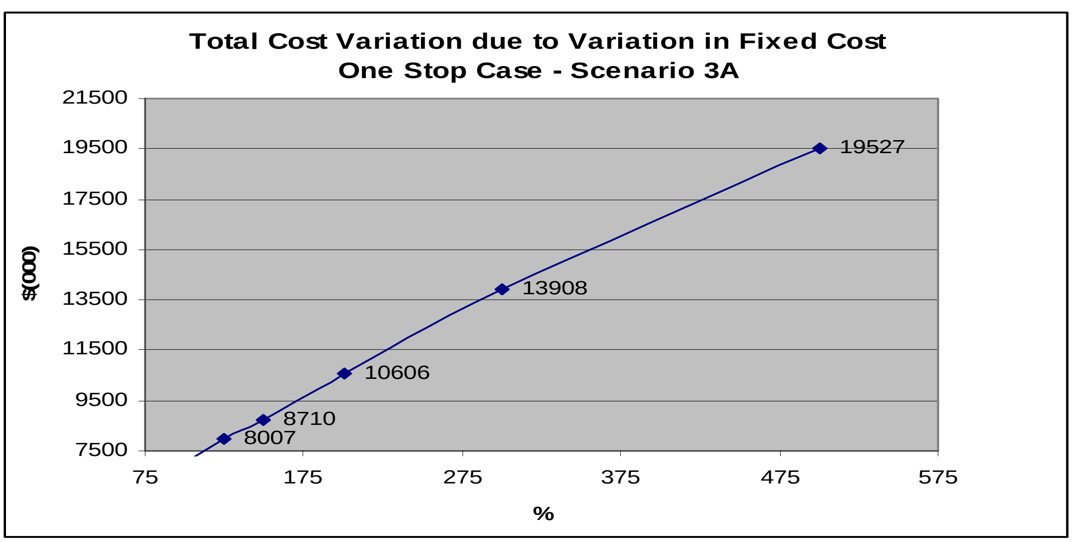
[Figure 7.22: One Stop- Scenario 1 Regional Hubs Case Fixed Cost Sensitivity (Total Cost)]

7.3.2.3.1 Scenario 3A: Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up

On the pick-up side, demands are routed from the origin either through one-stop routes to the destination regional hubs or through no stop routes through the origin regional hub (see Figure 6.8). The delivery side becomes the case where we allow one-stop routes to the destination. Table 7.22 and Figure 7.23 show the results of the MIP runs.

Scenario 3A	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
Base	**4210**	**2814**	**7024**	
125%	**4759**	**3248**	**8007**	**14%**
150%	**5067**	**3643**	**8710**	**24%**
200%	**6287**	**4319**	**10606**	**51%**
300%	**8342**	**5566**	**13908**	**98%**
500%	**12434**	**7093**	**19527**	**178%**

[Table 7.22 One Stop- Scenario 3A Fixed Cost Sensitivity (Total Cost)]



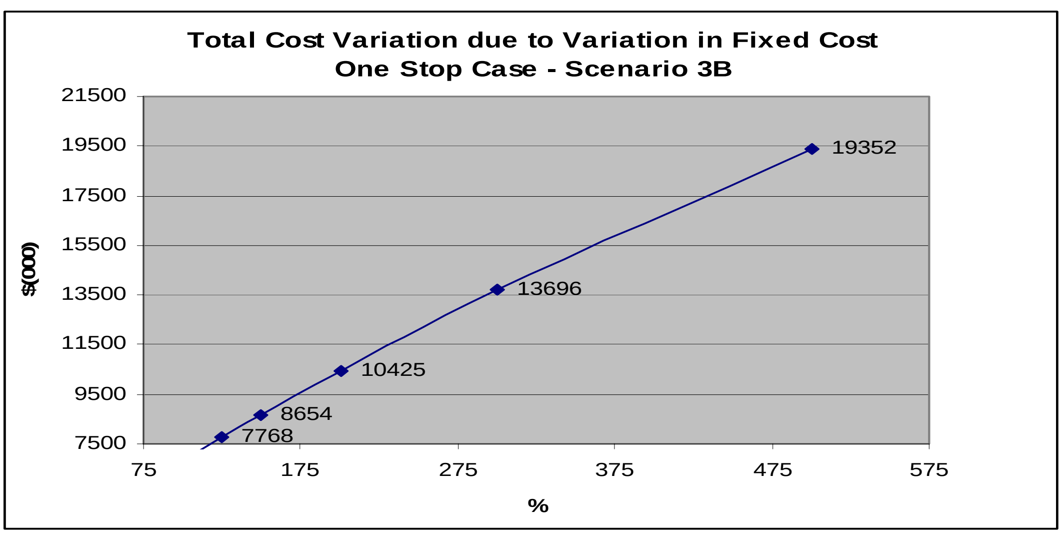
[Figure 7.23: One Stop- Scenario 3A Fixed Cost Sensitivity (Total Cost)]

7.3.2.3.2 Scenario 3B: Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery

The pick-up side is the case where we allow one-stop routes from origin to origin regional hub. On the delivery side, demands are routed from origin regional hubs either through one-stop routes to destinations or through no stop routes through destination regional hub on delivery. Table 7.23 and Figure 7.24 show the results of the MIP runs.

Scenario 3B	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
Base	**2789**	**4025**	**6814**	
125%	**3213**	**4555**	**7768**	**14%**
150%	**3591**	**5063**	**8654**	**27%**
200%	**4271**	**6154**	**10425**	**53%**
300%	**5536**	**8160**	**13696**	**101%**
500%	**7075**	**12277**	**19352**	**184%**

[Table 7.24: One Stop- Scenario 3B Demand Sensitivity (Total Cost)]



[Figure 7.24: One Stop- Scenario 3B Demand Sensitivity (Total Cost)]

7.4 Variable Cost Sensitivity

In this section, we vary the variable cost component of the problem and analyze it's sensitivity. The variable cost primarily varies with the fuel usage. Usage of fuel may vary depending on the type of aircraft flown, payload of the aircraft, percent full etc. Fuel price varies due to various uncertainties and this affects our problem context. In this section, we study the effect of fuel prices which affects the variable cost component. Keeping the fixed cost component constant, we vary the fuel price by 125%, 150%, 175%, 200% and 300% and study its impacts on the cost function.

7.4.1 Scenario-1: No Intermediate Stop Scenarios

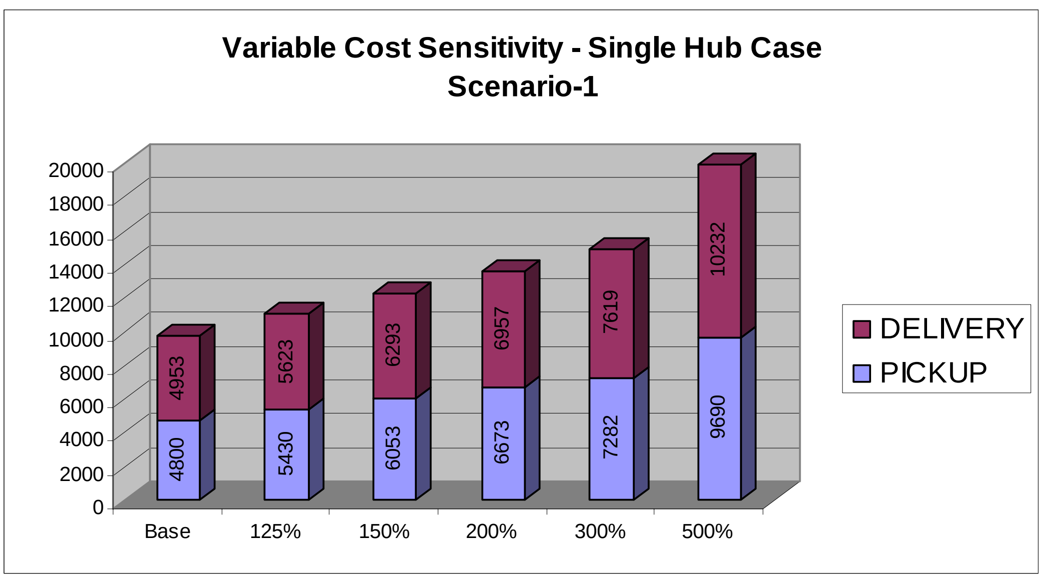
7.4.1.1 Scenario-1: Only one Origin-Hub pair and only one Hub-Destination pair

(i) Single Hub Case

Results of the MIP runs are shown in Table-7.24 and Figure-7.25.

SINGLE HUB AT LOUISVILLE	Base	125%	150%	175%	200%	300%
	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)
PICK-UP	**4800**	**5430**	**6053**	**6673**	**7282**	**9690**
DELIVERY	**4953**	**5623**	**6293**	**6957**	**7619**	**10232**
TOTAL	**9753**	**11053**	**12346**	**13630**	**14901**	**19922**
% Increase from Base		**13%**	**27%**	**40%**	**53%**	**104%**

[Table 7.24: No Stop Scenario 1- Single Hub Case Variable Cost Sensitivity Results]



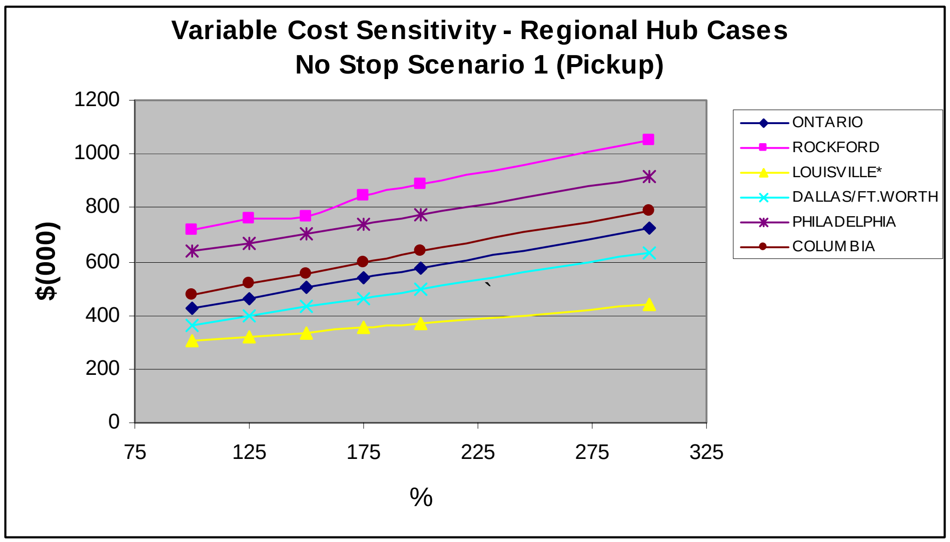
[Figure 7.25: Variable Cost Sensitivity- No Stop Scenario1- Single Hub Case]

(ii) Regional Hubs Present

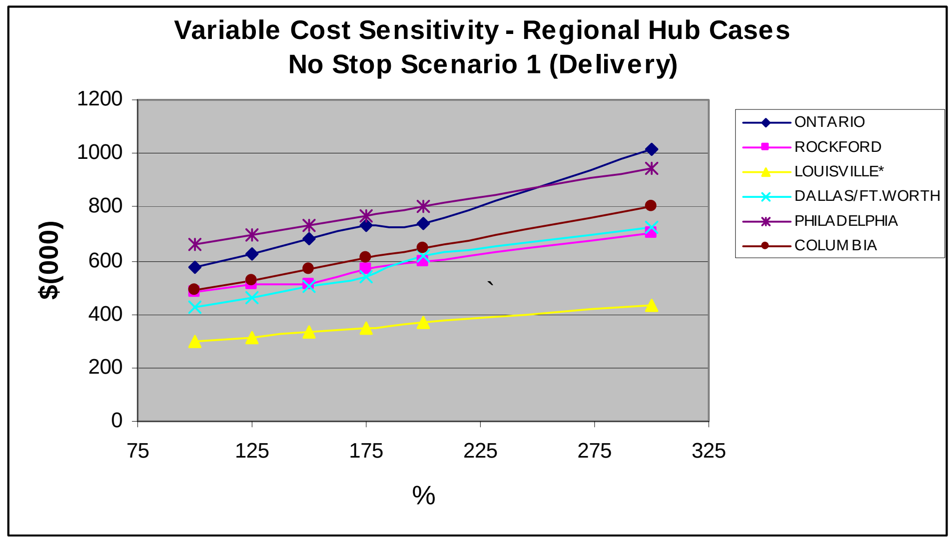
Table 7.25 shows the results of the MIP runs for the case when demands are routed through origin regional hubs only. Figures 7.26a and 7.26b show the variation of total cost with respect to variation in the variable cost.

	Pick-up Side						Delivery Side					
REGIONAL HUBS	Base	125%	150%	175%	200%	300%	Base	125%	150%	175%	200%	300%
	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)
ONTARIO	423	463	501	539	576	724	572	628	683	728	739	1015
ROCKFORD	720	762	766	845	887	1053	484	512	512	566	593	700
LOUISVILLE*	303	320	337	354	371	439	295	314	332	350	368	436
DALLAS/FT.WORTH	360	395	430	465	500	635	428	465	503	540	618	727
PHILADELPHIA	636	671	706	741	776	916	662	697	733	769	805	947
COLUMBIA	478	518	557	596	636	790	488	528	569	609	647	802
TOTAL	**2920**	**3129**	**3297**	**3540**	**3746**	**4557**	**2929**	**3144**	**3332**	**3562**	**3770**	**4627**

[Table 7.25: No Stop Scenario 1 Regional Hub Case - Variable Cost Sensitivity Results]



[Figure 7.26a: Variable Cost Sensitivity- No Stop Scenario1- Regional Hubs Case (Pickup)]



[Figure 7.26b: Variable Cost Sensitivity- No Stop Scenario1- Regional Hubs Case (Delivery)]

Interhub Cost

Interhub costs for the change in variable costs are shown in Table 7.26.

Base	125%	150%	175%	200%	300%
('000)	('000)	('000)	('000)	('000)	('000)
4915	**5704**	**6492**	**7277**	**8063**	**11194**

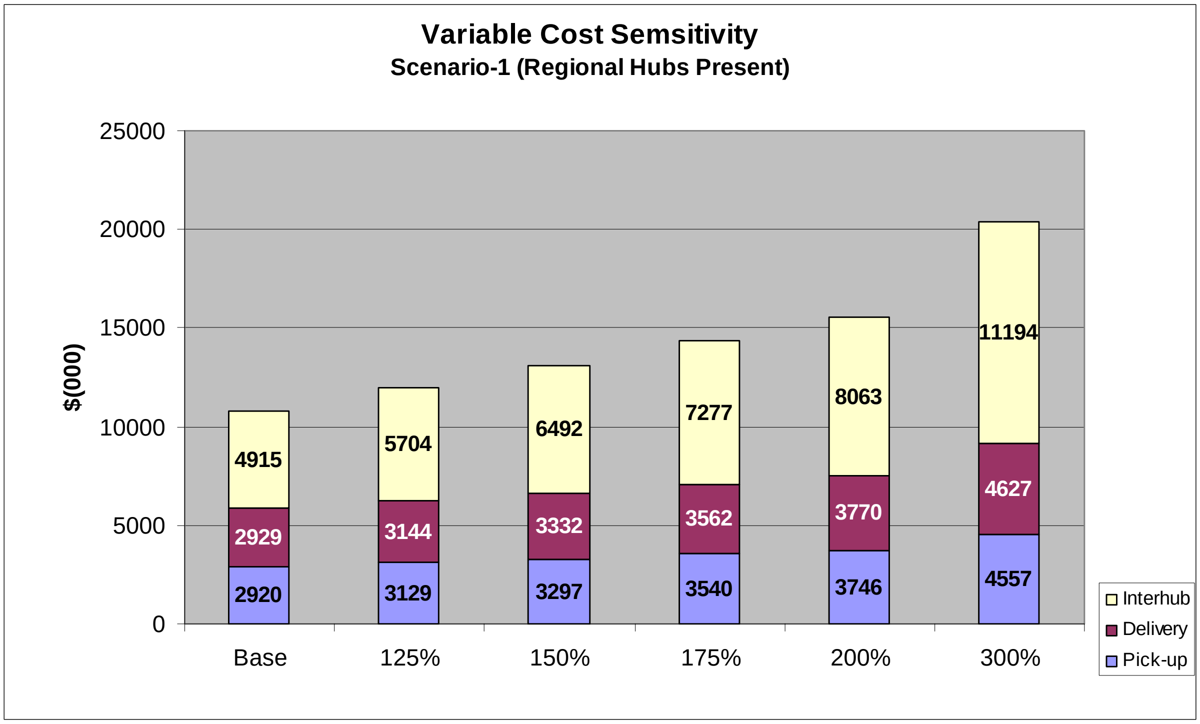
[Table 7.26: Interhub Transportation Costs]

Total Cost

This is sum of the pick-up side cost, delivery side cost and the interhub transportation cost. The results are shown in Table 7.27 and Figure 7.27.

TOTAL COST						
REGIONAL HUBS	**Base**	**125%**	**150%**	**175%**	**200%**	**300%**
	('000)	('000)	('000)	('000)	('000)	('000)
ONTARIO	995	1091	1184	1267	1315	1739
ROCKFORD	1204	1274	1278	1411	1480	1753
LOUISVILLE*	598	634	669	704	739	875
DALLAS/FT.WORTH	788	860	933	1005	1118	1362
PHILADELPHIA	1298	1368	1439	1510	1581	1863
COLUMBIA	966	1046	1126	1205	1283	1592
INTERHUB	**4915**	**5704**	**6492**	**7277**	**8063**	**11194**
TOTAL	10764	11977	13121	14379	15579	20378
% Increase from Base		11%	22%	33%	43%	89%

[Table 7.27: Variable Cost Sensitivity of Total Cost for Scenario 1 Regional Hub Case]



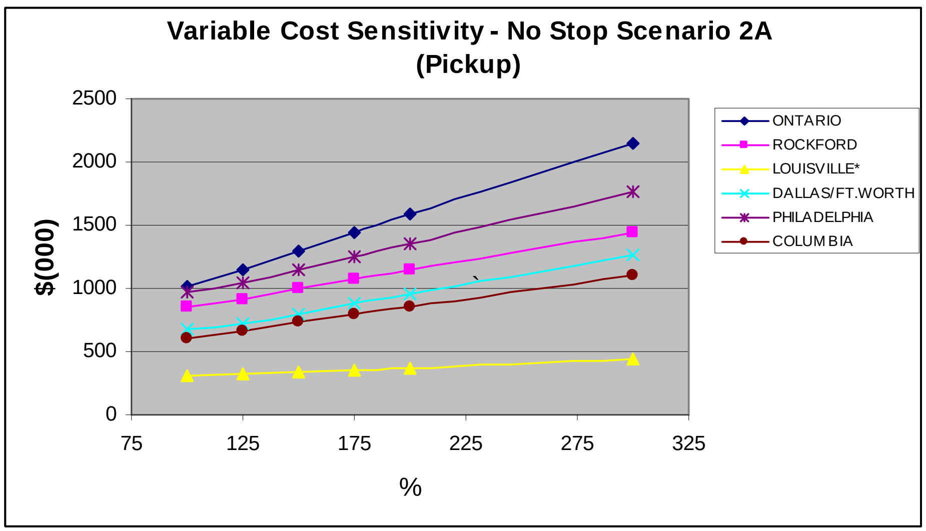
[Figure 7.27: Variable Cost Sensitivity of Total Cost for Scenario 1 Regional Hub Case]

7.4.1.2 Scenario-2: No Intermediate Stops with demands routed from Origin through multiple hubs

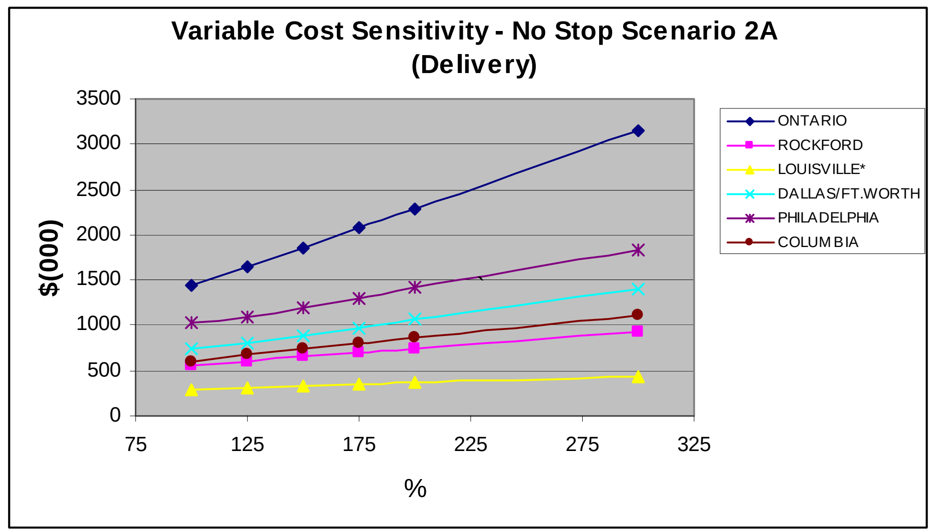
In this case, demands are routed either through Origin Regional Hub or directly to main hub on the pick-up side. On the delivery side, demands are routed either through destination regional hub or to destination Table 7.28 shows the result of MIP runs. Figures 7.28a and 7.28b show the cost impact of the variation in variable cost on pick-up and delivery sides respectively.

Scenario-2	Base		125%		150%		175%		200%		300%	
	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery
	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)
ONTARIO	1011	1433	1144	1643	1292	1862	1440	2077	1584	2291	2149	3145
ROCKFORD	848	566	917	607	993	654	1068	701	1143	748	1442	932
LOUISVILLE*	303	295	320	314	337	332	354	350	371	368	439	436
DALLAS/FT.WORTH	671	740	715	799	796	887	876	975	956	1062	1264	1405
PHILADELPHIA	969	1021	1042	1097	1145	1202	1248	1307	1351	1411	1758	1824
COLUMBIA	604	606	666	670	731	737	794	804	858	869	1108	1122
TOTAL	**9067**		**9934**		**10968**		**11994**		**13012**		**17024**	
% Increase from Base			**10%**		**21%**		**32%**		**44%**		**88%**	

[Table 7.28: No Stop- Scenario 2 Variable Cost Sensitivity Results]



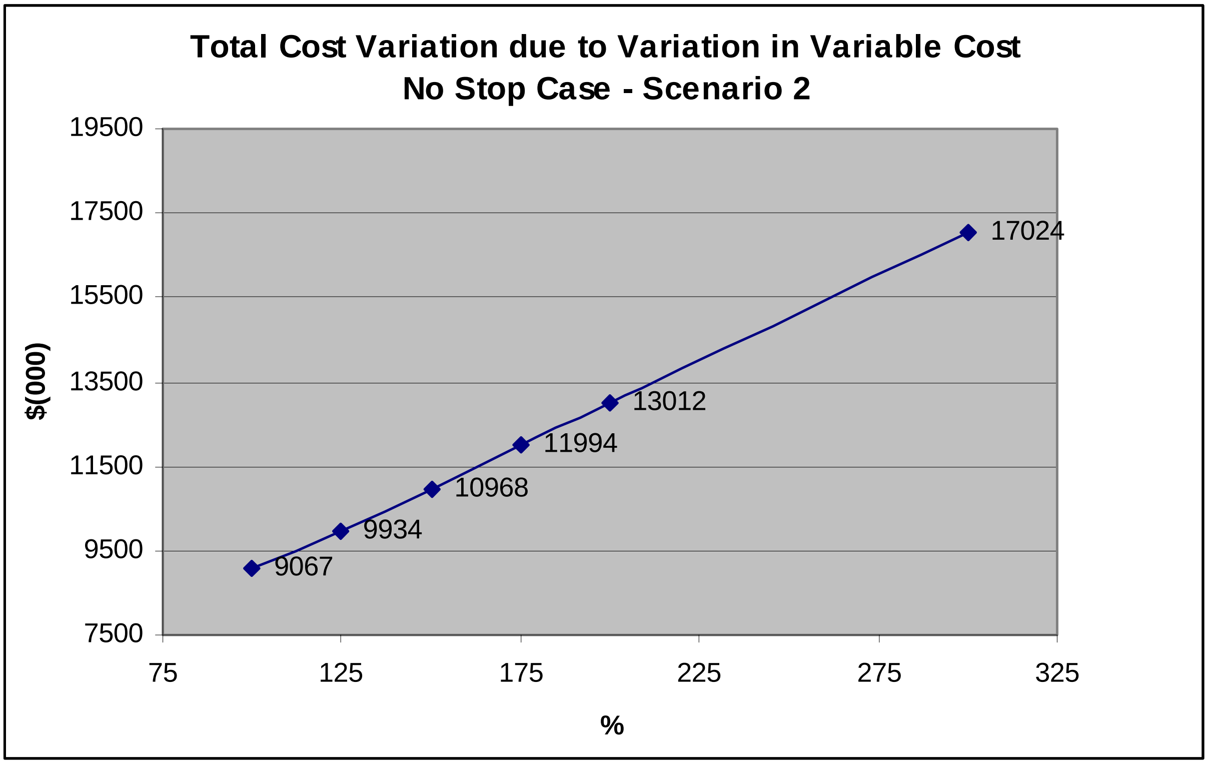
[Figure-7.28a: No Stop- Scenario 2 Variable Cost Sensitivity (Pickup)]



[Figure-7.28b: No Stop- Scenario 2 Fixed Cost Sensitivity (Delivery)]

Total Cost

Figure 7.29 shows the variation of total cost with respect to variable cost.



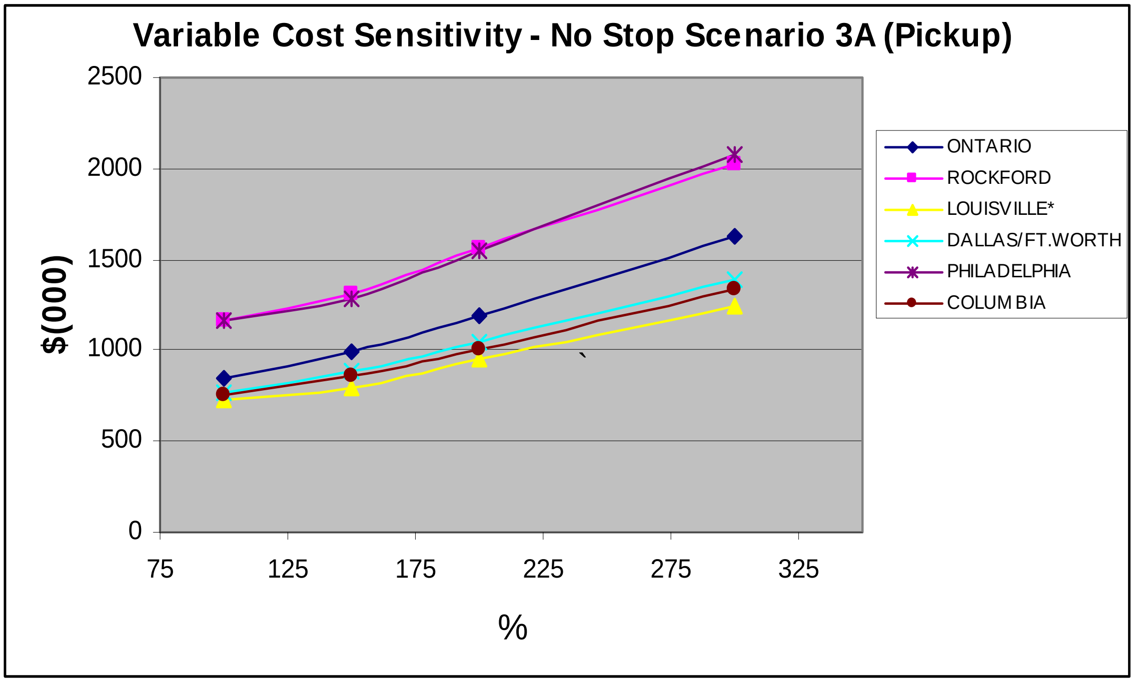
[Figure 7.29: No Stop- Scenario 2 Demand Sensitivity (Total Cost Variation)]

7.4.1.3.1 Scenario 3A: No Main Hubs, Demands routed through Regional Hubs only

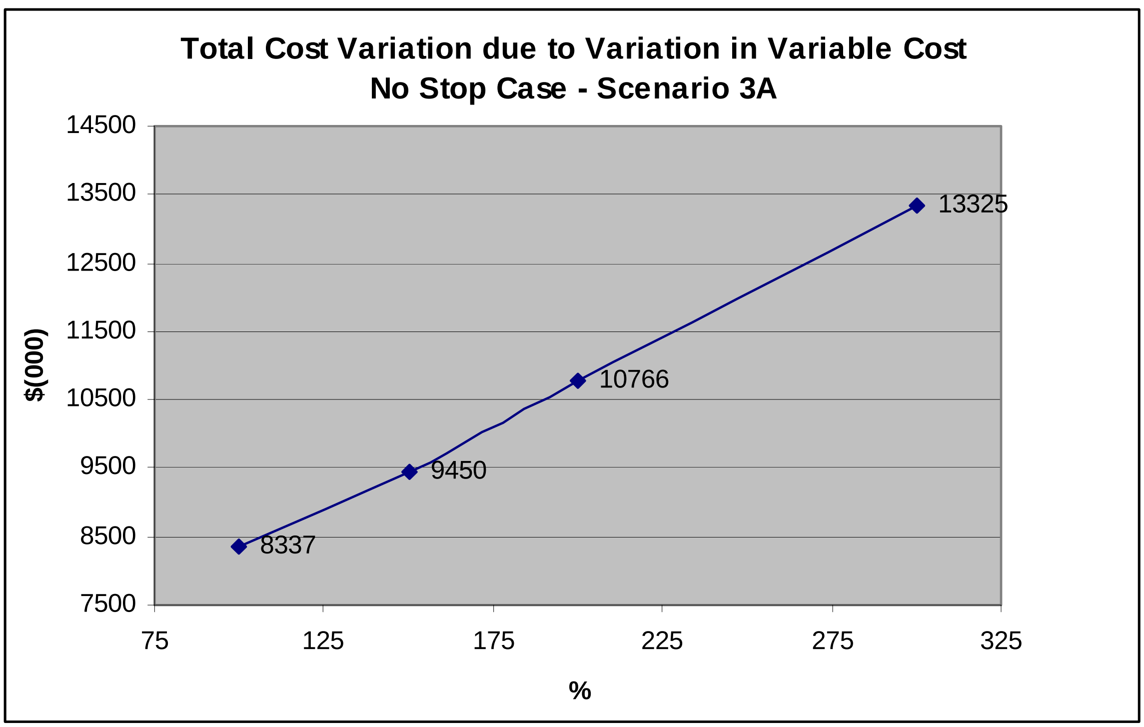
In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only. On the pick-up side, demands routed either through Origin Regional Hub or directly to Destination Regional Hub. On the delivery side, demands are routed directly to the destination. Table 7.30 shows the results of the MIP runs. Figure 7.30a shows the variation of pick-up cost with respect to change in fixed costs. Figure 7.30b shows the variation of pick-up, delivery and total costs with respect to variation in fixed cost.

Scenario-3A	Base		150%		200%		300%	
	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery	Pick-up	Delivery
	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)
ONTARIO	849	572	988	683	1196	628	1627	739
ROCKFORD	1158	484	1303	512	1555	566	2030	593
LOUISVILLE*	726	295	798	332	955	350	1248	368
DALLAS/FT.WORTH	763	428	887	503	1043	540	1384	478
PHILADELPHIA	1160	662	1286	733	1545	769	2074	805
COLUMBIA	752	488	856	569	1010	609	1332	647
TOTAL	**8337**		**9450**		**10766**		**13325**	
% Increase from Base			**13%**		**29%**		**60%**	

[Table 7.30: No Stop- Scenario 3A Variable Cost Sensitivity]



[Figure 7.30a: No Stop- Scenario 3A Variable Cost Sensitivity of Regional Hubs]



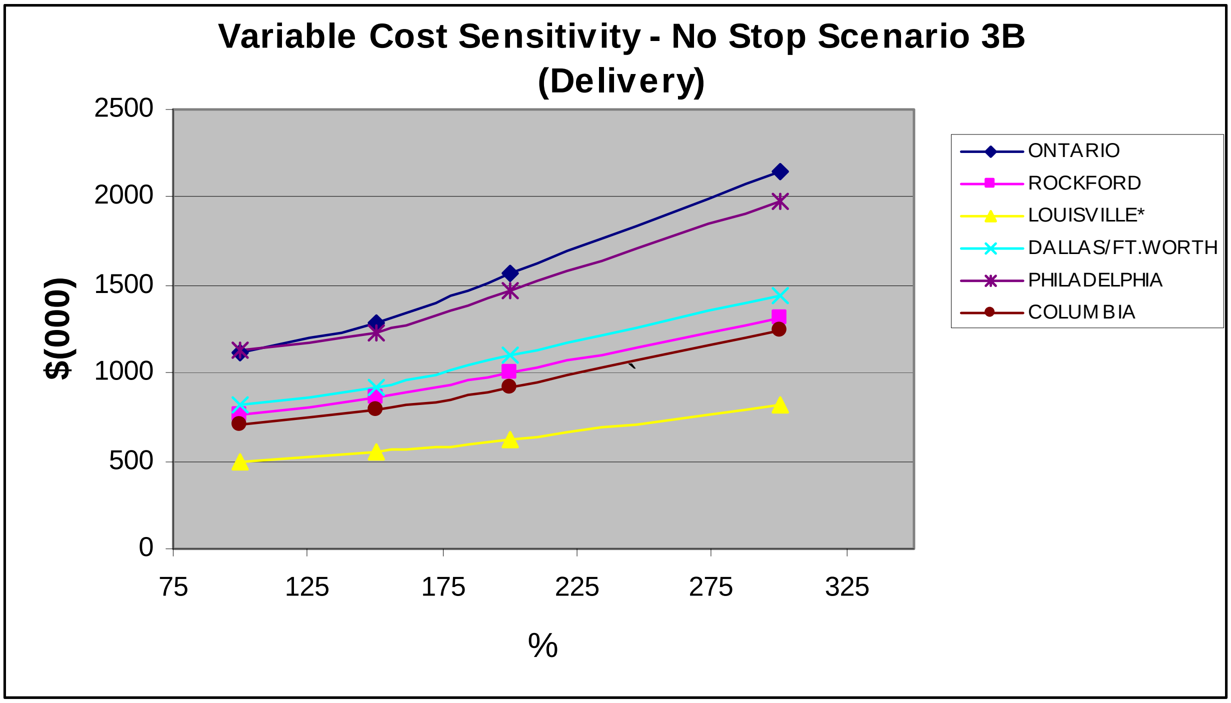
[Figure 7.30b: No Stop- Scenario 3A Variable Cost Sensitivity (Total Cost)]]

7.4.1.3.2 Scenario 3B: No Main Hubs, Demands routed from Origin Regional Hubs to destination or Destination Regional Hub

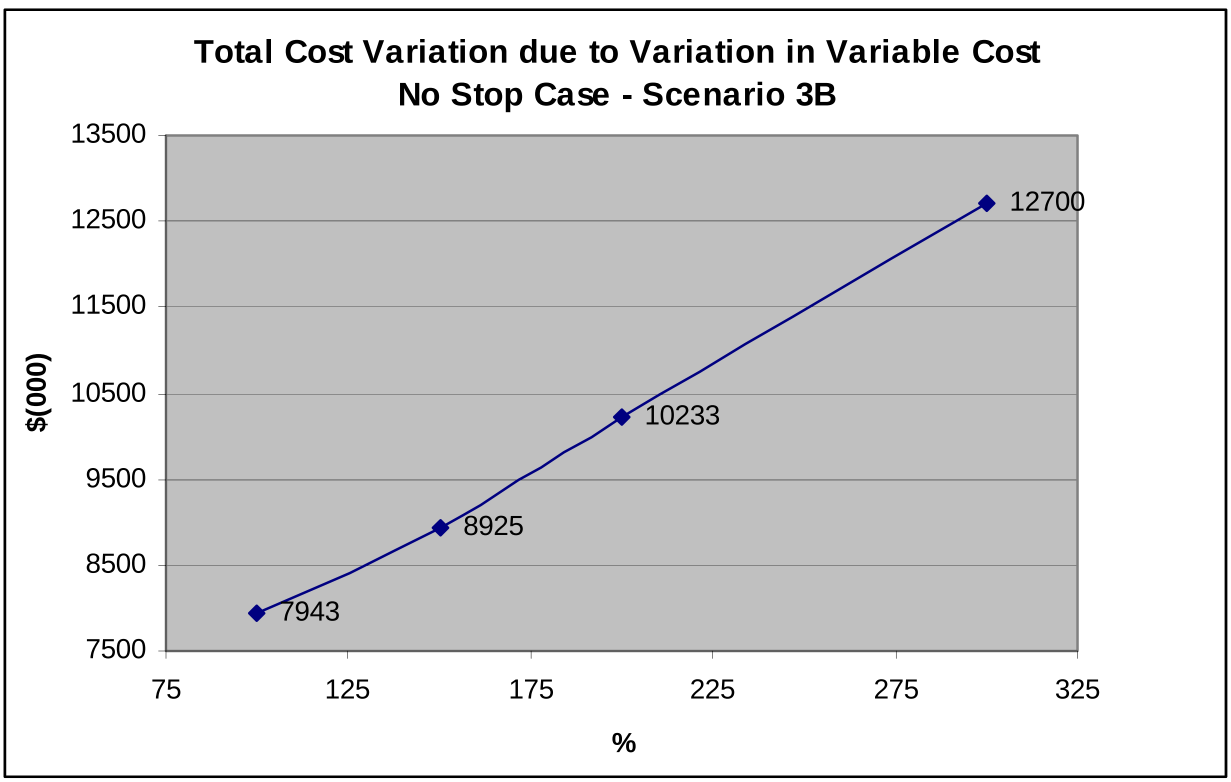
In this analysis conducted, we exclude the presence of main hub and assume that there are only regional hubs and the demands are routed through them only. On the pick-up side, demands are routed to the Origin Regional Hub directly. On the delivery side, demands are routed directly to the destination. Table 7.31 shows the results of the MIP runs. Figure 7.31a shows the variation of pick-up cost with respect to change in variable costs. Figure 7.31b shows the variation of pick-up, delivery and total costs with respect to variation in variable cost.

Scenario-3B	Base		150%		200%		300%	
	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)	Pick-up $(000)	Delivery $(000)
ONTARIO	423	1112	501	1288	539	1562	576	2148
ROCKFORD	720	769	766	862	845	1006	887	1318
LOUISVILLE*	303	490	337	545	354	623	371	821
DALLAS/FT.WORTH	360	821	430	914	465	1103	500	1445
PHILADELPHIA	636	1128	706	1234	741	1475	776	1984
COLUMBIA	478	703	557	785	596	924	636	1238
TOTAL	**2920**		**5023**		**3297**		**5628**	
% Increase from Base			**12%**		**29%**		**60%**	

[Table 7.31: No Stop- Scenario 3B Variable Cost Sensitivity]



[Figure 7.31a: No Stop- Scenario 3B Variable Cost Sensitivity of Regional Hubs]



[Figure 7.31b: No Stop- Scenario 3A Variable Cost Sensitivity (Total Cost)]

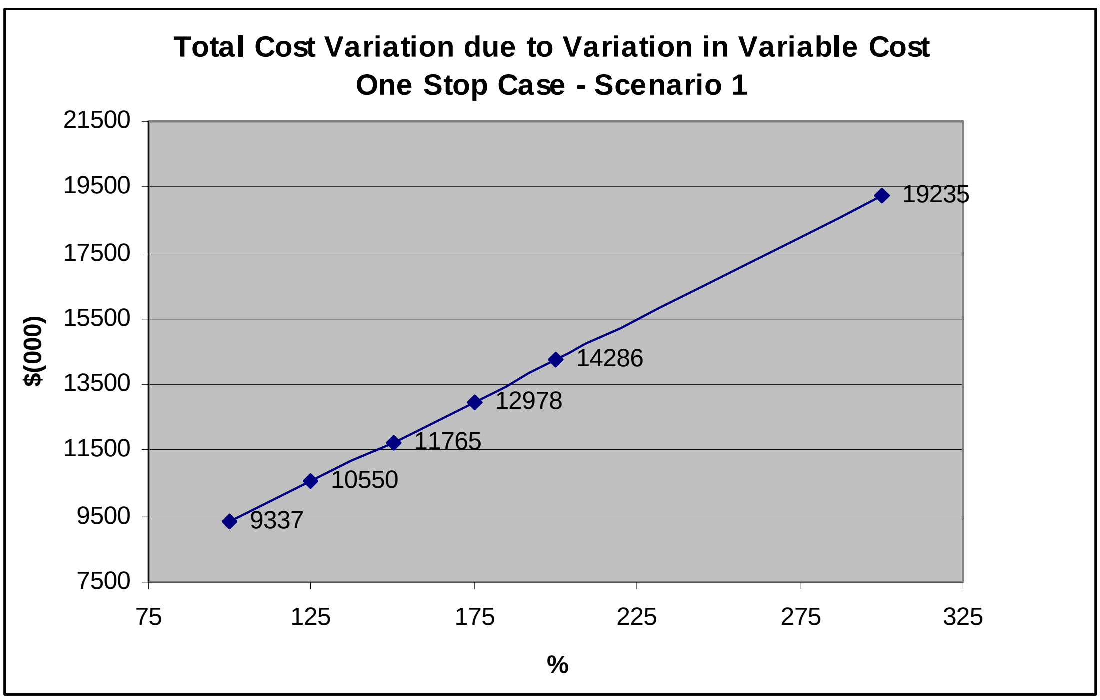
7.4.2 One Intermediate Stop Scenarios

7.4.2.1 Scenario 1: Single Hub Case

Table-7.32 and Figure-7.32 show the results of the MIP runs.

SINGLE HUB AT LOUISVILLE	Base	125%	150%	175%	200%	300%
	('000)	('000)	('000)	('000)	('000)	('000)
PICK-UP	4556	5176	5757	6316	6941	9338
DELIVERY	4781	5374	6008	6662	7345	9897
TOTAL	9337	10551	11765	12978	14286	19234
% Increase from Base		13%	26%	39%	53%	106%

[Table 7.32: One Stop- Single Hub Case Variable Cost Sensitivity Results]



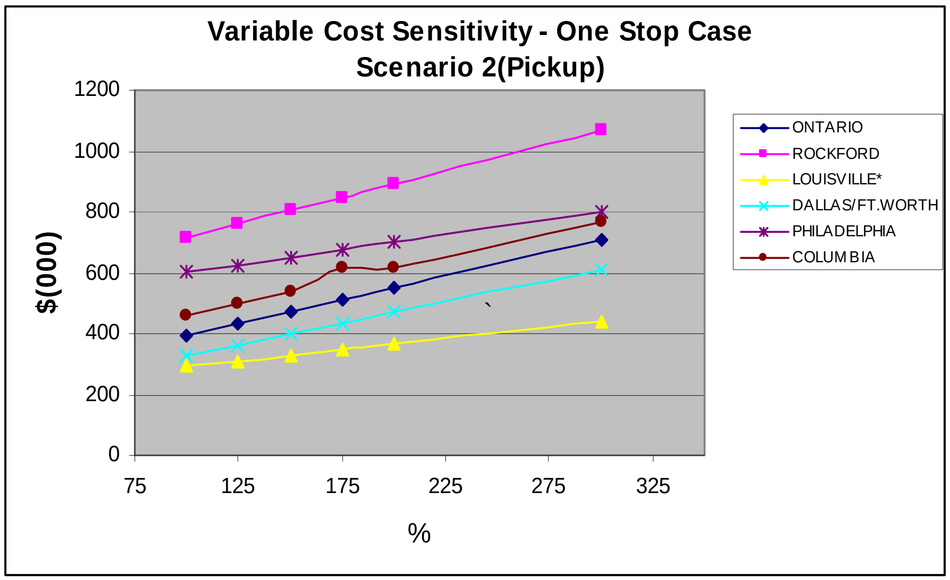
[Figure 7.32: One Stop- Single Hub Case Variable Cost Sensitivity Results]

7.4.2.2 Scenario 2: Regional Hubs Present-All demands dispatched through origin regional hubs

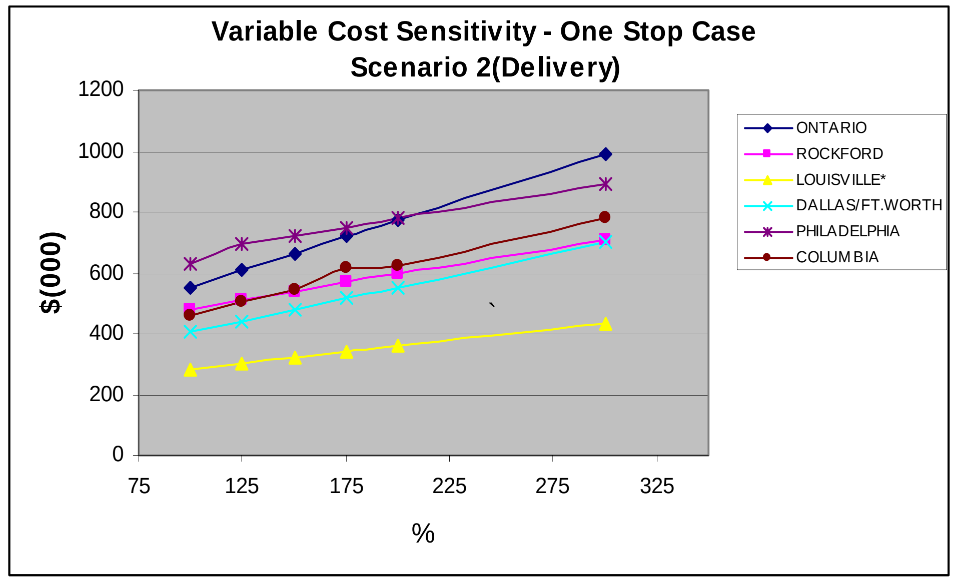
Results for the pick-up and delivery sides are shown in Table-7.33. Figures 33a and 33b show the variation of total cost with respect to variable cost.

	Pick-up Side						Delivery Side					
REGIONAL HUBS	**Base**	**125%**	**150%**	**175%**	**200%**	**300%**	**Base**	**125%**	**150%**	**175%**	**200%**	**300%**
	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)	$('000)
ONTARIO	391	431	470	511	553	709	554	610	664	719	773	989
ROCKFORD	715	759	804	849	893	1068	481	510	539	569	595	707
LOUISVILLE*	293	311	330	348	367	439	283	303	320	340	358	431
DALLAS/FT.WORTH	325	363	397	433	469	608	405	439	480	516	554	702
PHILADELPHIA	606	622	649	674	700	799	632	692	720	750	779	890
COLUMBIA	459	500	538	614	618	767	459	502	541	617	623	780
TOTAL	**2789**	**2985**	**3187**	**3428**	**3600**	**4390**	**2817**	**3055**	**3264**	**3510**	**3682**	**4498**

[Table 7.33: One Stop- Scenario 1 Regional Hubs Case Variable Cost Sensitivity Results]



[Figure 7.33a: One Stop- Scenario 1 Regional Hubs Case Variable Cost Sensitivity (Pickup)]



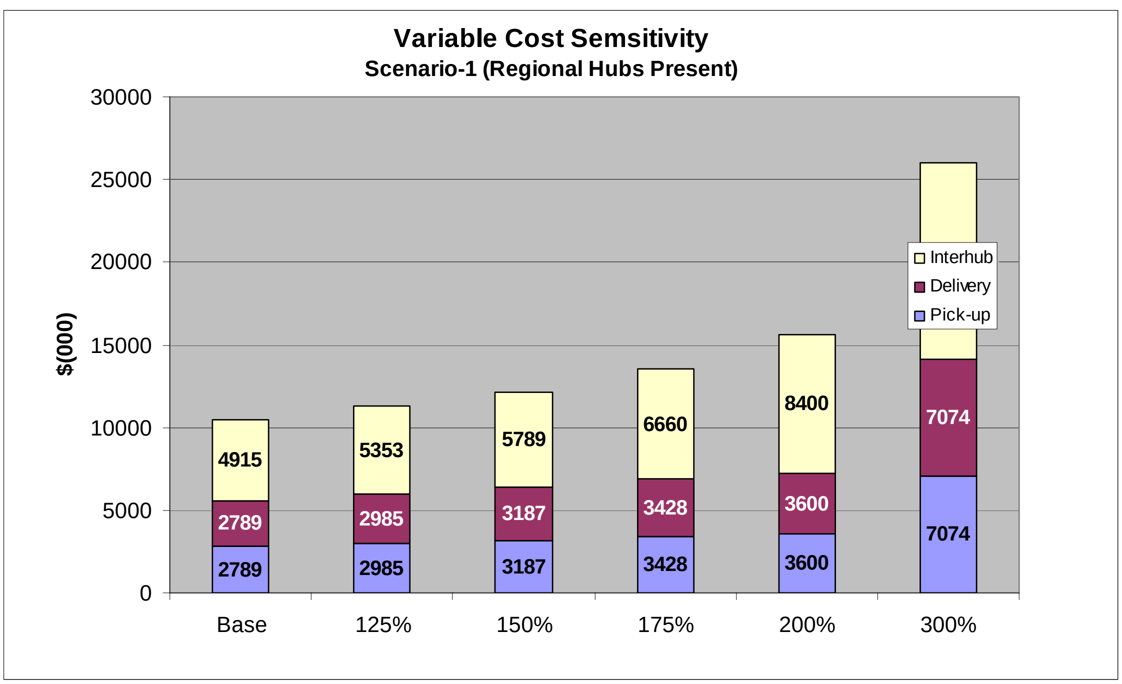
[Figure 7.33b: One Stop- Scenario 1 Regional Hubs Case Variable Cost Sensitivity (Delivery)]

Total Cost of operations is shown in Table 7.34.

TOTAL COST						
REGIONAL HUBS	Base	125%	150%	200%	300%	500%
	('000)	('000)	('000)	('000)	('000)	('000)
ONTARIO	946	1040	1134	1230	1326	1697
ROCKFORD	1196	1269	1343	1417	1488	1775
LOUISVILLE*	576	614	650	688	725	869
DALLAS/FT.WORTH	730	801	877	949	1023	1310
PHILADELPHIA	1238	1314	1369	1423	1479	1689
COLUMBIA	918	1001	1078	1231	1241	1547
INTERHUB	4915	5353	5789	6660	8400	11855
TOTAL	10519	11393	12240	13598	15682	20743
% Increase from Base		8%	16%	29%	49%	97%

[Table 7.34: One Stop- Scenario 1 Regional Hubs Case Variable Cost Sensitivity (Total Cost)]

Figure 7.34 shows the variation of total cost with respect to changes in the variable cost.



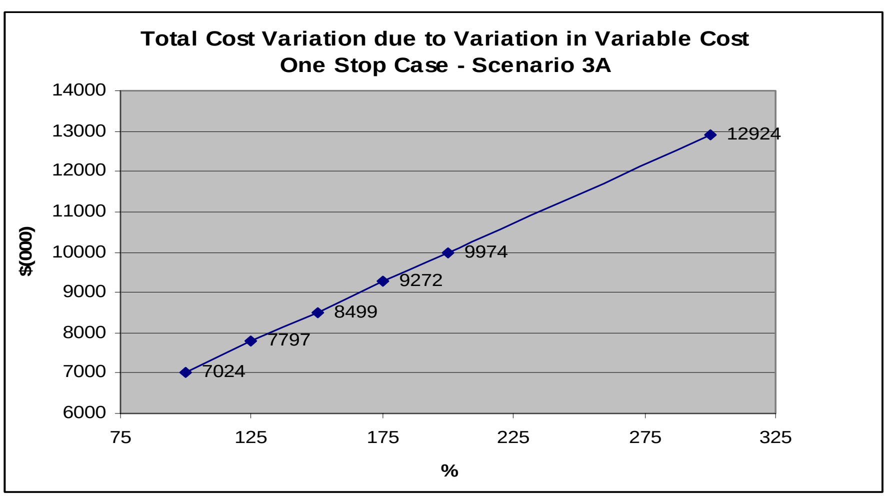
[Figure 7.34: One Stop- Scenario 1 Regional Hubs Case Variable Cost Sensitivity (Total Cost)]

7.4.2.3.1 Scenario 3A: Demands routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on Pick-up

On the pick-up side, demands are routed from the origin either through one-stop routes to the destination regional hubs or through no stop routes through the origin regional hub (see Figure 6.8). The delivery side becomes the case where we allow one-stop routes to the destination. Table 7.35 and Figure 7.35 show the results of the MIP runs.

Scenario 3A	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
Base	**4210**	**2814**	7024	
125%	**4549**	**3248**	7797	11%
150%	**4856**	**3643**	8499	21%
175%	**4953**	**4319**	9272	32%
200%	**4408**	**5566**	9974	42%
300%	**5831**	**7093**	12924	84%

[Table 7.35: One Stop- Scenario 3A Variable Cost Sensitivity (Total Cost)]



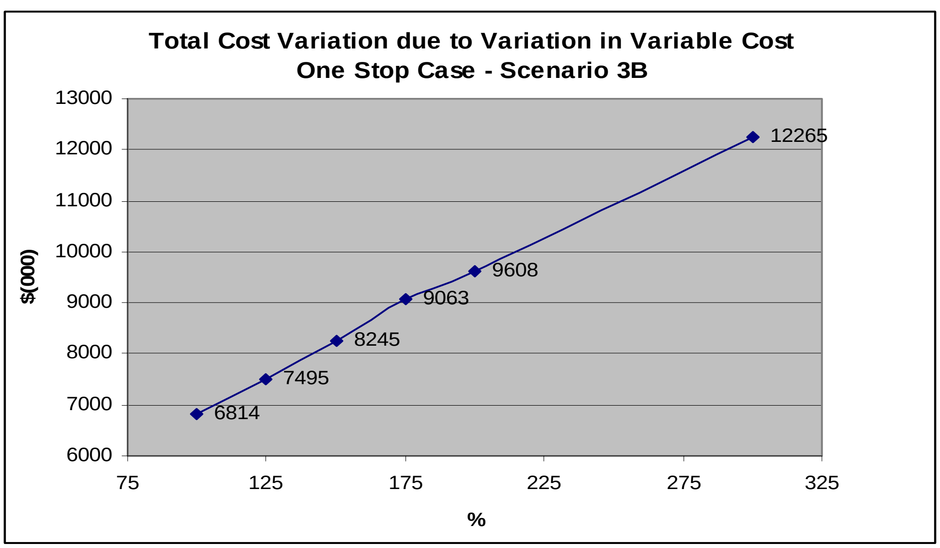
[Figure 7.35: One Stop- Scenario 3A Variable Cost Sensitivity (Total Cost)]

7.4.2.3.2 Scenario 3B: Demands routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on Delivery

The pick-up side is the case where we allow one-stop routes from origin to origin regional hub. On the delivery side, demands are routed from origin regional hubs either through one-stop routes to destinations or through no stop routes through destination regional hub on delivery. Table 7.36 and Figure 7.36 show the results of the MIP runs.

Scenario 3B	Pick-up Side	Delivery Side	TOTAL	% Increase from Base
	$000	$000	$000	
Base	**2789**	**4025**	**6814**	
125%	**3213**	**4282**	**7495**	**10%**
150%	**3591**	**4654**	**8245**	**21%**
175%	**4271**	**4792**	**9063**	**33%**
200%	**5536**	**4072**	**9608**	**41%**
300%	**7075**	**5190**	**12265**	**80%**

[Table 7.36: One Stop- Scenario 3B Sensitivity (Total Cost)]



[Figure 7.36: One Stop- Scenario 3B Sensitivity (Total Cost)]

7.5 Bounds on Flights Sensitivity

In this section, we analyze the effect of imposing bounds on the number of aircraft between an origin-hub and hub-destination pair. This constraint has real world significance owing to the fact that FAA and Airport Authorities often impose restrictions on the number of flights between an origin-destination pair. Due to the restrictions on gate availability and numerous other factors, there may be bounds on the number of aircraft of certain kind that can take-off and land at an airport. We study the effects by comparing the "no bound" case (unlimited take-off and landing) to cases where the maximum take-offs and landings are for each aircraft type are bounded. These constraints are kind of generalized but the model has the capability of handling these real world airport constraints. New airport constraints could be easily incorporated within the model for example constraints on the total number of gates available for a company, which would be a restriction on the number of aircraft that a SSP may fly between a origin-hub or hub-destination pair. We study the effect of bounds for the following scenarios.

7.5.1 No Intermediate Stop Scenario

7.5.1.1 Scenario-1 No Intermediate Stops with demands routed through multiple hubs

(i) Pick-up Side: Demands routed either through Origin Regional Hub or directly to main hub

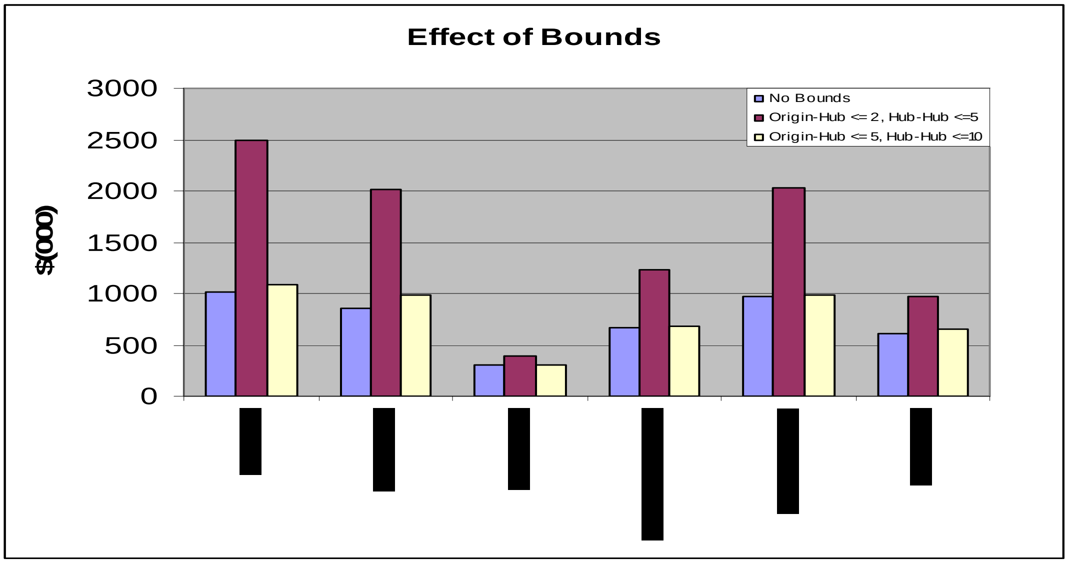
Following are the results obtained from MIP runs on a CPLEX 9.0 Solver. Louisville was assumed to be the main hub and all demands were routed from origins and origin regional hubs (Ontario, Rockford, Dallas/ Fort Worth, Philadelphia and Columbia) to the destinations or destination regional hubs through this main hub. As explained before, we have assumed three sub cases in each regional hub: Sub Case (a): no limits on number of aircraft that can fly between an origin-hub / regional hub-hub pair; Sub Case (b): maximum number of aircraft of a certain type that can fly between a origin-hub pair is 2 and maximum number of regional hub-hub pair is 5; Sub Case (c): the maximum number of aircraft of a certain type that can fly between a origin-hub pair and maximum number of regional hub-hub pair are 5 and 10 respectively. The results are shown in Table 7.37a.

REGIONAL HUBS	Sub Case a	Sub Case b	Sub Case c	b vs a	c vs a
	$(000)	$(000)	$(000)		
ONTARIO	1011	2497	1082	147%	7%
ROCKFORD	848	2018	992	138%	17%
LOUISVILLE *	303	391	303	29%	0%
DALLAS/FT.WORTH	671	1234	677	84%	1%
PHILADELPHIA	969	2035	989	110%	2%
COLUMBIA	604	972	658	61%	9%
TOTAL	4405	9119	4714	107%	7%

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 7.37a: Effect of Bounds on Take-Offs and Landings (Pickup Side)]

Clearly, the effects of bounds cannot be overstated. SSP have to incur a significant lot more cost to deliver packages. The bounds in Sub Case b have the largest impact in the Ontario hub region and most of the cost can be attributed to the demand arising from Los Angeles. Similarly, the second highest impacted hub is Rockford which is again due to the high demand from Chicago. As the number of take-offs from these cities are restricted to 2 by the constraint, it implies that the shipping is done by commercial airlines where the cost is assumed to be around 3 times. The bounds in Sub Case c are kind of weak as most of the demands would be routed adhering to the bounds. The increase of 7% is only due to cities with very high demands. Figure 7.37a shows these effects more elaborately.



[Figure 7.37a: Effect of Bounds on Pickup Side]

(ii) Delivery Side: Demands routed either through destination regional hub or directly to destination on delivery side

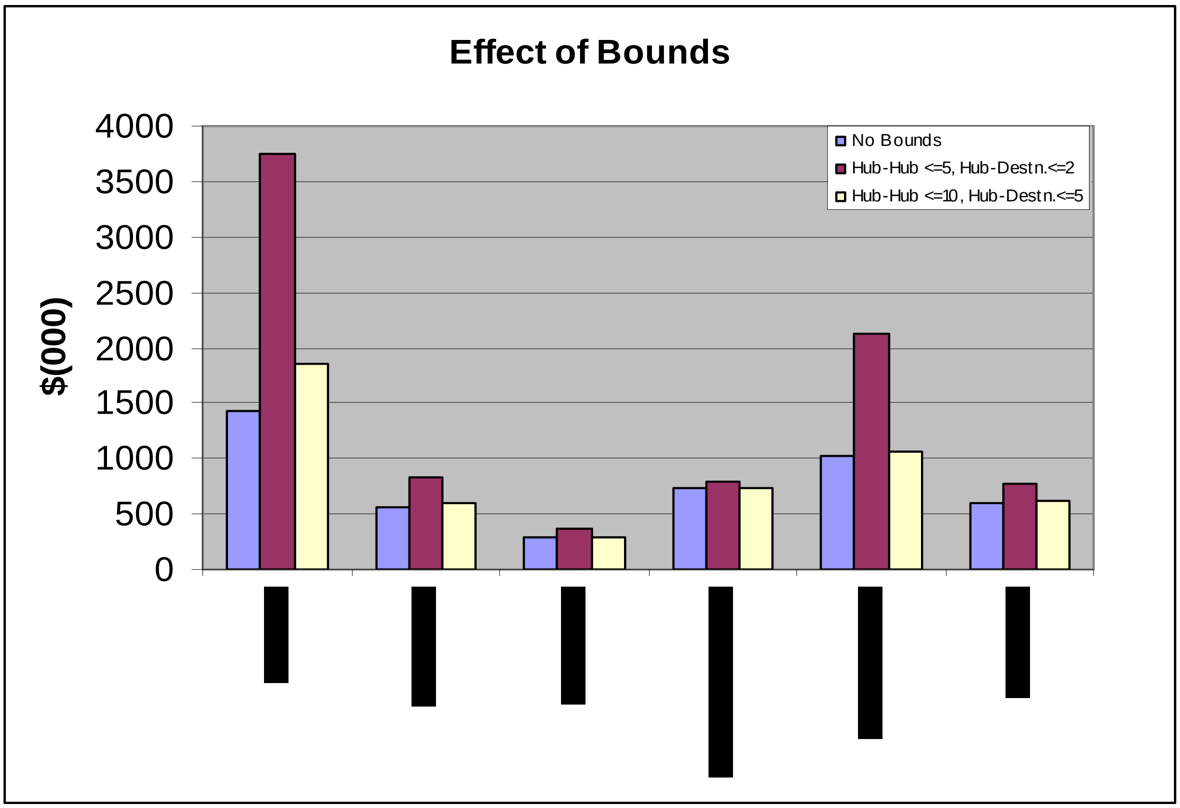
We adopt a similar methodology for the delivery side. The costs are shown in Table 7.35b.

REGIONAL HUBS	Sub Case a	Sub Case b	Sub Case c	b vs a	c vs a
	$(000)	$(000)	$(000)		
ONTARIO	1433	3740	1863	161%	30%
ROCKFORD	566	837	600	48%	6%
LOUISVILLE*	295	375	295	27%	0%
DALLAS/FT.WORTH	740	799	740	8%	0%
PHILADELPHIA	1021	2135	1072	109%	5%
COLUMBIA	606	782	618	29%	2%
TOTAL	4661	9042	5174	94%	11%

* In case of Louisville, there won't be two hubs as the main hub and the regional hub are same.

[Table 7.37b: Effect of Bounds on Take-Offs and Landings (Delivery Side)]

In this case, we restrict the number of hub-destination flights using a certain kind of aircraft. From the results for Sub Case b, it is found that Ontario hub operations is the worst affected by this policy, followed by Philadelphia. Apart from Ontario, we find that Sub Case c is not a binding constraint for the delivery side. These values again reinforce our inferences drawn from the pick-up side observations. Figure 7.37b shows the variations of total cost due to the bounds we provide.



[Figure 7.37b: Effect of Bounds on Delivery Side]

Chapter 8

Conclusion & Future Scope of Research

8.1 Conclusions

This chapter summarizes our observations, findings from our analysis and future scope of research in this area. Air transportation is a crucial component of the Express Package Delivery Services from and operational as well as cost standpoint. Due to the high values of the assets involved in terms of aircraft and huge operational cost implications, any small percentage savings could result in the order of savings of millions of dollars for the company. In the previous chapters, we analyzed the cost implications of various strategies that a company may think of implementing. We considered two main operational strategies: one involving no intermediate stops on pick-up and delivery sides and the other involving one intermediate stop between origin and hub on pick-up side and between hub and destination on delivery side. Under each strategy, we analyzed the cost implications under a single hub network configuration and regional hub network configuration. In Chapters 5 and 6, we studied various variants and logical combinations of these scenarios which gave a clear understanding of the network structure. In Chapter 7, we carried an extensive sensitivity analysis to understand the implications of variation in demand, fixed cost of operation and variable cost of operation. We also analyzed a few instances to test the implications of bounds on the number of aircraft taking off and landing in the airports.

8.2 Summary of Results

In this section, we summarize results from the sensitivity analysis. Figure 8.1 gives the brief description of the scenarios analyzed in Chapters 5 through 7.

No Stop Scenarios

Scenario-1(A):	Single Hub Case
Scenario-1(B):	Demands routed through Origin Regional Hubs on pick-up side Demands routed through Destination Regional Hubs on delivery side
Scenario-2:	Demands routed either through Origin Regional Hub or directly to Main Hub on pick-up Demands routed either through Destination Regional Hub or directly to Destination on delivery
Scenario-3(A):	Demands routed either through Origin Regional Hub or directly to Destination Regional Hub
Scenario-3(B):	Demands routed from Origin Regional Hubs to destination or Destination Regional Hub

One Stop Scenarios

Scenario-1:	Single Hub Case
Scenario-2:	Demands routed through Origin Regional Hubs on pick-up side Demands routed through Destination Regional Hubs on delivery side
Scenario-3(A):	
Scenario-3(B):	Demands consolidated at Origin Regional Hubs and are routed from there either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on delivery side

[Figure 8.1: Scenario Descriptions]

From the results of our analysis in Chapters 5 through 7, we find out that One Intermediate Stop Scenario 3 strategy has the least total cost of operations. We consistently observe that when demands are routed from Origin Regional Hubs either through One Stop routes to Destinations or through No Stop routes through Destination Regional Hubs on delivery side, we obtain the least cost of operation. The pickup side is the case where demands from the origins are consolidated at the Origin Regional Hub by means of one stop routes from Origins to the Origin Regional Hub. This strategy stands out as the best strategy across all demand ranges, fixed cost and variable cost ranges.

Total costs incurred for opting for a similar strategy, when demands are routed from Origin either through One Stop routes to Destination Regional Hubs or through No Stop routes through Original Regional Hubs on pick-up side and from dispatched to the destination by one stop routes from Destination Regional Hub, we get the second minimal total cost of operations.

From our sensitivity analysis, we find a clear understanding of the cost implications of various strategies. Our results show relative performances of various strategies and we have sufficient evidence to accept or reject a strategy. We can also find out how much better or worse we could perform by opting a certain strategy against another. For example, we can find out that Single Hub Case with one intermediate stop on pick-up and delivery has a certain percentage of less cost implications than the Single Hub Case with no intermediate stops on pick-up or delivery routes.

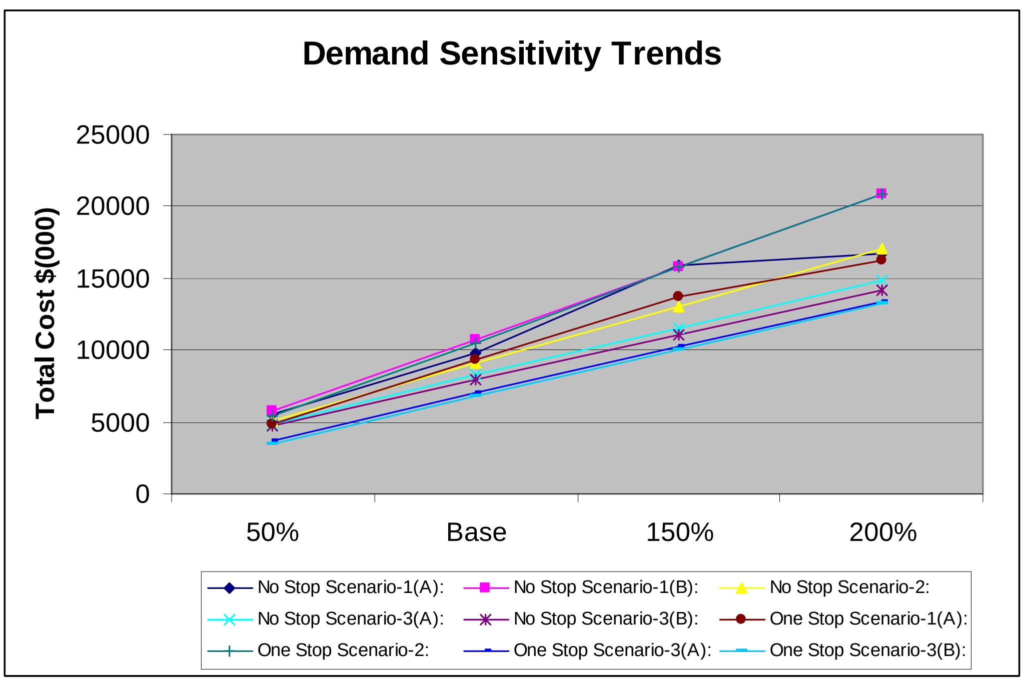
In the following sections, we summarize our findings of our research with respect to variation in demand, fixed and variable costs of operation. The data obtained give valuable information about the network structure. Based on the results obtained, we have developed equations relating the total costs with demand, fixed costs and variable costs. We find simple patterns in the network structure. These equations could be used with reasonable accuracy to study the network from a planning stand point. Needless to say, the model could also be used from a tactical or operational standpoint. With the proper data inputs, the model could serve for operational management decision inputs. With very few modifications, one can study implications of a plethora of strategies using this model. One could easily incorporate constraints to the problem.

8.2.1 Total Cost Implications of Demand

Table 8.1 summarizes the results of the demand sensitivity. We find that the total cost of operation under a strategy increases linearly with increase in demand. Scenario 3B under the one stop scenario has the least total cost of operations. We see that total cost varies linearly with demand and different strategies have different rates of increase of total cost (see Figure 8.2). We also show the percentage comparison of total cost with respect to demand across all scenarios.

Scenarios	50%		Base		150%		200%	
	$(000)	%	$(000)	%	$(000)	%	$(000)	%
No Stop Scenario-1(A):	5514	157%	9753	143%	15923	159%	16715	126%
No Stop Scenario-1(B):	5747	164%	10762	158%	15777	157%	20824	157%
No Stop Scenario-2:	5051	144%	9066	133%	13045	130%	17106	129%
No Stop Scenario-3(A):	4895	139%	8337	122%	11537	115%	14866	112%
No Stop Scenario-3(B):	4700	134%	7942	117%	11092	111%	14225	107%
One Stop Scenario-1(A):	4840	138%	9337	137%	13710	137%	16290	123%
One Stop Scenario-2:	5432	155%	10521	154%	15751	157%	20896	158%
One Stop Scenario-3(A):	3648	104%	7024	103%	10282	103%	13373	101%
One Stop Scenario-3(B):	3511	100%	6814	100%	10027	100%	13235	100%

[Table 8.1: Summary of Demand Sensitivity Analysis]



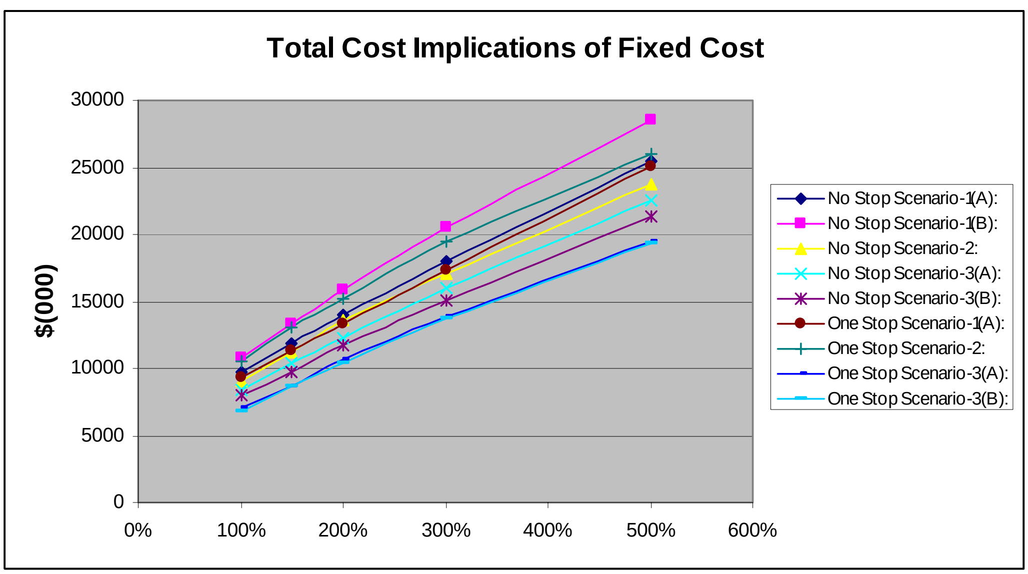
[Figure 8.2: Total Cost Variation versus Demand]

8.2.2 Total Cost Implications of Fixed Cost

Table 8.2 summarizes the results of the fixed cost sensitivity. Figure 8.3 shows the total cost trends with respect to fixed costs. We see a polynomial variation with the slope of the lines increasing as we move from lower fixed cost intervals to higher fixed cost intervals.

	Base	125%	150%	200%	300%	500%
	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)
No Stop Scenarios						
Scenario-1(A):	9753	10830	11891	13981	18027	25419
Scenario-1(B):	10763	12091	13369	15841	20593	28513
Scenario-2:	9066	10136	11196	13585	17017	23757
Scenario-3(A):	8337		10389	12272	16000	22525
Scenario-3(B):	7943		9770	11792	15111	21384
One Stop Scenarios						
Scenario-1(A):	9337	10364	11391	13352	17367	25023
Scenario-2:	10519	11813	13023	15250	19502	26023
Scenario-3(A):	7024	8007	8710	10606	13908	19527
Scenario-3(B):	6814	7768	8654	10425	13696	19352

[Table 8.2: Summary of Fixed Cost Sensitivity Analysis]



[Figure 8.3: Total Cost Variation versus Fixed Cost Variation]

Table 8.3 shows the percentage comparison of total cost with respect to fixed cost

Scenarios	Base	125%	150%	200%	300%	500%
No Stop Scenario-1(A):	143%	139%	137%	134%	132%	131%
No Stop Scenario-1(B):	158%	156%	154%	152%	150%	147%
No Stop Scenario-2:	133%	130%	129%	130%	124%	123%
No Stop Scenario-3(A):	122%		120%	118%	117%	116%
No Stop Scenario-3(B):	117%		113%	113%	110%	111%
One Stop Scenario-1(A):	137%	133%	132%	128%	127%	129%
One Stop Scenario-2:	154%	152%	150%	146%	142%	134%
One Stop Scenario-3(A):	103%	103%	101%	102%	102%	101%
One Stop Scenario-3(B):	100%	100%	100%	100%	100%	100%

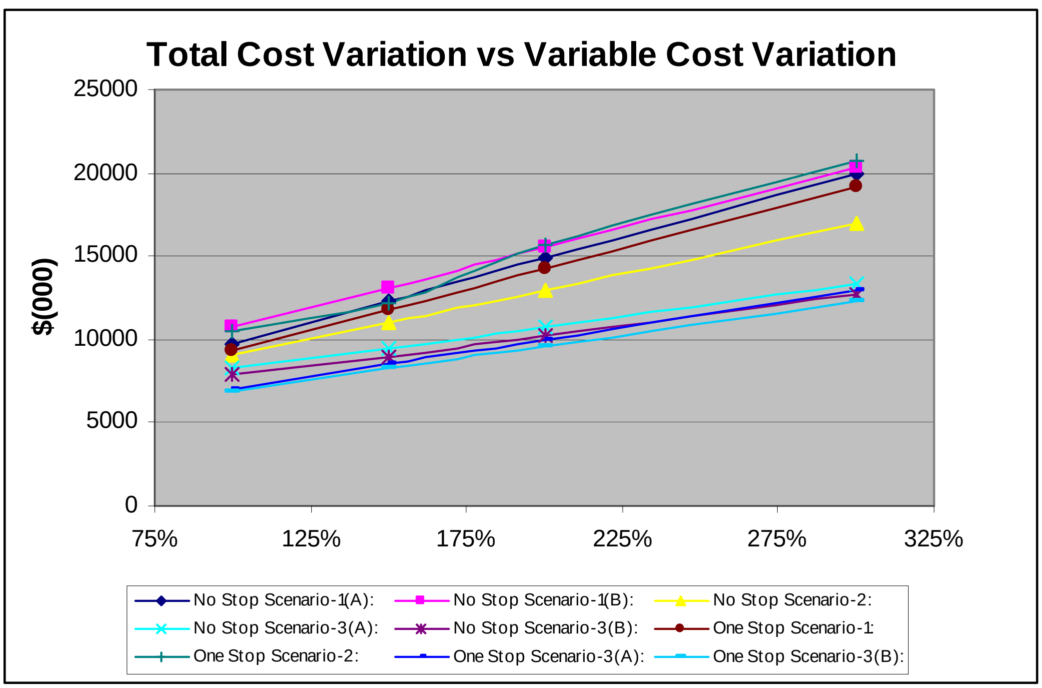
[Table 8.3: Percentage Comparison of Total Cost with respect to Fixed Cost across all Scenarios]

8.2.3 Total Cost Implications of Variable Cost

Table 8.4 summarizes the results of the variable cost sensitivity. Figure 8.4 shows the total cost trends with respect to variable costs. We see that the slope of the lines remains constant till the variable cost increases by 200%.

	Base	125%	150%	175%	200%	300%
	$(000)	$(000)	$(000)	$(000)	$(000)	$(000)
No Stop Scenarios						
Scenario-1(A):	9753	11053	12346	13630	14901	19922
Scenario-1(B):	10764	11977	13121	14379	15579	20378
Scenario-2:	9067	9934	10968	11994	13012	17024
Scenario-3(A):	8337		9450		10766	13325
Scenario-3(B):	7943		8925		10233	12700
One Stop Scenarios						
Scenario-1:	9337	10551	11765	12978	14286	19234
Scenario-2:	10519	11393	12240	13598	15682	20743
Scenario-3(A):	7024	7797	8499	9272	9974	12924
Scenario-3(B):	6814	7495	8245	9063	9608	12265

[Table 8.4: Summary of Variable Cost Sensitivity Analysis]



[Figure 8.4: Total Cost Variation versus Variable Cost]

Table 8.5 shows the percentage comparison of total cost with respect to variable cost across all scenarios.

Scenarios	**Base**	**125%**	**150%**	**175%**	**200%**	**300%**
No Stop Scenario-1(A):	143%	147%	150%	150%	155%	162%
No Stop Scenario-1(B):	158%	160%	159%	159%	162%	166%
No Stop Scenario-2:	133%	133%	133%	132%	135%	139%
No Stop Scenario-3(A):	122%		115%		112%	109%
No Stop Scenario-3(B):	117%		108%		107%	104%
One Stop Scenario-1(A):	137%	141%	143%	143%	149%	157%
One Stop Scenario-2:	154%	152%	148%	150%	163%	169%
One Stop Scenario-3(A):	103%	104%	103%	102%	104%	105%
One Stop Scenario-3(B):	100%	100%	100%	100%	100%	100%

[Table 8.5 Percentage Comparison of Total Cost with respect to Variable Cost across all Scenarios]

8.3 Computation Times

All the models were run using a CPLEX 9.0 MIP Solver on a 512MB Pentium IV processor. The computation time varied with respect to the problem size and scenario modeled. Table 8.6 gives the order of average computational time observed for various scenarios. Scenario 1 cases with no intermediate stops were the fastest to reach optimality followed by Regional Hub Cases and Single Hub case with one stop routes and Scenario 2 with no stops. Scenario 3 with no stops was computationally the most demanding. Some of the cases ran for more than 18 hours. In our analysis, in some cases, whenever there was a problem of convergence i.e it took a really long time for optimal solutions, we stopped the solver when it reached 1.0% or 1.5% of optimality. These convergence problems were only encountered in some of Scenario 3 no stop cases. Scenario 3A and Scenario 3B by their structure resulted in huge MIP programs and the problem read and presolve time were comparatively high (in the order of 3-5 seconds). The time for a single iteration took an average of 12-15 minutes, but the models converged to less than 1.5% of optimality in less than 30-40 minutes most of the cases. Due to time constraints, some of the Scenario 3A and Scenario 3B cases were not solved to optimality and the solver was terminated once we reached 0.5% optimality.

Scenarios	Average Computation Time Order
No Stop Scenario-1(A):	10^{1} (usually ~ 30 seconds)
No Stop Scenario-1(B):	10^{-1} (usually ~ 10 seconds)
No Stop Scenario-2:	10^{1} (usually ~ 45 seconds)
No Stop Scenario-3(A):	10^{3} (usually ~ 7200 seconds)
No Stop Scenario-3(B):	10^{3} (usually ~ 7200 seconds)
One Stop Scenario-1(A):	10^{1} (usually ~ 7200 seconds)
One Stop Scenario-2:	10^{-1} (usually ~ 1800 seconds)
One Stop Scenario-3(A):	10^{3} (usually ~ 7200 seconds)
One Stop Scenario-3(B):	10^{3} (usually ~ 7200 seconds)

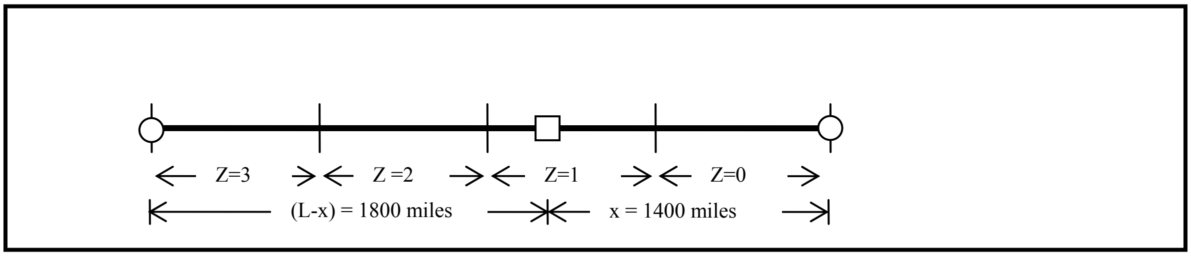
[Table 8.6: Computation Times]

8.4 Future Scope

The MIP models used in the analysis could easily be updated to study other strategies that a shipment service provider wishes to employ. Constraints could easily be incorporated in the model to reflect more real life situations. The dataset used in our analysis was created from the Commodity Flow Survey and NAICS data. We only considered two kinds of aircraft in our analysis. The models could easily be run with real data and more aircraft types. One of the areas where the model could be updated is running it on a time horizon. With these trial runs with actual data, one could come up with recurrent patterns of flights selected, demand allocations to the flights. There could be potentially two main lines of research: one would be to come up with more innovative operational strategies and the other is to optimize the model performance. Reliability of the paths chosen by the model and introduction of penalty terms to reflect more decision scenarios would be a logical step in this direction. Air transportation network design for express package delivery problems comes under the difficult class of multi-commodity flow problems. There is enormous potential in this area of application from a research as well as industry stand point.

Appendix 1: Sample calculation showing the effect of time-zones.

Figure-A1 shows a sample calculation for time windows with reference to a service region comparable to US. Let segment length, L = 3200 miles and hub is located at x = 1400 miles from east end on time zone 1.



[Fig – A1]

Number of time zones, Z = 4

West bound aircraft cruise velocity, v_w = 500 mph

East bound aircraft cruise velocity, v_e = 600 mph

Latest Departure Time at airport (local time) = 18:00 hours

Take-off / Landing time, f = 30 min.

Arrival time at hub (local time) from western end of segment $T_w(x) = 18{:}00 + f + (Z_o - Z_h) + x/v_e$

$= 18{:}00 + (0.5 + 3 – 1 + 1800/600) = 23{:}30$ hours

Arrival time at hub (local time) from eastern end of segment $T_w(x) = f - (Z_o - Z_h) + (L\text{-}x)/v_w$

$= 18{:}00 + (0.5 – (0 – 1) + 1400/500) = 22{:}20$ hours

Maximum Arrival Time at hub = 23:30 hours

If 7:00 hours is the latest delivery time at the destination, then latest delivery time from the hub for

East bound destination $= 7{:}00 + (Z_d - Z_h) – x/v_w – f$

$= 7{:}00 + (3\text{-}1) – 1800/500 – 0.5 = 5{:}00$ hours

West bound destination $= 7{:}00 + (Z_d - Z_h) – (L\text{-}x)/v_e – f$

$= 7{:}00 + (0\text{-}1) – 1400/600 – 0.5 = 3{:}10$ hours

So, the east bound shipment is critical and should be dispatched prior to the westbound shipment.

Appendix 2A: List of Cities and Codes in the sample Air Network

1	SEATTLE	31	BIRMINGHAM	61	NEWARK
2	BILLINGS	32	NASHVILLE	62	WASHINGTON-DULLES
3	BOISE	33	CLEVELAND	63	NEW YORK
4	BURBANK	34	CINCINNATI	64	HARRISBURG
5	FRESNO	35	DAYTON	65	NORFOLK
6	SPOKANE	36	FORT WAYNE	66	PITTSBURGH
7	LAS VEGAS	37	HUNTSVILLE	67	RICHMOND
8	LOS ANGELES	38	INDIANAPOLIS	68	ALBANY(NY)
9	LONG BEACH	39	COLUMBUS	69	HARTFORD
10	SACRAMENTO	40	MEMPHIS	70	BOSTON
11	OAKLAND	41	KNOXVILLE	71	MANCHESTER
12	PORTLAND	42	ALBUQUERQUE	72	PROVIDENCE
13	PHOENIX	43	AUSTIN	73	NEWBURGH
14	RENO	44	DENVER	74	SYRACUSE
15	SAN DIEGO	45	HOUSTON	75	PHILADELPHIA
16	SAN JOSE	46	EL PASO	76	ALBANY(GA)
17	SALT LAKE CITY	47	HOUSTON	77	ATLANTA
18	CEDAR RAPIDS	48	WICHITA	78	MOBILE
19	DECATUR	49	JACKSON	79	CHARLOTTE
20	DES MOINES	50	LAFAYETTE	80	GREENSBORO
21	DETROIT	51	LITTLE ROCK	81	GREENVILLE
22	SIOUX FALLS	52	NEW ORLEANS	82	JACKSONVILLE
23	LANSING	53	OKLAHOMA CITY	83	RALEIGH
24	KANSAS CITY	54	SAN ANTONIO	84	ROANOKE
25	MILWAUKEE	55	SPRINGFIELD	85	FT. LAUDERDALE
26	MINNEAPOLIS	56	SHREVEPORT	86	ORLANDO
27	OMAHA	57	TULSA	87	MIAMI
28	CHICAGO	58	DALLAS / FT. WORTH	88	PALM BEACH
29	SOUTH BEND	59	BUFFALO	89	ST. PETERSBURG
30	ST. LOUIS	60	BALTIMORE	90	FORT MYERS

[Table – A2A]

Appendix 2B: Regional Hubs and Connected Cities in the sample Air Network

Regional Hub -1	Regional Hub -2	Regional Hub -3	Regional Hub -4	Regional Hub -5	Regional Hub-6
ONTARIO	DALLAS / FT. WORTH	ROCKFORD	LOUISVILLE	PHILADELPHIA	COLUMBIA
SEATTLE	ALBUQUERQUE	CEDAR RAPIDS	BIRMINGHAM	BUFFALO	ALBANY(GA)
BILLINGS	AUSTIN	DECATUR	NASHVILLE	BALTIMORE	ATLANTA
BOISE	DENVER	DES MOINES	CLEVELAND	NEWARK	MOBILE
BURBANK	HOUSTON	DETROIT	CINCINNATI	WASHINGTON-DULLES	CHARLOTTE
FRESNO	EL PASO	SIOUX FALLS	DAYTON	NEW YORK	GREENSBORO
SPOKANE	HOUSTON	LANSING	FORT WAYNE	HARRISBURG	GREENVILLE
LAS VEGAS	WICHITA	KANSAS CITY	HUNTSVILLE	NORFOLK	JACKSONVILLE
LOS ANGELES	JACKSON	MILWAUKEE	INDIANAPOLIS	PITTSBURGH	RALEIGH
LONG BEACH	LAFAYETTE	MINNEAPOLIS	COLUMBUS	RICHMOND	ROANOKE
SACRAMENTO	LITTLE ROCK	OMAHA	MEMPHIS	ALBANY(NY)	FT. LAUDERDALE
OAKLAND	NEW ORLEANS	CHICAGO	KNOXVILLE	HARTFORD	ORLANDO
PORTLAND	OKLAHOMA CITY	SOUTH BEND		BOSTON	MIAMI
PHOENIX	SAN ANTONIO	ST. LOUIS		MANCHESTER	PALM BEACH
RENO	SPRINGFIELD			PROVIDENCE	ST. PETERSBURG
SAN DIEGO	SHREVEPORT			NEWBURGH	FORT MYERS
SAN JOSE	TULSA			SYRACUSE	
SALT LAKE CITY					

[Table – A2B]

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