The Pennsylvania State University

The Graduate School

College of Engineering

OPTIMIZATION OF AN INBOUND LOGISTICS NETWORK:

AN AUTOMOTIVE CASE STUDY

A Thesis in

Industrial Engineering

by

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ABSTRACT

The design, execution and coordination of a logistics network are essential activities of any supply chain. Although outbound logistics is very important to ensure high responsiveness for customer satisfaction, improper planning of the inbound process could cause disruptions further down the supply chain and affect the overall performance. The two most important factors to be considered for inbound logistics planning are: overall costs and the delivery time.

This thesis aims at building an optimization model to aid an Indian automotive OEM in determining the most suitable option to ship material into their plant. The firm currently receives a variety of material at the plants via direct shipments from remotely located suppliers leading to high inventory holding costs. To address the issues of limited plant capacity and increased delivery lead times, including a warehouse and distributors located closer to the plant is proposed. The bi-criteria mixed integer linear program is developed to help determine if: (1) the plants should receive material from the suppliers by direct delivery or (2) from the distributors. The objectives of the model are to minimize overall costs (inventory and transportation) and lead time. The model is solved using Non Pre-emptive Goal Programming by assigning a set of weights to either objective. The model determines the most suitable option to ship material to the plant in the shortest time and at the lowest cost to the company. A scenario analysis is also performed to consider the uncertainty in demand. The most frequently selected shipping option is selected as the best strategy for a given material. The model is illustrated using a combination of real and simulated data from the OEM.

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Chapter 1

Introduction

Delivery of a product/service to the customer requires a high level of coordination among the different departments in an organization. The entire system that ensures this delivery is referred to as the *supply chain*. Procuring material from suppliers, transportation, storage, manufacturing, distribution and customer service are typical stages of this system. Each industry uses a specific model that is based on their needs which need not necessarily include every one of these stages. Performance of one stage is directly/indirectly affected by changes in the others. This has led to the shift in focus from individual stages to the efficient management of the entire supply chain.

1.1 Logistics Management: Definition and Importance

An essential part of any supply chain is the **logistics**, which deals with the **flow of product, information and other resources**. Inventory, transportation, storage, materials handling and packaging, constitute various activities of logistics. It supports procurement, manufacturing (if present) and customer service. It also requires a high level of integration for smooth functioning. Information exchange to support this integration is also essential. Hence logistics management is an important task to ensure constant flow. Figure.1.1 illustrates the integrated logistics process.

1.1.1 Planning and Control

The planning and implementation of the logistics operations affects the competitiveness and responsiveness of the supply chain. Decisions are taken at the strategic, tactical and operational levels.

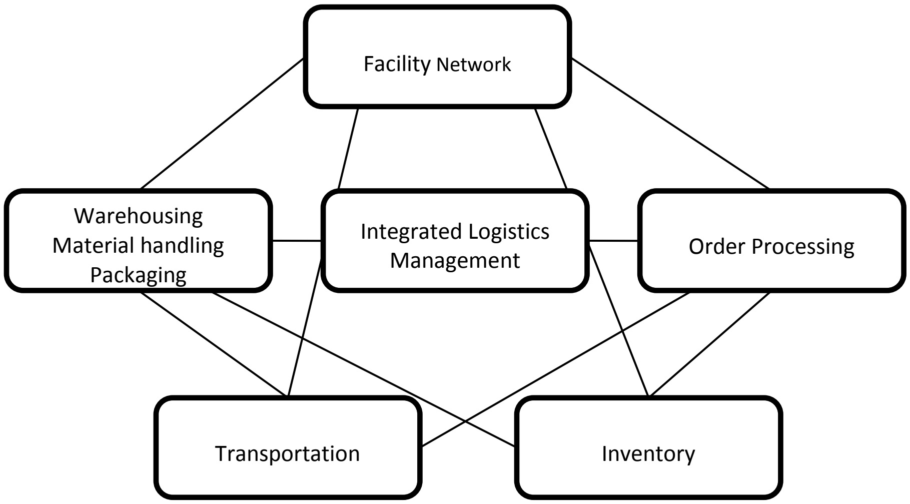

Figure 1.1: Integrated Logistics Process (Bowersox et al., 2010)

Some of the areas that need to be addressed during the design phase are listed below along with the associated decision making levels:

	Strategic	**Tactical**	**Operational**
Procurement	Sourcing, Supplier Selection	Order Allocation	Order picking
Inventory & Warehousing	Location of warehouses, Capacities	Policy decisions	Reorders, back orders
Transportation & Routing	Network planning	Vehicle routing, Route scheduling	Vehicle Dispatching

Table 1.1 Supply Chain activities and decision making levels

After design and implementation, the next important step is to monitor the activities to ensure that the required level of performance is maintained. Areas of improvement are identified and suitable decisions are taken. In order to do so, companies must use measurement systems based on their requirements. Metrics are developed to analyze the operational and financial performance (Bowersox et al., 2010). *Cost, Quality, Productivity* and *Customer service* are few of the metrics that are considered. With supply chain integration, parameters such as *number of inventory days*, *cash-to-cash cycle* and *total supply chain cost* have also been included. However the choice of the metrics depends on the objective of the study being performed.

1.1.2 Classification

Logistics can be classified into: *inbound, in-plant* and *outbound*, based on points of origin and destination. In the manufacturing setting, inbound logistics deals with all the activities that are involved in bringing the raw material to the facility, while outbound logistics focuses on the delivery of the finished/services to the customer. In-plant logistics refers to the movement of raw material, semi-finished and finished goods within the facility.

1.2 Significance of inbound logistics

The responsiveness of the supply chain relies heavily on the performance of outbound logistics. However, inbound logistics does pose potential problems that could hinder the overall performance. This was confirmed by the extensive interviewing process carried out by Miemczyk and Holweg (2004) where most of the automotive firms stated that links between suppliers and assembly plants were of primary concern to them. As inbound logistics is one of the earliest activities in the supply chain, improper planning could cause disruptions further down the chain.

Before entering the design phase of the inbound logistics process, firms must fully understand the various dimensions to it. Coyle et al (2003) identified one of them to be the **differences that exist in the set up of inbound logistics between companies**. What could be considered as an inbound process for one company might be another's outbound process. Also, depending on a firm's location in the overall supply chain, they could be involved with not only inbound activities but also outbound. For example, a manufacturer would be concerned with both the inbound and outbound processes whereas an end user/customer would focus on the inbound process. **Complexity** of the inbound process is a very important dimension that should not be overlooked. With the need for over thousands of different components, the automotive sector is the best example for a complex inbound logistics that requires a great deal of planning and coordination. The following section will provide more information on its importance.

1.3 Inbound Logistics in the Automotive Supply Chain

In the automotive sector, there is interaction with numerous suppliers to fulfill requirements of several hundreds of components. Planning involves coordination of routes, order quantities, mode of transport, warehousing, type of packaging and labor. Purchasing is also affected by this coordination. Managing all of these activities as part of the overall supply chain also requires a great deal of effort and selecting the strategy that ensures smooth functioning becomes important.

Automotive companies are faced with the decision of selecting the right logistics plan for their network. Instead of employing a single operation across all products, a firm can select the most suited one for each component or a group of components.

There are several options available to plan their inbound logistics. Figure1.2 illustrates a generic process (Miemczyk and Holweg, 2004) based on feedback from various firms. Direct delivery, consolidated pick up, cross-docking and milk runs can be employed at different stages. These techniques are used by a variety of industries to optimize their inbound logistics.

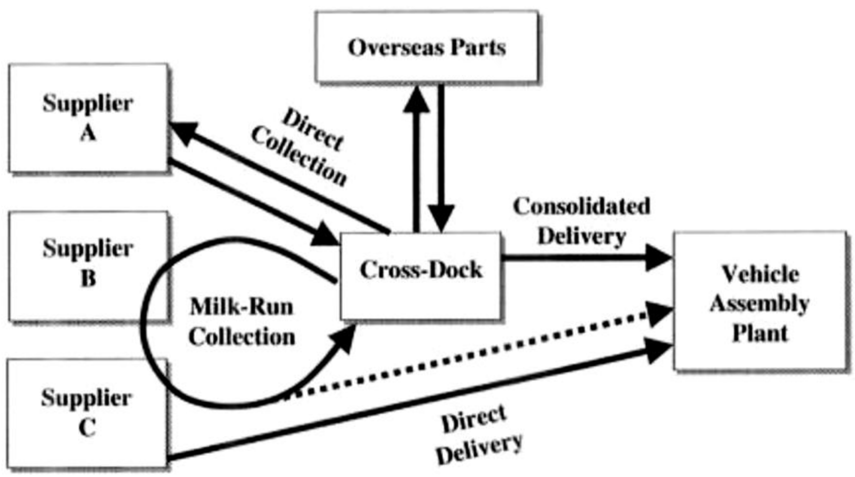

Figure 1.2: Generic Inbound Logistics Process – Automotive Companies (Miemczyk and Holweg, 2004)

A milk run is often referred to as an inverse distribution run (C.M. van Baar, 2011) during which the same vehicle picks up material from multiple suppliers. This form of consolidated pickup reduces inventory levels and transportation costs but leads to increased coordination complexity.

Cross docking involves moving material from the receiving dock to the shipping dock with little or almost no storage in between. Full truck load (FTL) shipments help reduce transportation costs as well as the average inventory in the system (Apte and Viswanathan, 2002). Improved flexibility, better responsiveness and reduced order cycle time are other benefits of employing cross docking.

Most research deals with the selection of these options by reducing the overall costs in the system and the cycle time. The decision is based on factors such as unit stock out costs, product demand rate and location of warehouses and demand/supply points.

Having established the need for proper inbound logistics planning, the subsequent sections will provide a formal introduction to the thesis research with details of a problem faced by an automotive firm and the proposed method to arrive at a solution.

1.4 Problem statement

This research aims at building a model that would help optimize the inbound logistics set up at an automotive company in India by minimizing costs and delivery time. The firm's existing process and the problems faced will be discussed in the section below, followed by the methodology proposed for improvements.

1.4.1 Existing Inbound Logistics Process

The firm currently owns several plants that place orders at different suppliers. The material from each supplier is then shipped directly to each plant and stored before use. The firm is in charge of transportation and rents vehicles (trucks) based on requirements. (See Figure 1.3)

On analyzing the set up, the firm has highlighted two main concerns:

- Directly shipping to the plant has led to the increase in inventory holding costs. Also, with limited capacity at the plant, material often overflows out of the assigned storage space.
- Some of the orders take a long time to be delivered, which causes delay in assembly/production.

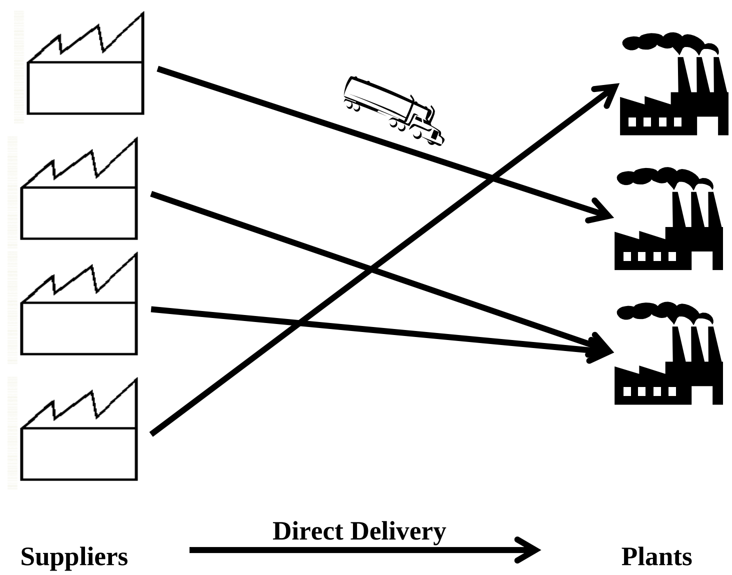

Figure 1.3: Current inbound network

To address the issues mentioned above, the management is considering the following plans of action:

- The overflowing of material at the plants' storage area can be avoided by utilizing a central warehouse located close to the plants. The raw material can be stored until it is required at each plant.

- The plants have the option of placing orders at independent distributors who are located closer to them. However, some of the distributors quote higher prices than the suppliers and the company needs to choose wisely without incurring very high costs.

The decision to modify the existing inbound logistics processes forms the basis of this research.

1.4.2 Proposed Research

In order to select the most appropriate inbound logistics strategy for each material, building an optimization model has been considered. The new network under review consists of: **multiple suppliers, independent distributors, a warehouse owned by the firm** and **several plants**. (See Figure 1.4)

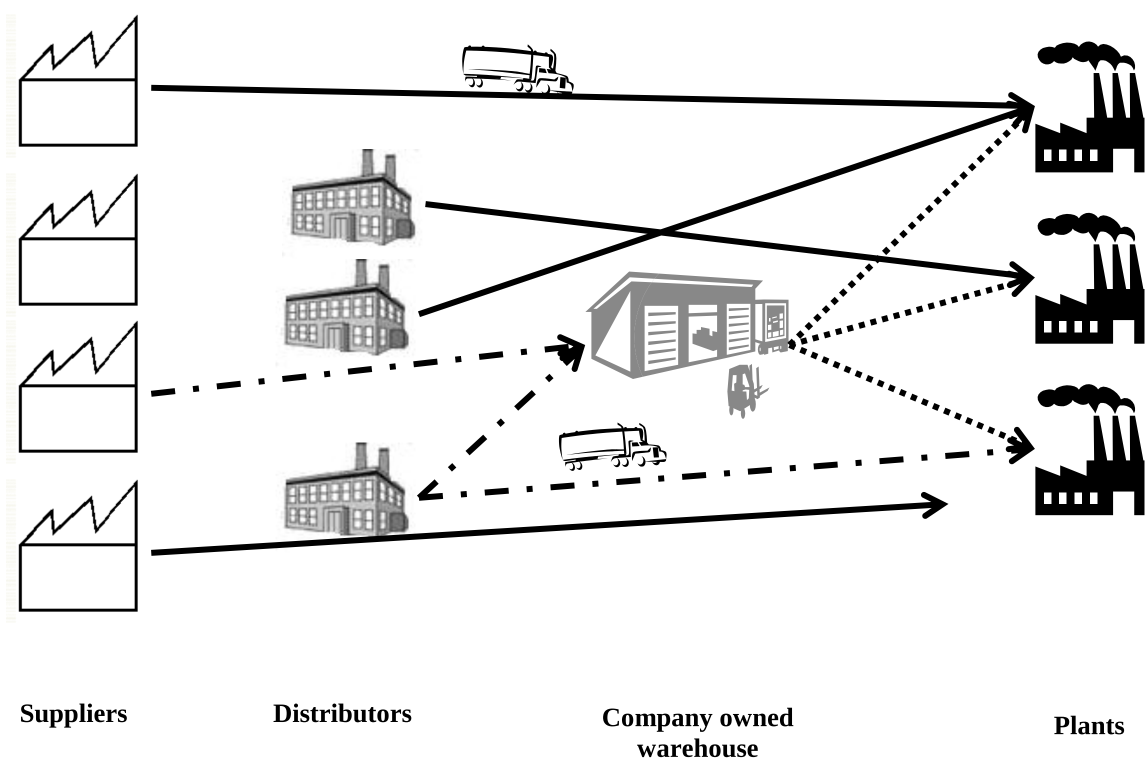

Figure 1.4: Modified inbound network

The firm has the option to place orders at the distributors or suppliers and the delivery of the material can take place via the warehouse or directly to the plants.

Figure 1.5 illustrates the various options available to the company:

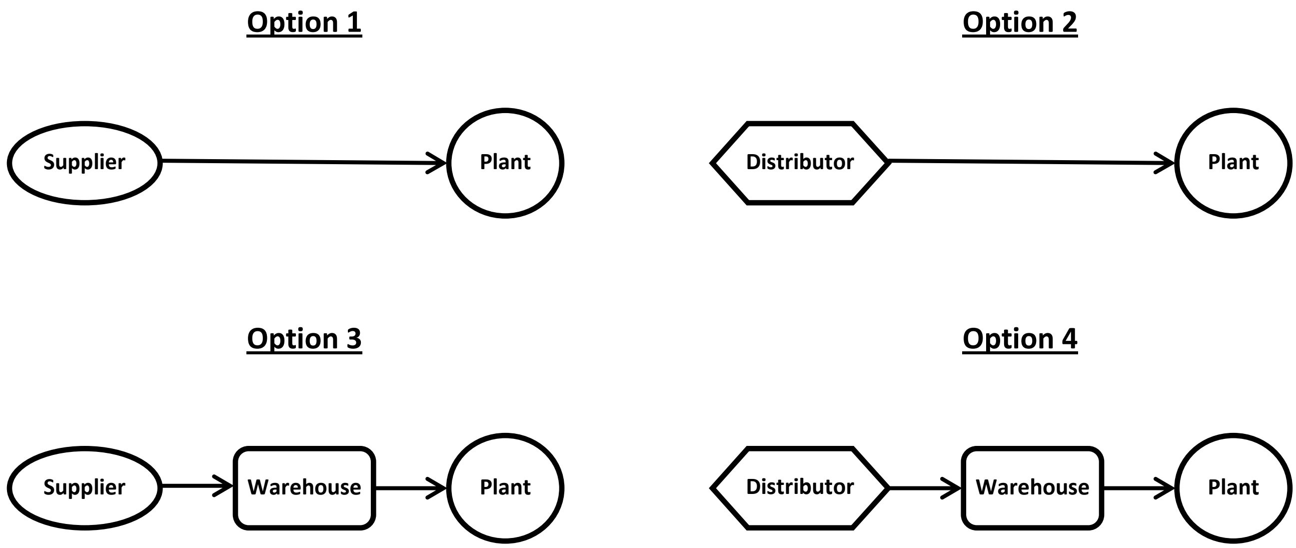

Figure 1.5: Available options to ship material

1.4.2.1 Essential Features of the Model

As mentioned in Section 1.1.1, **cost** is an essential factor that is considered while designing and measuring the performance of a logistics process. Procurement, Inventory, Transportation and Warehousing are important costs that are included in most models. **Delivery time** is also incorporated in the decision making process so that systems are not only efficient but highly responsive as well.

Hence, the two criteria to be considered are **overall costs** and **delivery lead time**. The best strategy for the firm will be the option that minimizes both criteria while taking into account the constraints. **A bi-criteria mixed integer linear program** will be used to select one of the shipping options. A **goal programming approach** will be used to solve the bi criteria model.

The essential features of the model have been discussed below. A detailed description of the mathematical formulation will be provided in Chapter 3.

Objectives: To minimize overall costs and lead time.

- **Costs:**

  The key costs to be considered are:

  - Inventory holding costs (at the warehouse and plant):

    This will be based on the **interest rate** (that accounts for cost of capital, physical storage and obsolescence) and the **cost of the product**. The inclusion of product cost is based on the hierarchy of price measurement approaches mentioned by Coyle et al (2003) which states that tactical decisions are based on the lowest unit price in addition to landed costs.
  - Transportation cost:

    The rental charge for each vehicle and the number of trucks required will determine the transportation costs.

- **Lead Time:**
  - Deterministic lead times will be used in the decision making process.

Constraints:

- The model will be constrained by the capacities of the warehouse and plant.
- There is a limit on the capacity of the vehicles rented for transporting the material and the number of vehicles available.
- Only a single option is to be selected for each supplier/distributor – plant pair.

Additional features:

As the model is being built for tactical decision making, initial supplier and distributor selection and warehouse location will not be considered.

- Vehicle routing and consolidation from the warehouse are not included. The model would have to be developed further in order to address the operational decisions.
- The inventory holding costs at the suppliers and distributors are not being included in the model.
- Material is always available at the supplier/distributors and their lead times are included in the model.
- Shortages and backorders are not considered.
- Only one mode of transportation (i.e. by road) is to be used.

Chapter 2 will provide information on inbound logistics from existing literature, while Chapter 3 will focus on the development of the optimization model. The model will be validated with data provided by an OEM (original equipment manufacturer) and then the results will be analyzed in Chapter 4. The work carried out as part of this research will be summarized in Chapter 5 and suggestions for future work will be provided.

Chapter 2

Literature Review

This chapter reviews the literature on logistics research in general and inbound logistics in particular. The various models pertaining to inbound logistics and the automotive industry have been discussed.

2.1 Research on Logistics

2.1.1 The role of Competitiveness, Strategy, Structure and Performance

As mentioned in section 1.1, logistics management is an important task in supply chain management. To ensure better decision making for an integrated logistics process, it is essential to understand the importance of *organizational structure*, *strategy* and *overall performance*.

Chow, Heaver and Hennikson (1995) identified the need for building a framework for logistics research by standardizing the definitions and ideas surrounding these elements. Centralization, scope, span of control, integration and formalization of policies are the dimensions of structure that have received maximum focus. An organization's strategy should encompass both the functional strategies as well as the overall competitive strategy to attain logistics goals. Performance is multi-dimensional and is best measured by considering the overall performance of the entire supply chain. To understand the relationship between structure, strategy and performance, it is necessary to consider the uncertainty and complexity of the supply chain. The management of information is also a key performance indicator.

Stock, Greis and Kasarda (1998) proposed that the competitive forces in the market (environment) shape the formulation of an organization's strategy and structure. Their model is based on the emerging trends in the manufacturing domain, where the development of enterprise wide logistics have come into effect. The decisions made with regard to strategy, structure and logistic activities affect the performance of the organization under consideration. While forming a strategy, a firm must choose the right competitive priorities such as cost, speed, delivery and quality. The authors also state that logistics is affected by geographic dispersion, which is an important dimension of organizational and network structure. There has been a shift in trend from focusing on individual functional roles to considering logistics as a coordinating mechanism among various enterprises within the supply chain. The performance of the new "enterprise logistics" is measured internally by the firm using parameters such as **cost**, **delivery speed**, **reliability** and **flexibility**. Market share, return on investment and sales growth constitute the external performance measures. The most important factor that will determine a firm's success will be its ability to develop competitive strategies and structures that will coordinate the different geographically dispersed logistics activities.

The globalization of various business units has led to the reformulation of strategies at every level of the supply chain. Innovation in logistics, such as Postponement, is a good example of how global companies are redesigning their existing set ups to respond faster to local demands. Cooper (1993) has identified the key product variables that are considered to define the best strategy for firms to ensure logistics reach. Value density, product price and brand/technical superiority are some of these variables. Global companies often have multiple logistics strategies for a variety of products that they handle. Such set ups require effective management and a well-established information exchange system. An efficient organizational structure is also essential for the smooth functioning of the global logistics system.

With an understanding of how strategy, structure and competitive market forces affect various logistic activities, the next challenge a firm faces is performance measurement. The authors mentioned above, have only briefly discussed its importance. It is necessary to first define performance and then select suitable measurement systems.

Mentzer and Konrad (1991) consider performance as a function of efficiency and effectiveness. With regard to logistics, they have classified performance measures into five broad areas: ***transportation, warehousing, inventory control, order processing*** and ***logistics administration***. The most important measures that have been highlighted among these categories are those related to **cost**, **delivery time** and **equipment**. The component of efficiency compares the actual measurements of time, dollar value and space to the amount that was planned or budgeted. The effectiveness component focuses on the goals of cost and customer service level.

The importance of quantifying effectiveness and efficiency was also stressed on by Angappa and Kobu (2007). The authors state that key performance measures for value adding areas of an organization and factors that affect revenue adding business processes should be identified. Their research has helped categorize various *Key Performance Indicators* (KPIs). Financial performance (costs), time and delivery constitute a major portion of the KPIs. These measures should be selected based on the organization under consideration and the research objectives. Intangible measures are used for strategic level decision making, while tangible measures are used at the operational level. A combination of the two can be employed at the tactical level.

Chow et al. (1994) state that logistic performance is multidimensional and also emphasize on the significance of selecting the dimensions based on short term and long term horizons.

A common observation made by every author is the need for understanding the various activities of the firm and selecting the suitable KPIs. This decision is based on the data available and data collection tools being used. Also, there is a wide gap between theory and practice and it will benefit both researchers and firms alike, if they collaborated more often.

2.1.2 Cost and Delivery Time

Two of the most widely considered performance measures in logistics are *cost* and *delivery time*.

Among the different costs associated with a logistics process, studies have mostly focused on those incurred due to **inventory** and **transportation**. Based on information from the State of Logistics report for 2010 and 2011(http://www.scdigest.com/ASSETS/NEWSVIEWS/11-06-16-1.php?cid=4639), transportation accounts for almost 63% of the overall cost of logistics while inventory carrying costs make up for 33%. Tseng, Yue and Taylor (2005) studied the importance of transportation and the role it plays in a logistics system. They further reinforced the fact that a well-established transportation system can improve the performance of the selected logistics plan.

An optimal shipping strategy for logistics often involves a trade-off between inventory and transportation costs. *Vehicle routing* (Dethloff, 2001; Fisher and Jaikumar, 1981), *carrier mode* (Cochran and Ramanujam, 2006), *scheduling* and *dispatching* (Yu and Egbelu, 2008), *shipping* *frequency* and *shipment sizes* (Blumenfield et al., 1985; Burns et al., 1985; Bertazzzi and Speranza, 1999) are some of the decision making criteria that are used to calculate costs.

Blumenfield et al. (1985) studied the trade-off between transportation and inventory costs by considering them as a function of shipment sizes or frequency. Direct shipping, shipping via a consolidation terminal and a combination of the two were analyzed and compared. The authors consider production set up costs as well. The model developed helps determine optimal routes, shipment sizes and lot sizes. Similarly, Burns et al. (1985) developed an analytical model to compare direct shipping and peddling (milk run). Expressions for inventory and transportation costs were formed as a function of shipment size. Based on the cost trade-off, an optimal shipping strategy was determined to transport material from one supplier to different customers. Their results proved that a shipment size based on EOQ was suitable for direct shipping whereas a Full truck load could be used for peddling. The simple formulas presented can be used by shippers and carriers to approximately calculate distribution costs without using complex modeling techniques.

Bertazzzi and Speranza (1999) built a mathematical model to minimize transportation and inventory costs over a series of links with multiple products, where shipping frequencies and transportation capacities for each link are known. The heuristic algorithms presented helped address questions related to comparison of multiple/single frequencies per link and coordination. Also, the performance of EOQ based heuristics was studied.

While most research solely focuses on the costs incurred, Cooper (1984) studied centralized and decentralized systems to determine which provided the lowest distribution costs or delivery time. Direct less than truckload (LTL) shipments and consolidated shipments were considered for the study. Freight consolidation under different scenarios was analyzed and the author observed that it lowers costs but at the expense of an increase in delivery times. Managers should thus decide on an acceptable level of delivery time based on customer expectations.

Cintron, Ravindran and Ventura (2010) considered profit (cost) and lead time to redesign a distribution network for a consumer goods company. The criterion of power, credit performance and reputation were also included in a multi criteria mathematical model built for tactical decision making. A non preemptive goal program was used to select the best option for customers to receive products either by direct shipments, via a distribution center or through distributors. The model was validated with data from a consumer goods company and provides scope for extension to operational decision making as well.

2.2 Inbound Logistics

Many companies and research groups base their studies on improving the distribution network (outbound logistics) with the aim of lowering costs and increasing customer responsiveness. The inbound network has received very little attention. However, with the introduction of concepts such as **JIT**, **consolidation** and **crossdocking**, the shift in focus has been towards optimizing inbound models. Chatur (2006) discussed the salient features of these practices in his article on inbound logistics programs. It is essential for companies to understand the impact of these practices on their business before implementation.

In their paper on the effect of JIT on inbound transportation, Harper and Goodner (1990) indicated the change in choice of transportation modes and shipping frequencies based on data collected from manufacturing firms. The main concerns highlighted were that of increase in costs and vehicle utilization. One of the impacts of JIT has been the need for developing suitable cost effective consolidation strategies. When faced with shipping small loads frequently, companies are looking to include consolidation and take advantage of freight rate discounts. Buffa (1988) identified the importance of analyzing inventory ensembles by utilizing attributes such as weight, volume and freight class. The iterative approach to determine logistics costs helps establish important relations between inventory characteristics and cost reductions. The multi attribute approach (with weight, volume and inventory holding costs) was used by Popken (1994) who considered a network with consolidation via transshipment terminals. The service levels incorporated in the inventory holding costs, added an additional dimension for network analysis.

Cochran and Ramanujam (2006) use a different approach to inbound supply chain planning. The optimization model enables a manufacturer to select a combination of packaging and container options, to reduce overall costs. Additional material/pallet handling costs have been included in the cost function.

2.3 Research on Automotive Supply Network

As mentioned in Section 1.3, the inbound (supply) network of automotive supply chains are the most complex and pose a great deal of challenges to companies and researchers alike.

One of the most popular inbound strategies for automotive firms is the implementation of **peddling** or **milk runs**. In a recent study conducted on Toyota's network in Thailand, Nemoto et al. (2010) concluded that a milk run system can be achieved in conditions of severe road congestion through proper planning, coordination and monitoring. Its implications for city logistics were also discussed. Sadjadi, Jafari and Amini (2008) developed a mathematical model along with a genetic algorithm to solve the milk run problem for an automotive firm. The approach helped the firm determine: suppliers and quantities required based on service levels, scheduled shipment time and routes for trucks.

Blumenfield et al. (1987) built a model for Delco, a General Motors (GM) division, to examine different shipping strategies that would reduce inventory and transportation costs in the system. Direct shipping, shipping via a warehouse and peddling were considered. With the decision variables of *shipment sizes along links* and *network routes*, the model enabled the firm to perform a trade off analysis between inventory and transportation costs. Although the effort provided valuable insights to the most effective strategies available to GM, there was no analytical model to provide a sound basis for future research/model extensions.

A similar study was carried out by Berman and Wang (2006), who used a two step approach to picking between direct delivery and cross docking for shipping a family of products from multiple suppliers to multiple plants in the automotive sector. With the objective of minimizing transportation, pipeline inventory and plant inventory costs, the authors developed a greedy heuristic to find an initial feasible solution and an upper bound. The solution obtained was fine tuned with the use of a Lagrangian Relaxation (LR) heuristic and a Branch and Bound algorithm. The performance of the two was compared and the LR heuristic generated results closest to the optimal. The complicated two step approach tried to capture the essential features of direct shipping and cross docking by focusing entirely on the total cost of delivering material to the plants. The delivery time was incorporated in the calculation of pipeline inventory costs. Also, the selection of a distribution strategy had operational implications.

This thesis aims at building a mathematical model that would select either direct shipment or shipment via a warehouse by considering costs and delivery time as conflicting criteria. Using an approach similar to the one developed by Cintron et al. (2010), a bi-criteria mixed integer linear program will be developed and solved using non preemptive goal programming. The model will further be validated with data from an automotive firm.

The following chapters will provide details of the model, test runs and analysis of results obtained.

Chapter 3

Model Formulation

3.1 Assumptions

- Demand for material and delivery lead times are deterministic
- Supplier manufacturing lead times are not included
- Material at the suppliers/distributors is always available.
- Shortages and delays are not included in the model.
- Inventory holding costs at the supplier/distributor are not considered.
- Single mode of transport (road) is considered.
- Capacities of the trucks are known in advance.
- The transportation cost includes rental charges (fixed) of the trucks and cost of fuel/gas (variable).
- The OEM incurs the transportation cost and is responsible for shipping the material.
- Routing is not considered and pre-determined routes are used.
- For ease of modeling, the suppliers and independent distributors are grouped together.
- Limited storage capacity is available at the plants.
- Locations of all entities are known.

3.2 Definition of variables and data

Index sets:

i	material	$\forall\, i \in \{1,2 \ldots I\},$
j	supplier/distributor	$\forall\, \mathrm{j} = \begin{cases} 1,2 \ldots . m \quad are\ suppliers \\ \mathrm{m}+1, \mathrm{m}+2, \ldots . J \quad are\ distributors \end{cases}$
k	plant	$\forall\, k \in \{1,2, \ldots K\}$
l	vehicle types	$\forall\, l \in \{1,2, \ldots L\}$

Data:

d_{ik} demand of material 'i' at plant 'k' (in pallets)

$capw$ capacity of warehouse (in pallets)

$capp_k$ storage capacity at plant 'k' (in pallets)

$vcap_l$ capacity of vehicle 'l'

C_{ij} cost per pallet of material 'i' as quoted by supplier 'j'

HC_{ijk} inventory holding cost of one pallet of material 'i' supplied by 'j' held at plant 'k'

Where, $HC_{ijk} = h_k C_{ij}$

h_k *is the inventory holding cost / \$ at plant k used* (*includes cost of capital, cost of physically storing inventory and cost of labor*)

HCW_{ij} inventory holding cost of one pallet of material 'i' supplied by 'j' held at the warehouse

Where, $HCW_{ij} = hwC_{ij}$

hw is the inventory holding cost / \$ at warehouse (*includes cost of capital, cost of* *physically storing inventory and cost of labor*)

TCP_{ijkl} transportation cost per trip to ship material 'i' from supplier 'j' to plant 'k' using vehicle 'l'

$TCSW_{ijl}$ transportation cost per trip to ship material 'i' form supplier 'j' to the warehouse using vehicle 'l'

$TCWP_{ikl}$ transportation cost per trip to ship material 'i' from the warehouse to plant 'k' using vehicle 'l'

LTD_{ijk} lead time (transit time) for delivering material 'i' from supplier 'j' to plant 'k' (in days)

$LTDW_{ij}$ lead time (transit time) for delivering material 'i' from supplier 'j' to warehouse(in days)

$LTWP_{k}$ lead time (transit time) for delivering material from the warehouse to plant 'k' (in days)

m_{l} Maximum number of vehicles of type 'l' that are available

Variables:

x_{ijk} 1 if material 'i' is shipped directly from supplier/distributor 'j' to plant 'k'; 0 otherwise (option 1 or 2)

y_{ijk} 1 if material 'i' is shipped directly from supplier/distributor 'j' to the warehouse for plant 'k'; 0 otherwise (option 3 or 4)

α_{ijkl} number of vehicles of type 'l' needed to ship material 'i' from supplier 'j' to plant 'k' *(integers)*

β_{ijl} number of vehicles of type '*l*' needed to ship material '*i*' from supplier '*j*' to the warehouse *(integers)*

γ_{ikl} number of vehicles of type '*l*' needed to ship material '*i*' from the warehouse to plant '*k*' *(integers)*

3.3 Objective function

The model focuses on two objectives: ***total costs (inventory and transportation)*** and ***lead time***.

- Minimize Costs:

  Total cost = Inventory costs + Transportation Costs

  - Inventory costs are incurred at the plant and warehouse:

$$\underbrace{\sum_i \sum_j \sum_k HC_{ijk} d_{ik} x_{ijk}}_{\textit{At plant}} + \underbrace{\sum_i \sum_j \sum_k HCW_{ij}\, d_{ik} y_{ijk}}_{\textit{At warehouse}}$$

  - Transportation Costs:

$$\underbrace{\sum_i \sum_j \sum_k \sum_l TCP_{ijkl}\alpha_{ijkl}}_{\substack{\textit{Shipped from} \\ \textit{supplier to plant}}} + \underbrace{\sum_i \sum_j \sum_l TCSW_{ijl}\beta_{ijl}}_{\substack{\textit{Shipped from} \\ \textit{supplier to} \\ \textit{Warehouse}}} + \underbrace{\sum_i \sum_k \sum_l TCWP_{ikl}\gamma_{ikl}}_{\substack{\textit{Shipped from} \\ \textit{warehouse to plant}}}$$

Objective$_1$: Total Cost =

$$\sum_i \sum_j \sum_k HC_{ijk} d_{ik} x_{ijk} + \sum_i \sum_j \sum_k HCW_{ij}\, d_{ik} y_{ijk} + \sum_i \sum_j \sum_k \sum_l TCP_{ijkl} \alpha_{ijkl} + \sum_i \sum_j \sum_l TCSW_{ijl} \beta_{ijl} + \sum_i \sum_k \sum_l TCWP_{ikl} \gamma_{ikl}$$

- Minimize Delivery Lead time:

Objective$_2$: Delivery Lead time =

$$\underbrace{\sum_i \sum_j \sum_k LTD_{ijk} x_{ijk}}_{\textit{Supplier to plant delivery lead time}} + \underbrace{\sum_i \sum_j \sum_k LTDW_{ij} y_{ijk}}_{\textit{Supplier to warehouse delivery lead time}} + \underbrace{\sum_i \sum_j \sum_k LTWP_k y_{ijk}}_{\textit{Warehouse to plant average delivery lead time}}$$

3.4 Constraints

- Only one option is selected per order placed by plant ‘k’ for material ‘i’

$$\sum_j x_{ijk} + \sum_j y_{ijk} = 1, \forall \; material\; i, plant\; k \tag{3.1}$$

- Capacity constraints at warehouse:

  The amount of material flowing into the warehouse is limited by the capacity of the warehouse.

$$\sum_i \sum_j \sum_k d_{ik} y_{ijk} \leq capw \tag{3.2}$$

- Capacity constraint at each plant:

  If direct delivery is selected for a plant, there is a limit on how much material can be stored at each plant.

$$\sum_i \sum_j d_{ik} x_{ijk} \leq capp_k \,, \forall \; plant\; k \tag{3.3}$$

- Constraint to ensure material shipped per trip is never greater than the capacity of the vehicle used:

$$\boldsymbol{d_{ik}x_{ijk}} \le \sum_{\boldsymbol{l}} \boldsymbol{\alpha_{ijkl}vcap_l} \;\; \forall \; \boldsymbol{material\ i, supplier\ j, plant\ k} \qquad (3.4.1)$$

$$\sum_{\boldsymbol{k}} \boldsymbol{d_{ik}y_{ijk}} \le \sum_{\boldsymbol{l}} \boldsymbol{\beta_{ijl}vcap_l} \;\; \forall \; \boldsymbol{material\ i, supplier\ j} \qquad (3.4.2)$$

$$\boldsymbol{d_{ik}y_{ijk}} \le \sum_{\boldsymbol{l}} \boldsymbol{\gamma_{ikl}vcap_l} \;\; \forall \; \boldsymbol{material\ i, supplier\ j, plant\ k} \qquad (3.4.3)$$

- Limit on total number of vehicles available:

$$\sum_{\boldsymbol{i}} \left(\sum_{\boldsymbol{j}} \sum_{\boldsymbol{k}} \boldsymbol{\alpha_{ijkl}} + \sum_{\boldsymbol{j}} \boldsymbol{\beta_{ijl}} + \sum_{\boldsymbol{k}} \boldsymbol{\gamma_{ikl}} \right) \le \boldsymbol{m_l} \;\; \forall \;\; \boldsymbol{vehicle\ type\ l} \qquad (3.5)$$

- Non negativity constraints:

$$\boldsymbol{\alpha_{ijkl}}, \boldsymbol{\beta_{ijl}}, \boldsymbol{\gamma_{ikl}} \ge \boldsymbol{0} \;, \qquad \forall \; \boldsymbol{i, j, k, l} \qquad (3.6)$$

- Integer constraints:

$$\boldsymbol{\alpha_{ijkl}}, \boldsymbol{\beta_{ijl}}, \boldsymbol{\gamma_{ikl}} \; \boldsymbol{integer} \;\; \forall \;\; \boldsymbol{i, j, k, l} \qquad (3.7)$$

- Binary variables

$$\mathbf{x_{ijk}}, \mathbf{y_{ijk}} \in \{\boldsymbol{0}, \boldsymbol{1}\}, \quad \forall \;\; \boldsymbol{i, j, k} \qquad (3.8)$$

3.5 Non Preemptive Goal Programming (NPGP)

It often becomes difficult to find the best solution when the problem consists of multiple conflicting criteria. A practical method to address these problems is by using *goal programming* (Ravindran et al, 1987). In this method, target levels are determined for the objectives and are treated as "goals" to be achieved. An attempt is made to find an optimal solution that is as close as possible to the target levels, in the order of specified priorities.

The general model of the goal programming problem is shown below:

$$Minimize\ Z = \sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} (\boldsymbol{w_i^+ d_i^+} + \boldsymbol{w_i^- d_i^-}) \qquad (Eq\ 1)$$

$$Subject\ to: \sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} \boldsymbol{a_{ij} x_j} + \boldsymbol{d_i^-} - \boldsymbol{d_i^+} = \boldsymbol{b_i} \quad \forall\, i \qquad (Eq\ 2)$$

$$\boldsymbol{g_j(x)} \leq \boldsymbol{0} \quad \forall\, j \qquad (Eq\ 3)$$

$$\boldsymbol{x_j}, \boldsymbol{d_i^+}, \boldsymbol{d_i^-} \geq \boldsymbol{0}\ for\ all\ i, j \qquad (Eq\ 4)$$

The objective function (Eq 1) consists of the sum of the weighted deviations from the set goals. The next group of equations represents the goal constraints (Eq 2), real constraints (Eq 3) and the non-negativity constraints (Eq 3), where:

$$\boldsymbol{x_j}\ \ is\ the\ decision\ variable, \boldsymbol{b_i}\ \ is\ the\ target$$

$$\boldsymbol{d_i^+}\ and\ \boldsymbol{d_i^-}\ are\ the\ over\ and\ under\ achievement\ of\ each\ goal$$

The weights w_i can be determined in two ways:

- Prespecified / Non Preemptive / Cardinal:

  To represent the decision makers tradeoffs, predetermined values are assigned to the weights. This reduces the problem to a single objective optimization problem.

- Preemptive / Ordinal:

  After goals are prioritized, those with higher priority are satisfied first before moving to ones at lower priority. A sequence of single objective optimization problems is formed.

The current optimization problem will be solved using the Non Preemptive Goal Programming method. As mentioned above, weights are used to reduce the problem to a single objective optimization problem. Due to the difference in the units of measurement of each objective, ***ideal solutions*** can be used for scaling. An *ideal solution* is defined as the best achievable solution for an individual objective when all other objectives are ignored. Solving the individual objectives, helps find the upper and lower bounds for each. *Target values* can be set within these bounds.

The problem is reformulated as shown below:

- **Calculating Ideal Solutions:**
  - Minimizing total cost while ignoring delivery lead time:

    Minimize Objective_1 =

$$\sum_i \sum_j \sum_k HC_{ijk} d_{ik} x_{ijk} + \sum_i \sum_j \sum_k HCW_{ij}\, d_{ik} y_{ijk} + \sum_i \sum_j \sum_k \sum_l TCP_{ijkl} \alpha_{ijkl} + \sum_i \sum_j \sum_l TCSW_{ijl} \beta_{ijl} + \sum_i \sum_k \sum_l TCWP_{ikl} \gamma_{ikl}$$

subject to the set of constraints 3.1 – 3.8.

Let **Ideal$_1$** be the minimum cost obtained.

- Minimizing delivery lead time while ignoring total cost:

  Minimize Objective$_2$ =

$$\sum_i \sum_j \sum_k LTD_{ijk} x_{ijk} + \sum_i \sum_j \sum_k LTDW_{ijk} y_{ijk} + \sum_i \sum_j \sum_k LTWP_k y_{ijk}$$

subject to the set of constraints 3.1 – 3.8.

Let **Ideal$_2$** be the minimum delivery time obtained.

- **Obtaining target values:**

On solving the single objective problems, upper and lower bounds are obtained. As both the objectives are minimization problems, the target values can be set as a percentage of the lower bound (ideal solution).

Target value for Objective 1:

$$Target_1 = p_1 * Ideal_1$$

where p_1 is the percentage increase from the ideal solution for objective 1.

Target value for Objective 2:

$$Target_2 = p_2 * Ideal_2$$

where p_2 is the percentage increase from the ideal solution for objective 2.

- **Solution by Non Preemptive Goal Programming:**

Goal constraint for total cost:

$$Objective_1 + d_1^- - d_1^+ = Target_1$$

Goal constraint for delivery lead time:

$$Objective_2 + d_2^- - d_2^+ = Target_2$$

The ideal values are used to scale the objective and target values. The goals can be rewritten as shown below:

$$\frac{Objective_1}{Ideal_1} + d_1^- - d_1^+ = \frac{Target_1}{Ideal_1}$$

$$\frac{Objective_2}{Ideal_2} + d_2^- - d_2^+ = \frac{Target_2}{Ideal_2}$$

The new objective function under consideration is:

$$\boldsymbol{Minimize\ w_1\ (d_1^+) + w_2\ (d_2^+)}$$

Subject to the set of constraints mentioned in 3.4

Chapter 4

Model Validation and Analysis

4.1 Case Study - Illustrative Example

This section will help illustrate the model discussed in Chapter 3. The objective of the case study is to select the most suitable option to ship material from suppliers to the plants, either directly or via a warehouse, such that costs and lead time are lowered. The data used for illustration is a combination of real inputs from the OEM (an automotive manufacturer in India) and some assumed values.

4.1.1 Network description

The network considered for the case study consists of:

Raw material	**5**
Suppliers	**2**
Distributors	**3**
Plants	**1**
Warehouse	**1**
Vehicle Types	**5**

The index sets used are:

i	**material**	$\forall\, \boldsymbol{i} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4}, \mathbf{5}\}$
j	**distributor/ supplier**	$\forall\, \mathbf{j} = \begin{cases} \mathbf{1}, \mathbf{2}, \mathbf{3} & \boldsymbol{are\ distributors} \\ \mathbf{4}, \mathbf{5} & \boldsymbol{are\ suppliers} \end{cases}$
k	**plant**	$\forall\, \boldsymbol{k} \in \{\mathbf{1}\}$
l	**vehicle types**	$\forall\, \boldsymbol{l} \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4}, \mathbf{5}\}$

The data used in the model are listed below:

- d_{ik} - demand of material '*i*' at plant '*k*' (in pallets):

	plant (k)
material (i)	**1**
1	**95**
2	**180**
3	**60**
4	**100**
5	**205**

- *capw* - capacity of warehouse (in pallets) = **375**
- $capp_k$ - storage capacity at plant '*k*' (in pallets) - $\boldsymbol{capp_1}$ **= 400**
- $vcap_l$ - capacity of vehicle '*l*':

l	**vcap(l)**
1	**10**
2	**18**
3	**24**
4	**30**
5	**40**

- C_{ij} - cost per pallet of material 'i' as quoted by supplier '*j*' (in Indian Rupees - Rs):

	supplier (j)				
material (i)	**1**	**2**	**3**	**4**	**5**
1	1899.5	2374.375	1804.525	1728.545	1576.585
2	12640	13272	15168	10617.6	10744
3	1546	2319	1700.6	1283.18	1113.12
4	2200	1980	2090	1716	1760
5	7000	5250	5950	4690	6790

- h_k is the inventory holding cost at plant 'k' in percentage (includes cost of capital, cost of physically storing inventory and cost of labor) (**h_1 = 26 %**)
- *hw* is inventory holding cost at warehouse in percentage (includes cost of capital, cost of physically storing inventory and cost of labor) (**hw = 20 %**)
- HC_{ijk} - inventory holding cost of one pallet of material '*i*' supplied by '*j*' held at plant 'k'(in Indian Rupees - Rs): (*Note:* $HC_{ijk} = h_k*C_{ij}$)

	supplier (j)	1	2	3	4	5
	plant(k)	1	1	1	1	1
material (i)	1	493.87	617.3375	469.1765	449.4217	409.9121
	2	3286.4	3450.72	3943.68	2760.576	2793.44
	3	401.96	602.94	442.156	333.6268	289.4112
	4	572	514.8	543.4	446.16	457.6
	5	1820	1365	1547	1219.4	1765.4

- HCW_{ij} - inventory holding cost of one pallet of material '*i*' supplied by '*j*' held at the warehouse (in Indian Rupees - Rs): (*Note:* $HCW_{ij} = hw*C_{ij}$)

	supplier (j)				
material (i)	1	2	3	4	5
1	379.9	474.875	360.905	345.709	315.317
2	2528	2654.4	3033.6	2123.52	2148.8
3	309.2	463.8	340.12	256.636	222.624
4	440	396	418	343.2	352
5	1400	1050	1190	938	1358

- TCP_{ijkl} - transportation cost per trip to ship material '*i*' from supplier '*j*' to plant '*k*' using vehicle '*l*' (in Indian Rupees - Rs). It is assumed that the cost of shipping from supplier '*j*' using vehicle '*l*' is the same for all materials.

	plant (k)	1	1	1	1	1
	vehicle type	1	2	3	4	5
supplier (j)	1	850	1250	1400	1700	2000
	2	850	1100	1850	2000	2600
	3	850	1000	1300	1600	2100
	4	950	1350	1850	2200	2500
	5	950	1350	1750	2100	2400

(The table above gives the cost of supplying raw materials directly to the plant by a supplier)

- $TCSW_{ijl}$ - transportation cost per trip to ship material '*i*' form supplier '*j*' to the warehouse using vehicle '*l* ' (in Indian Rupees - Rs). It is assumed that the cost of shipping from a supplier '*j*' using vehicle '*l*' is the same for all materials.

		vehicle type				
		1	2	3	4	5
supplier (j)	1	637.5	937.5	1050	1275	1500
	2	637.5	825	1387.5	1500	1950
	3	637.5	750	975	1200	1575
	4	712.5	1012.5	1387.5	1650	1875
	5	712.5	1012.5	1312.5	1575	1800

(The table above gives the cost of supplying raw materials to the warehouse by a supplier)

- $TCWP_{ikl}$ - transportation cost per trip to ship material '*i*' from the warehouse to plant '*k*' using vehicle '*l*' (in Indian Rupees - Rs). It is assumed that the cost of shipping from the warehouse to the plant using vehicle '*l*' is the same for all materials.

	vehicle type				
plant(k)	1	2	3	4	5
1	637.5	937.5	1050	1275	1500

- LTD_{ijk} - lead time for delivering material 'i' from supplier 'j' to plant 'k' (in days). It is assumed that the lead time for shipping from a supplier 'j' using vehicle 'l' is the same for all materials.

	supplier(j)				
plant(k)	1	2	3	4	5
1	8	10	9	15	13

- $LTDW_{ij}$ - lead time for delivering material 'i' from supplier 'j' to warehouse (in days). It is assumed that the lead time for shipping from a supplier 'j' using vehicle 'l' is the same for all materials.

	supplier(j)				
	1	2	3	4	5
$LTDW_{ij}$	5	8	7	12	10

- $LTWP_k$ - lead time for delivering material from the warehouse to plant 'k' (in days) – $\boldsymbol{LTWP_1 = 2}$

- m_l - maximum number of vehicles of type 'l' that are available:

vehicle type	Maximum
1	10
2	10
3	10
4	10
5	10

4.2 Mathematical Model

- Minimize Total Costs:

Objective$_1$: Total Cost =

$$\sum_{i}\sum_{j}\sum_{k} HC_{ijk} d_{ik} x_{ijk}$$

$$+\sum_{i}\sum_{j}\sum_{k} HCW_{ij}\, d_{ik} y_{ijk}$$

$$+\sum_{i}\sum_{j}\sum_{k}\sum_{l} TCP_{ijkl}\alpha_{ijkl}$$

$$+\sum_{i}\sum_{j}\sum_{l} TCSW_{ijl}\beta_{ijl}+\sum_{i}\sum_{k}\sum_{l} TCWP_{ikl}\gamma_{ikl}$$

- Minimize Delivery Lead time:

Objective$_2$: Delivery Lead time =

$$\sum_{i}\sum_{j}\sum_{k} LTD_{ijk}x_{ijk}+\sum_{i}\sum_{j}\sum_{k} LTDW_{ij}y_{ijk}+\sum_{i}\sum_{j}\sum_{k} LTWP_{k}y_{ijk}$$

Subject to the constraints (Equations 3.1 – 3.8) mentioned in Section 3.4 of Chapter 3.

4.3 Solution – Approach and Initial Results

4.3.1 Obtaining Ideal Values

- Minimizing Objective 1 (Cost) while ignoring Objective 2 (Delivery Time):

  The total cost obtained = Rs. 757,010

  The total lead time obtained = 68 days

  The ideal solution for objective 1 - **$Ideal_1$** = **Rs. 757,010**

- Minimizing Objective 2 (Delivery Lead Time) while ignoring Objective 1 (Cost):

  The total cost obtained = Rs. 1,115,285

  The total lead time obtained = 37 days

  The ideal solution for objective 2 – **$Ideal_2$** = **37 days**

4.3.2 Obtaining Target Values

The upper and lower bounds on each of the objectives are listed in the table below:

	Lower Bound	Upper Bound
Total Cost	Rs. 757,010	Rs. 1,115,285
Total Delivery Lead Time	37 days	68 days

Table 4.1 Upper and Lower Bounds on the objectives

The percentage difference between the upper and lower bounds for cost is 47.328%. The percentage difference between the bounds for delivery time is 83.784%. We can set the increase for both Cost and Delivery Time at 110 % of the ideal value i.e. $\boldsymbol{p_1 = 1.1}$ and $\boldsymbol{p_2 = 1.1}$.

- Target for Objective 1 (Cost):

$\text{Target}_1 = p_1 * \text{Ideal}_1 = 1.1 * 757{,}010 = \text{Rs. } 832{,}711$

- Target for Objective 2 (Delivery Lead Time):

$\text{Target}_2 = p_2 * \text{Ideal}_2 = 1.1 * 37 = 41 \text{ days}$

4.3.3 Solution by Non Pre-emptive Goal Programming (NPGP)

- Setting the goal constraints for each objective and scaling using ideal values to normalize the deviational variables:

  Goal constraint for total cost:

$$\frac{Objective_1}{Ideal_1} + d_1^- - d_1^+ = \frac{Target_1}{Ideal_1}$$

$$\frac{Objective_1}{757{,}010} + d_1^- - d_1^+ = \frac{832711}{757{,}010}$$

$$\frac{Objective_1}{757{,}010} + d_1^- - d_1^+ = 1.1$$

  Goal constraint for total delivery time:

$$\frac{Objective_2}{Ideal_2} + d_2^- - d_2^+ = \frac{Target_2}{Ideal_2}$$

$$\frac{Objective_2}{37} + d_2^- - d_2^+ = \frac{41}{37}$$

$$\frac{Objective_2}{37} + d_2^- - d_2^+ = 1.1$$

The objective function can be rewritten as:

$$\boldsymbol{Minimize\ w_1\ (d_1^+) + w_2\ (d_2^+)}$$

Subject to the set of constraints (Equations 3.1 – 3.8)mentioned in Chapter3

4.3.4 NPGP solutions

The mathematical model was run in LINGO 13 on a Pentium® Dual-Core CPU, E5200 @ 2.50 GHz with 4.00 GB RAM, with the input data given in Section 4.1.

The weights assigned to the deviational variables have been used such that they add up to 1, i.e., $w_1 + w_2 = 1$. The following set of weights was used for an initial analysis. The total cost and lead time achieved in each case are listed in Table 4.2.

Weight of the deviational variable associated with cost (w_1)	Weight of the deviational variable associated with lead time (w_2)	Total Cost (Rs.)	Target values for Cost (Rs.)	Total Lead Time (days)	Target values for Lead time (days)
1.0	0.0	774,742	832,711	69	41
0.7	0.3	817607	832,711	44	41
0.5	0.5	876,793	832,711	39	41
0.3	0.7	876,793	832,711	39	41
0.0	1.0	1,056,117	832,711	38	41

Table 4.2 Objective values achieved for the selected set of weights

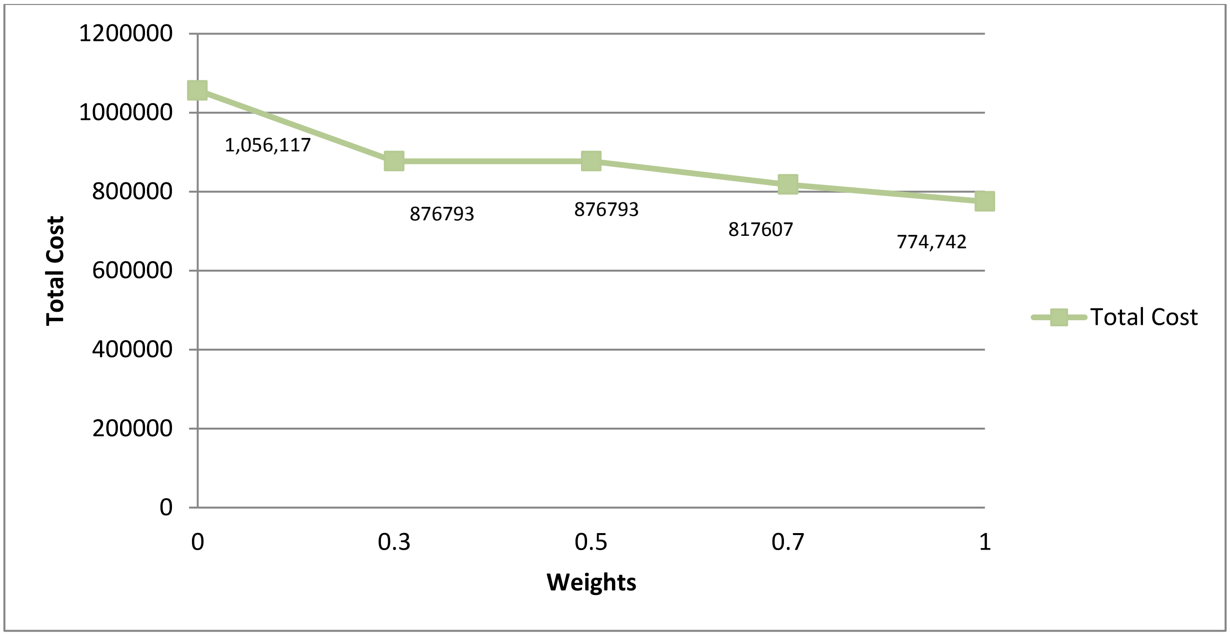

Figure 4.1 Variation in Total Cost with change in weights

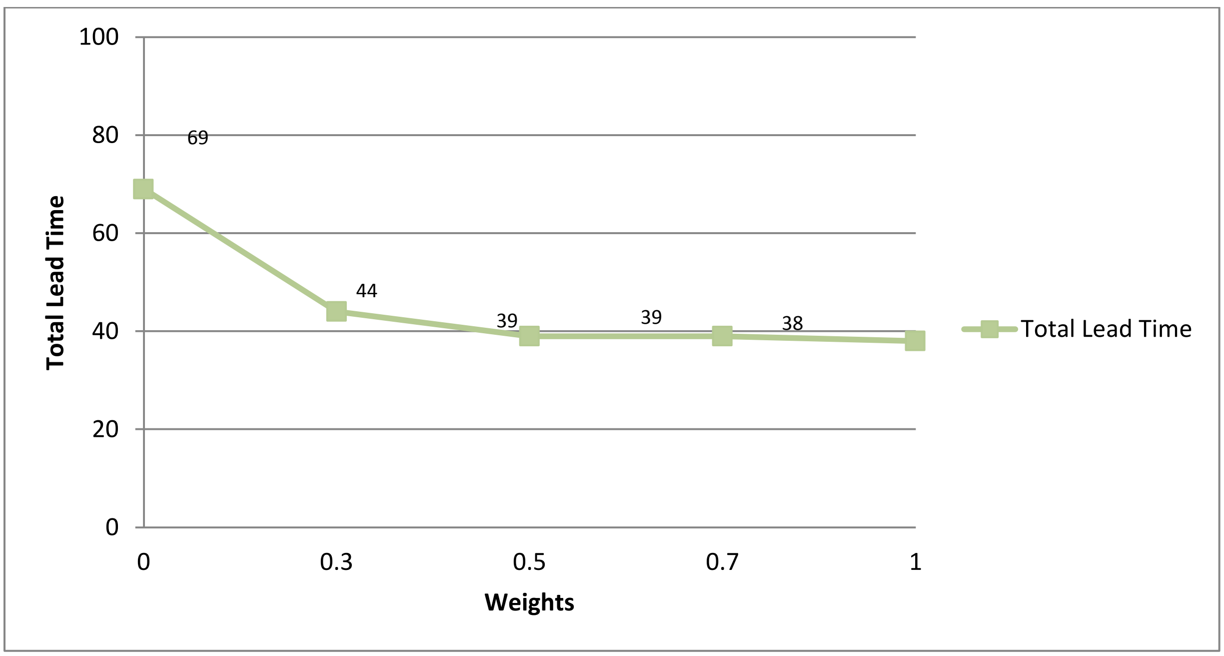

Figure 4.2 Variation in Total Lead Time with change in weights

It can be observed from the Figure 4.1 that as we increase the weight on achieving the cost target, the objective for total cost decreases. With a weight of w_1 = 1, the objective achieved is Rs. 774,742 while the set target is Rs. 832,711. When w_1 = 0, the cost increases to Rs.1,056,117. Similarly, with the weight of w_2 = 1, the delivery time reaches a value of 38 days and with a weight of w_2 = 0, the objective for delivery time attains a value of 68 days (Fig 4.2).

Table 4.3 represents the assignments made for each material to be shipped to the plant under each test scenario:

Material	Test Cases						
	Ideal Cost	$w_1 = 1$ $w_2 = 0$	$w_1 = 0.7$ $w_2 = 0.3$	$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0$ $w_2 = 1$	Ideal Lead Time
1	Supplier 5 – Via Warehouse	Supplier 5 – Direct Shipping	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Direct Shipping	Supplier 1 – Via Warehouse
2	Supplier 4 – Via Warehouse	Supplier 4 – Via Warehouse	Supplier 5 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Direct Shipping	Supplier 1 – Direct Shipping
3	Supplier 5 – Direct Shipping	Supplier 5 – Direct Shipping	Supplier 1 – Direct Shipping	Supplier 1 – Direct Shipping	Supplier 1 – Direct Shipping	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse
4	Supplier 4 – Via Warehouse	Supplier 4 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Via Warehouse	Supplier 1 – Direct Shipping	Supplier 1 – Via Warehouse
5	Supplier 4 – Direct Shipping	Supplier 4 – Direct Shipping	Supplier 2 – Direct Shipping	Supplier 2 – Direct Shipping	Supplier 2 – Direct Shipping	Supplier 1 – Via Warehouse	Supplier 1 – Direct Shipping

Table 4.3 Assignments made for each material to be shipped to the plant (Note: Suppliers 1, 2, 3 are distributors and suppliers 4, 5 are major suppliers)

For the cases with higher weights associated with costs, it can be observed that although located farthest from the plant and warehouse, Suppliers 4 and 5 are frequently selected as they quote the lowest price for the material.

It was found that a majority of the total cost was associated with the inventory holding cost (Fig 4.3) which depends on the cost of the material. On average, the transportation cost accounts only for 5.2% of the total cost. Hence preference is given to the suppliers that quote the lowest material price.

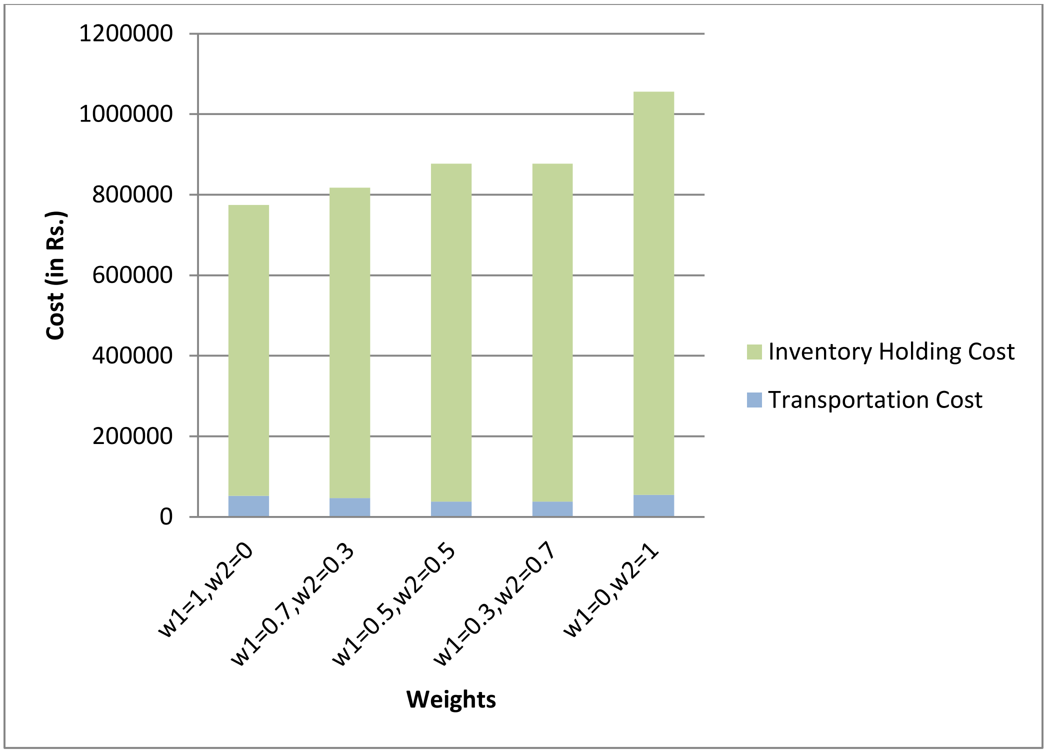

Figure 4.3 Distribution of Inventory and Transportation Costs

When the weight on the lead time is increased, the model selects shipping material from distributors 1 and 2 as they are located closest to the facility.

It is also found that distributor 1 is the most frequently selected option among all test cases. To obtain a better perspective on the different options available, a scenario analysis is performed in the next section to study demand uncertainty.

4.4 Scenario Analysis

To account for the variability in demand, the program is run for different demand scenarios to select the best solution for each material. The model is run for each month's demand over a period of one year (12 months) with a variation in the weights associated with the targets. Five sets of weights are selected for this analysis (Table 4.4). Hence the total number of runs for each material is 60 (i.e. 12 * 5). This implies that the model is run for **300 instances** for all 5 material types.

Weight of the deviational variable associated with cost (w_1)	Weight of the deviational variable associated with lead time (w_2)
1.0	0.0
0.7	0.3
0.5	0.5
0.3	0.7
0.0	1.0

Table 4.4 Weights selected for scenario analysis

A supply option is an assignment made to ship a particular material from a supplier to a plant. For the case study, it has been assumed that each raw material is available at all suppliers and distributors (5 in total). Each material can either be shipped directly or via the warehouse (i.e. 2 options). Hence a total of: 5 * 2 = 10 options are available for each material from which the model selects the optimal solution. For example the optimal options selected for material 4 from the 300 instances have been listed below:

- Distributor 1 – Direct Shipments
- Distributor 2 – Direct Shipments
- Distributor 3 – Direct Shipments
- Supplier 4 – Direct Shipments
- Supplier 5 – Direct Shipments
- Distributor 1 – Via Warehouse
- Distributor 2 – Via Warehouse
- Distributor 3 – Via Warehouse
- Supplier 4 – Via Warehouse

This sums up to a total of 9 different optimal options selected for material 4. Figure 4.4 lists the number of optimal options selected for each material.

Due to the difference in monthly demand and weights assigned to each criterion, the assignments made in each instance are also different. The supply option selected is optimal for a given scenario. This leads to a variety of supply options selected for each material to be shipped.

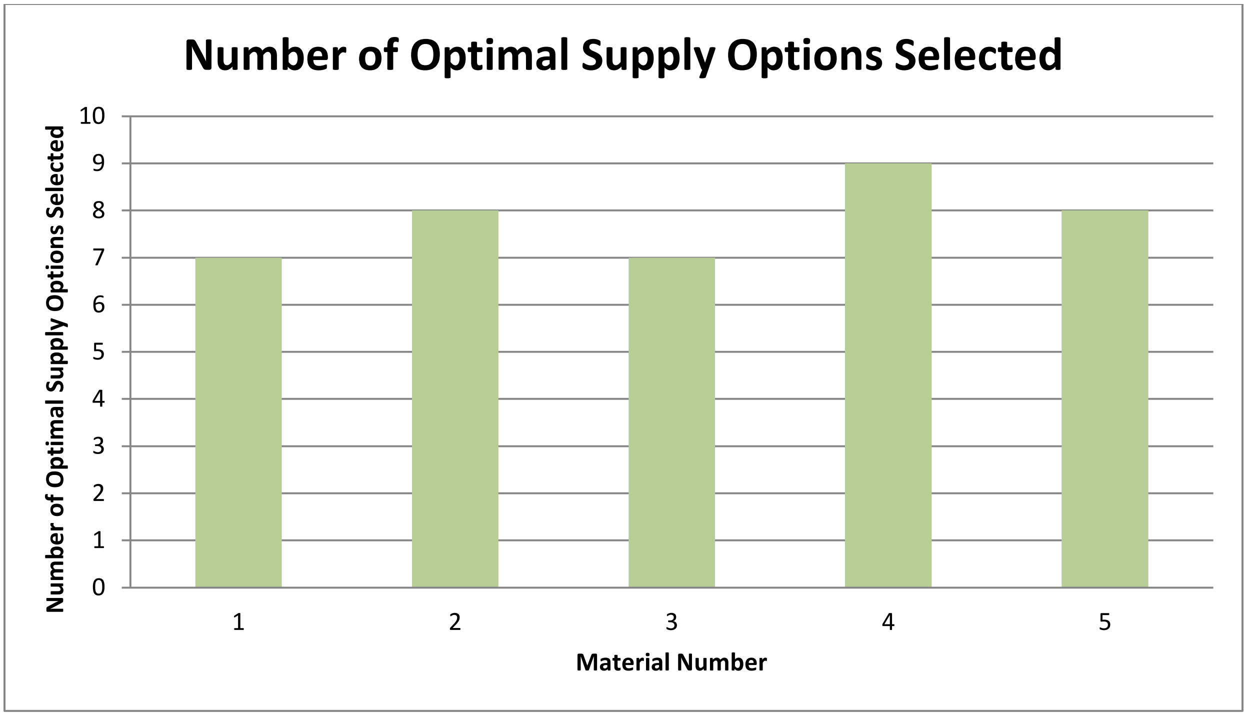

Figure 4.4 Number of optimal supply options selected for each material

There is a difference in the number of times each optimal supply option is selected for each material. As mentioned before, material 4 has a total of 9 different supply options selected as optimal solution in different instances. The most frequently occurring option (Distributor 1 – shipping via warehouse) was selected 34 times out of the 60 instances (56.67%). Hence this solution is selected as the best supply option for material 4 under all conditions. Table 4.5 lists the best supply option selected for each raw material along with the percentage occurrence of the solution.

Material	Best Supply Option	Percent occurrence of most frequently selected option
1	Distributor 1 –Direct Shipping	43.33
2	Distributor 1 –Via Warehouse	41.67
3	Distributor 1 –Direct Shipping	53.33
4	Distributor 1 –Via Warehouse	56.67
5	Distributor 2 –Direct Shipping	50

Table 4.5 Best supply option and percent occurrence of optimal solution for each material

4.5 Managerial Implications

The aim of this research has been to build a mathematical model that selects the best supply option for raw materials to be shipped from various suppliers to the plant. The firm wanted to answer two questions:

1. Would shipping from distributors located closer to the plant help address the problem of large lead times, in spite of the higher prices quoted?
2. Would the inclusion of a warehouse in the network benefit the company, with respect to cost and lead time?

Based on the scenario analysis and results, we can provide answers to the two questions mentioned above.

4.5.1 Best Supply Option:

The most frequently occurring optimal solution from the scenario analysis is selected as the best supply option for each material. This option minimizes total costs and delivery time in the system. Table 4.5 listed the best supply option for each raw material and the percentage of its occurrence. These assignments have been illustrated in Fig 4.5.

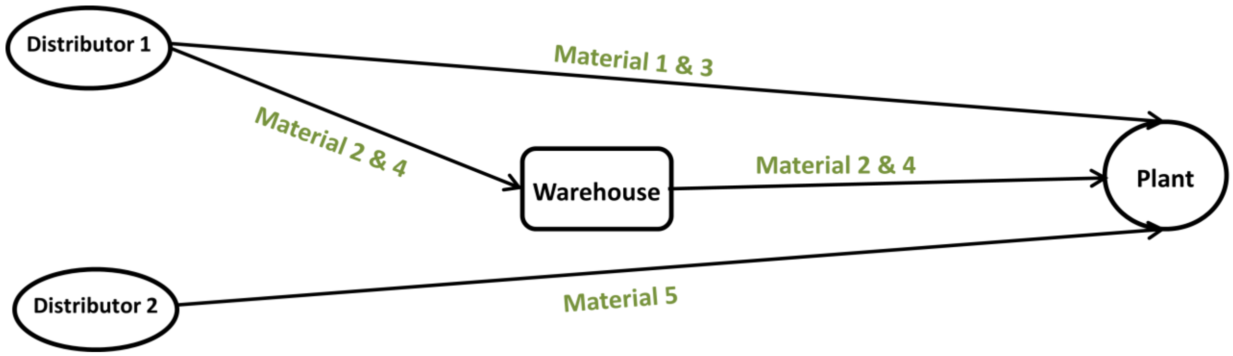

Figure 4.5 Illustration of best supply option for each material

As mentioned in Section 4.3.4, Distributor 1 continues to be the preferred option for each material. It is observed that in instances where a higher weight ($w_1 > 0.5$) is placed on the cost target, Distributor 1 is selected more often when compared to Suppliers 4 and 5, who quoted lower material prices. In the instances where only cost is minimized and lead time is ignored (i.e. calculation of ideal cost), suppliers 4 and 5 were selected as the optimal supply options. Although Distributor 1 quotes higher prices, it is located closer to the plant. This shows that the model selects the option that minimizes both criteria of cost and lead time. **One hundred out of 120 of the instances for cases with $w_1 > 0.5$ are made among Suppliers 1, 4 and 5. Distributor 1 is selected for 47% of the instances**.

The firm should thus consider switching to Distributors 1 and 2 to ship material to the plant. These are distributors that are located closer to the facility.

4.5.2 Use of a Central Warehouse:

The option of **shipping via the central warehouse is selected 143 times out of the 300 instances i.e. 47.67% of the runs**. The percentage of direct shipping and shipping via warehouse are illustrated in Fig 4.7.

Although, the inventory holding costs at the plant are higher, **direct shipping to the plant is selected in 52.33% of the instances**. This is due to the limited capacity of the warehouse.

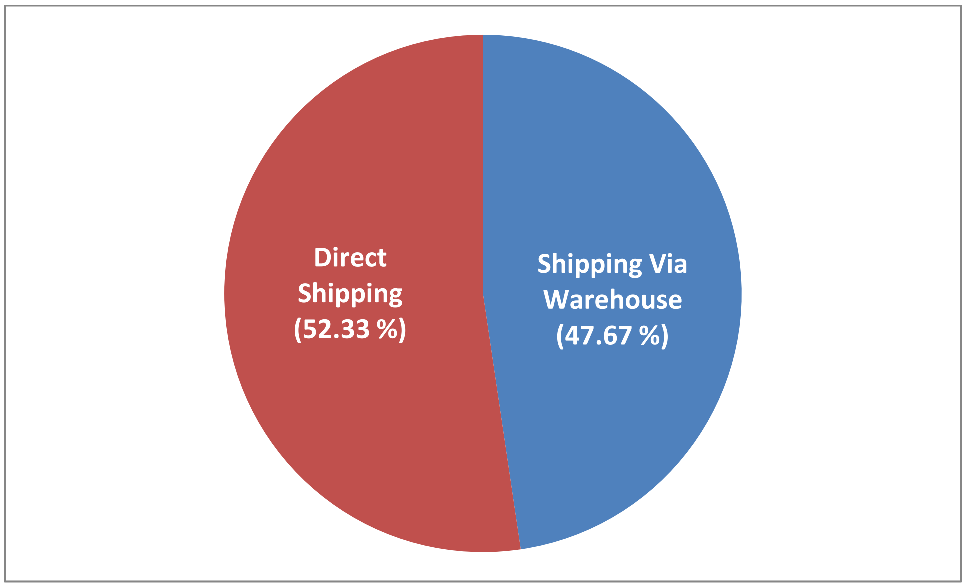

Figure 4.6 Ratio of assignments made to shipping via warehouse and direct shipping

To study the utilization of the warehouse space, Figures 4.8 to 4.12 are generated. They represent the inventory levels in the warehouse for each set of weights selected.

Set 1	Set 2	Set 3	Set 4	Set 5
$w_1 = 1, w_2 = 0$	$w_1 = 0.7, w_2 = 0.3$	$w_1 = 0.5, w_2 = 0.5$	$w_1 = 0.3, w_2 = 0.7$	$w_1 = 0, w_2 = 1$

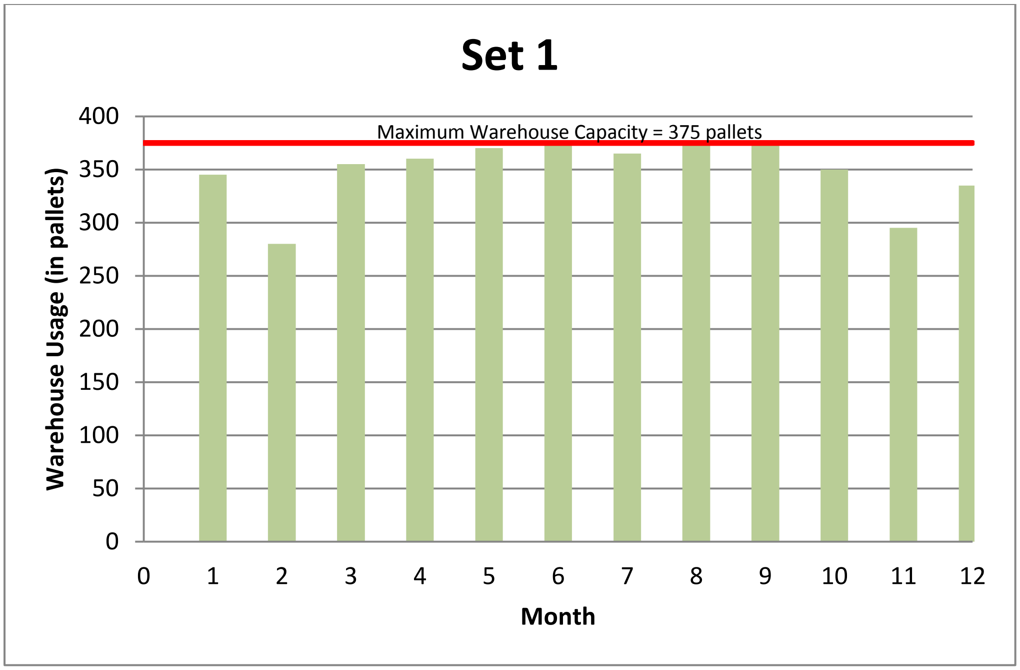

Figure 4.7 Monthly usage of warehouse capacity for weight Set 1

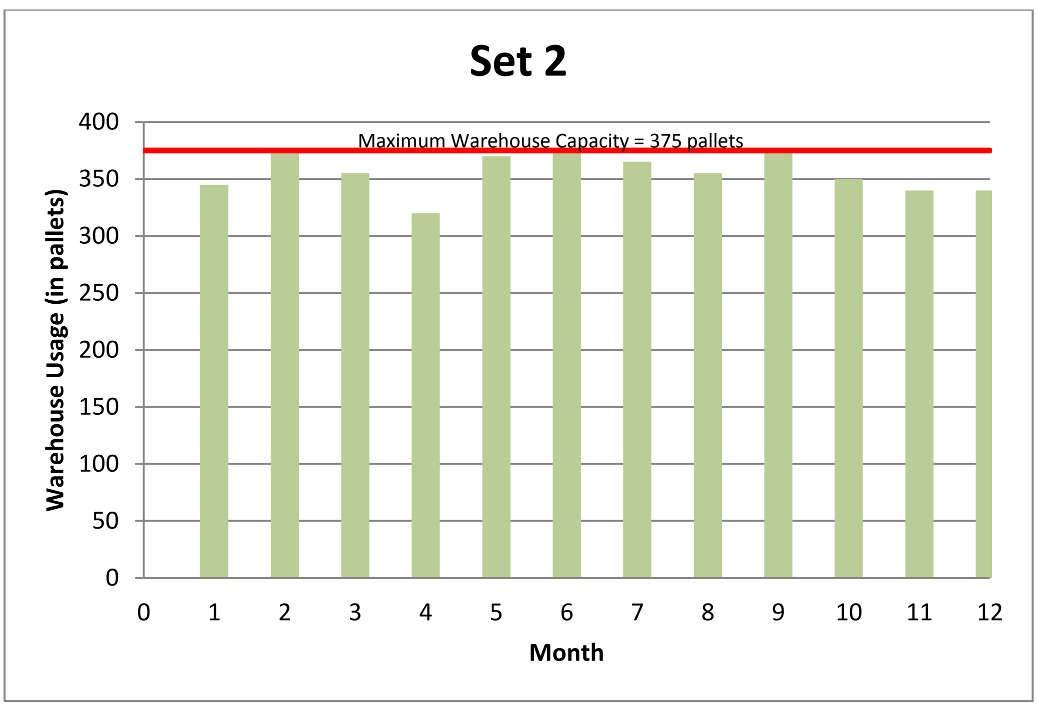

Figure 4.8 Monthly usage of warehouse capacity for weight Set 2

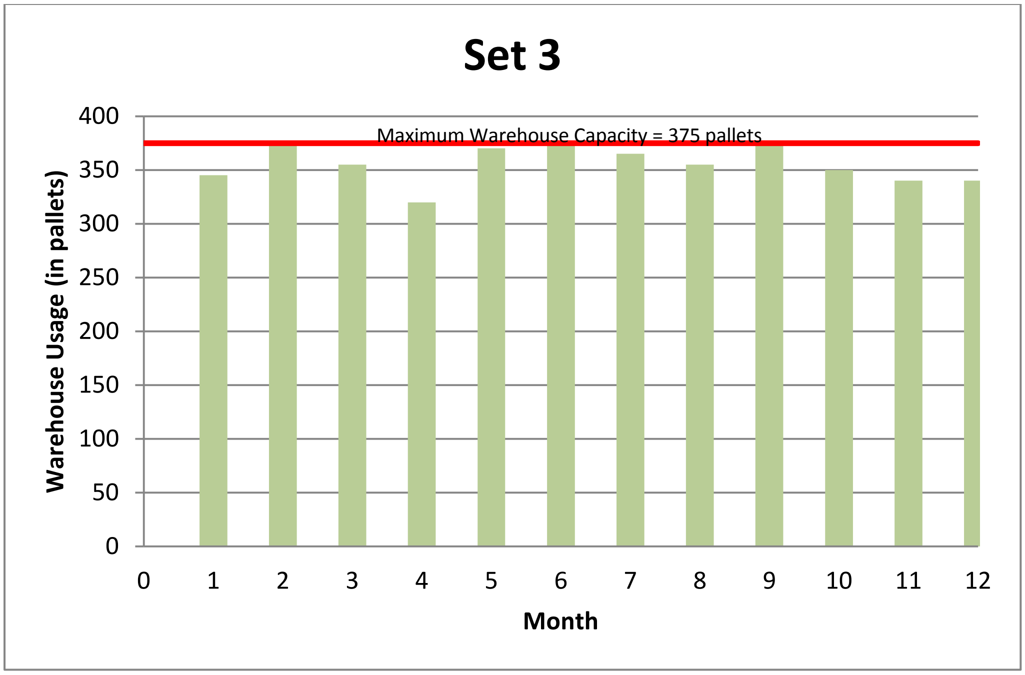

Fig 4.9 Monthly usage of warehouse capacity for weight Set 3

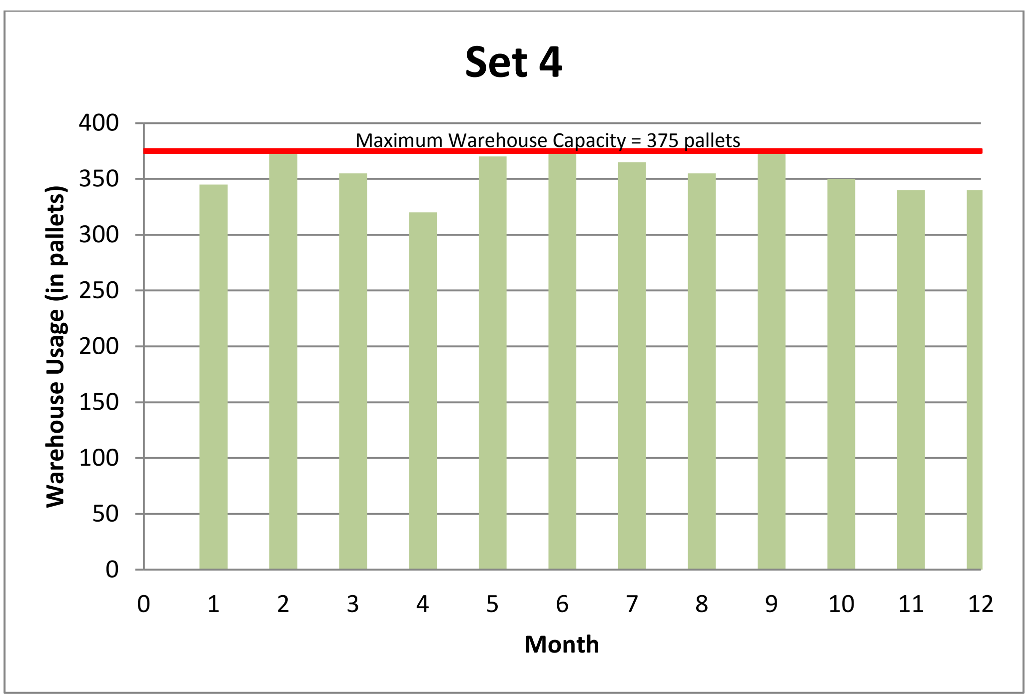

Fig 4.10 Monthly usage of warehouse capacity for weight Set 4

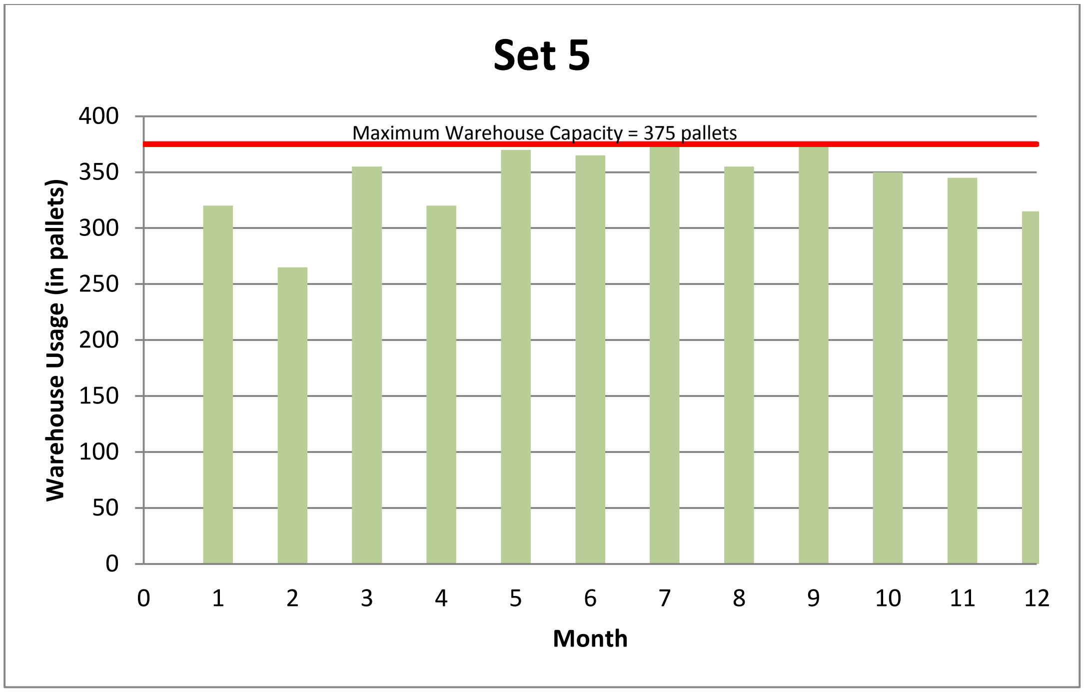

Fig 4.11 Monthly usage of warehouse capacity for weight Set 5

The average utilization of the warehouse for each set of weights is also studied. This is calculated by considering the average number of pallets in the warehouse over the 12 month period as a percentage of the overall capacity available at the warehouse. It is found that for Set 1, the warehouse space utilization was 92.89% while for Set 5, it was 91.33%. For weights in Sets 2, 3 and 4, the warehouse space utilization was 94.78%. Overall, the average warehouse space utilization was 93.71%.

Although, the warehouse is selected only 47.67% of the instances, the utilization of the warehouse space provides an insight into the benefits of including a warehouse in the network. Hence, the firm should consider shipping via a warehouse of increased capacity to address the issue of limited plant capacity and high inventory costs.

Chapter 5

Conclusions

Logistics is an essential part of any supply chain and involves activities such as inventory, transportation, storage, materials handling and packaging. The design, planning and timely monitoring of logistical activities affects ~~the~~ competitiveness and responsiveness of the supply chain. Logistics has been broadly classified into inbound, in plant and outbound logistics in the manufacturing domain. Although~~. While~~ outbound logistics affects responsiveness the most, inbound logistics is also a cause of concern. As it is one of the earliest activities of the supply chain, improper planning of the inbound process could cause disruptions further down the chain and hinder ~~the~~ overall performance. Hence, one must consider the differences in the ~~the~~ inbound logistics during the design of the supply chain network. The automotive sector is one of the best examples of an industry whose inbound logistics requires a great amount ~~deal~~ of planning and monitoring. Most research on automotive logistics focuses on the optimization of the ~~the~~ outbound (distribution) network. Inbound logistics has received comparatively less attention. However, this has changed with the introduction of lean strategies such as Cross docking, Milk Runs and Consolidation. Network selection, route planning and selection of shipping modes and frequencies are some of the factors that have been considered in the inbound logistics research. Cost and lead time are the ~~the~~ two most widely used key performance indicators that help monitor the performance of the inbound (supply) network.

This thesis was aimed at building an optimization model to aid an Indian automotive manufacturer (OEM) in tactical decision making by selecting the best option to ship material from suppliers to their facility at the lowest cost and lead time. The OEM's network consisted of multiple suppliers who shipped material directly to the plant. To address the issues of high inventory holding costs at the plant and increased lead time, it was proposed that shipping via a central warehouse and including distributors located closer to the plant, be considered. A bi-criteria mixed integer linear programming model was developed and solved using non pre-emptive goal (NPGP) programming. The objectives of the model were to minimize cost (inventory and transportation) and lead time subject to capacity constraints (plant, warehouse and vehicle) and a limitation on the number of vehicles. The four supply options available to the OEM were to ship material either from a supplier or distributor, via the warehouse or directly to the plant.

The model was solved using LINGO 13 with real and simulated data. The first stage of the approach was to find the ideal values for each of the objectives i.e. solving the single objective linear optimization problem by ignoring the other objective. The target values were set at a percentage of the ideal value and the goal programming problem was solved. The model helped identify the best shipping option for each material at the lowest cost and lead time. Different weights were assigned to the two objectives, to study the assignments made based on the importance of cost as opposed to lead time. It was observed from the results that with an increase in the weight assigned to the cost target, the objective for total cost decreased. A similar observation was made for the lead time objective. Suppliers located farthest from the plant were frequently selected for cases with higher weights associated with costs as they quoted the lowest material prices. Distributors located closest to the plant were selected for cases with higher weights assigned to lead time. It was also observed that one of the distributors was selected several times in spite of quoting higher material prices. This shows that the model takes both criteria of cost and lead time into account while selecting the most optimal assignment.

To study the uncertainty of demand, a scenario analysis was also performed over a year's data. The results helped validate the need for including distributors and a warehouse in the network. It was found that, even in cases with a higher weight assigned to the cost objective, one of the distributors quoting higher material prices was still selected in most of the instances. The option of shipping via the warehouse was selected in less number of instances due to the limitation on available warehouse space. On further analysis, it was found that the warehouse space was almost completely utilized. Thus the firm should consider shipping from distributors and storing material at the warehouse, to help reduce costs and lower delivery lead times. A warehouse of increased capacity or multiple warehouses could also be included in the network

The tactical model could be extended to include additional features for future research. Operational decisions such as Cross-docking, Milk Runs and Consolidation of material could be considered. The results of these models would help determine optimal routes, shipping modes and shipping frequencies. As this model used deterministic demand and lead times, the stochastic parameters could be introduced and the shipping options could be further analyzed under demand and lead time variations. A scenario with Dual Sourcing could also be considered where a part of the demand is met through the distributors and the remaining through the major suppliers.

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APPENDIX

LINGO code for finding Ideal Cost:

```
sets:
matrl;
sup;
plant:capp,LTWP,h;
veh:vcap,m;
source(matrl,sup):C,HCW,LTDW;
demand(matrl,plant):d;
matrlsup(matrl,sup);
matrlplant(matrl,plant);
matrlsupplant(matrl,sup,plant):HC,LTD,x,y;
matrlsupveh(matrl,sup,veh):beta,TCSW;
matrlplantveh(matrl,plant,veh):TCWP,gamma;
matrlsupplantveh(matrl,sup,plant,veh):TCP,alpha;
endsets

!data;
!d(i,k) = demand of material 'i' from plant 'k' (in pallets);
!capw = capacity of warehouse (in pallets);
!capp(k) = capacity of plant 'k' (in pallets);
!vcap(l) = capacity of vehicle 'l';
!C(i,j) = cost per pallet of material 'i' as quoted by supplier 'j';
!HC(i,j,k) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at plant 'k' where HC(i,j,k) = h(k)* C(i,j);
!h(k)is the interest rate of plant 'k' (includes cost of capital, cpst of
physically storing inventory and cost of jobs);
!HCW(i,j) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at the warehouse where HCW(i,j) = hw*C(i,j);
!hwis the interest rate of warehouse (includes cost of capital, cost of
physically storing inventory and cost of jobs);
!TCP(i,j,k,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to plant 'k' using vehicle 'l';
!TCSW(i,j,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to the warehouse using vehicle 'l';
!TCWP(i,k,l) = transportation cost per trip to ship material 'i' supplied by
'j' from the warehouse to plant 'k' using vehicle 'l';
!LTD(i,j,k) = lead time for delivering material 'i' from supplier j' to
plant 'k' (in days);
!LTDW(i,j) = lead time for delivering material 'i' from supplier j' to
warehouse (in days);
!LTWP(k) = lead time from the warehouse to plant 'k' (in days);

!variables;
!x(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to plant
'k', 0 otherwise;
!y(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to the
warehouse for plant 'k', 0 otherwise;
!alpha(i,j,k,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j'to plant 'k'
!beta(i,j,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j' to the warehouse;
!gamma(i,k,l) = number of vehicles of type 'l' needed to ship material 'i'
supplied by 'j' from the warehouse to plant 'k';
```

```
!minimize total costs;
!total cost = inventory costs + transportation costs;
[totalcost] min = @sum(matrlsupplant(i,j,k):HC(i,j,k)*d(i,k)*x(i,j,k)) +
@sum(matrlsupplant(i,j,k):HCW(i,j)*d(i,k)*y(i,j,k)) +
@sum(matrlsupplantveh:TCP*alpha)+@sum(matrlsupveh:TCSW*beta)+@sum(matrlplantv
eh:TCWP*gamma);

!minimize lead time;
totalleadtime = @sum(matrlsupplant:LTD * x) +
@sum(matrlsupplant(i,j,k):LTDW(i,j) * y(i,j,k)) +
@sum(matrlsupplant(i,j,k):LTWP(k)*y(i,j,k));

!constraints;
!only one option is selected per order plced for material i by plant k;
@for(demand(i,k):@sum(sup(j):x(i,j,k)+y(i,j,k)) = 1);

!capacity at warehouse is limited;
@sum(matrlsupplant(i,j,k):d(i,k)*y(i,j,k)) < capw;

!capapcity constraint at each plant;
@for(plant(k):@sum(matrlsupplant(i,j,k):d(i,k)* x(i,j,k)) < capp(k));

!capacity constraint on each vehicle;
!also gives number of vehicles used;
!shipping directly;
@for(matrlsupplant(i,j,k): d(i,k) * x(i,j,k) < @sum(veh(l):alpha(i,j,k,l) *
vcap(l)));

!shipping via warehouse;
@for(source(i,j): (@sum (plant(k):d(i,k) * y(i,j,k))) <
@sum(veh(l):beta(i,j,l) * vcap(l)));

!shipping from warehouse to plant;
@for(matrlsupplant(i,j,k): d(i,k) * y(i,j,k) < @sum(veh(l):gamma(i,k,l) *
vcap(l)));

!limit on number of vehicls available;
@for(veh(l):@sum(matrlsupplant(i,j,k):alpha(i,j,k,l)) +
@sum(matrlsup(i,j):beta(i,j,l)) + @sum(matrlplant(i,k):gamma(i,k,l)) < m(l));

!binary restrictions;
@for(matrlsupplant(i,j,k):@bin(x(i,j,k)));
@for(matrlsupplant(i,j,k):@bin(y(i,j,k)));

!integer restrictions;
@for(matrlsupplantveh(i,j,k,l):@gin(alpha(i,j,k,l)));
@for(matrlsupveh(i,j,l):@gin(beta(i,j,l)));
@for(matrlplantveh(i,k,l):@gin(gamma(i,k,l)));


!import data from the excel file thesis_data_cost;
data:
matrl,sup,plant,veh =
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - cost.xlsx','matrl','sup','plant','veh');
capw = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','capw');
```

```
capp = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','capp');
LTWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test RUn - MNEPL - cost.xlsx','LTWP');
vcap = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','vcap');
HCW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','HCW');
LTDW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','LTDW');
d = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','d');
TCP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','TCP');
TCWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','TC_WP');
HC = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','HC');
LTD = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','LTD');
TCSW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','TCSW');
m = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','m');

!export results to the excel file thesis_data_cost;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','direct') = x;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','whouse') = y;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','veh_direct') = alpha;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','veh_sup_whouse') = beta;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','vehwhousetoplant') = gamma;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','totalcost') = totalcost;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\Ideal\Test Run - MNEPL - cost.xlsx','totalleadtime') = totalleadtime;


enddata

end
```

LINGO code for finding Ideal Delivery Lead Time:

```
sets:
matrl;
sup;
plant:capp,LTWP,h;
veh:vcap,m;
source(matrl,sup):C,HCW,LTDW;
demand(matrl,plant):d;
matrlsup(matrl,sup);
matrlplant(matrl,plant);
matrlsupplant(matrl,sup,plant):HC,LTD,x,y;
matrlsupveh(matrl,sup,veh):beta,TCSW;
matrlplantveh(matrl,plant,veh):TCWP,gamma;
matrlsupplantveh(matrl,sup,plant,veh):TCP,alpha;
endsets

!data;
!d(i,k) = demand of material 'i' from plant 'k' (in pallets);
!capw = capacity of warehouse (in pallets);
!capp(k) = capacity of plant 'k' (in pallets);
!vcap(l) = capacity of vehicle 'l';
!C(i,j) = cost per pallet of material 'i' as quoted by supplier 'j';
!HC(i,j,k) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at plant 'k' where HC(i,j,k) = h(k)* C(i,j);
!h(k)is the interest rate of plant 'k' (includes cost of capital, cpst of
physically storing inventory and cost of jobs);
!HCW(i,j) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at the warehouse where HCW(i,j) = hw*C(i,j);
!hwis the interest rate of warehouse (includes cost of capital, cost of
physically storing inventory and cost of jobs);
!TCP(i,j,k,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to plant 'k' using vehicle 'l';
!TCSW(i,j,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to the warehouse using vehicle 'l';
!TCWP(i,k,l) = transportation cost per trip to ship material 'i' supplied by
'j' from the warehouse to plant 'k' using vehicle 'l';
!LTD(i,j,k) = lead time for delivering material 'i' from supplier j' to
plant 'k' (in days);
!LTDW(i,j) = lead time for delivering material 'i' from supplier j' to
warehouse (in days);
!LTWP(k) = lead time from the warehouse to plant 'k' (in days);

!variables;
!x(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to plant
'k', 0 otherwise;
!y(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to the
warehouse for plant 'k', 0 otherwise;
!alpha(i,j,k,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j'to plant 'k'
!beta(i,j,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j' to the warehouse;
!gamma(i,k,l) = number of vehicles of type 'l' needed to ship material 'i'
supplied by 'j' from the warehouse to plant 'k';
```

```
!minimize total costs;
!total cost = inventory costs + transportation costs;
totalcost = @sum(matrlsupplant(i,j,k):HC(i,j,k)*d(i,k)*x(i,j,k)) +
@sum(matrlsupplant(i,j,k):HCW(i,j)*d(i,k)*y(i,j,k)) +
@sum(matrlsupplantveh:TCP*alpha)+@sum(matrlsupveh:TCSW*beta)+@sum(matrlplantv
eh:TCWP*gamma);

!minimize lead time;
[totalleadtime] min = @sum(matrlsupplant:LTD * x) +
@sum(matrlsupplant(i,j,k):LTDW(i,j) * y(i,j,k)) +
@sum(matrlsupplant(i,j,k):LTWP(k)*y(i,j,k));

!constraints;
!only one option is selected per order plced for material i by plant k;
@for(demand(i,k):@sum(sup(j):x(i,j,k)+y(i,j,k)) = 1);

!capacity at warehouse is limited;
@sum(matrlsupplant(i,j,k):d(i,k)*y(i,j,k)) < capw;

!capapcity constraint at each plant;
@for(plant(k):@sum(matrlsupplant(i,j,k):d(i,k)* x(i,j,k)) < capp(k));

!capacity constraint on each vehicle;
!also gives number of vehicles used;
!shipping directly;
@for(matrlsupplant(i,j,k): d(i,k) * x(i,j,k) < @sum(veh(l):alpha(i,j,k,l) *
vcap(l)));

!shipping via warehouse;
@for(source(i,j): (@sum (plant(k):d(i,k) * y(i,j,k))) <
@sum(veh(l):beta(i,j,l) * vcap(l)));

!shipping from warehouse to plant;
@for(matrlsupplant(i,j,k): d(i,k) * y(i,j,k) < @sum(veh(l):gamma(i,k,l) *
vcap(l)));

!if direct shipping is not picked, then alpha is zero;
@for(matrlsupplantveh(i,j,k,l):alpha(i,j,k,l) < (x(i,j,k) * m(l)));

!limit on number of vehicls available;
@for(veh(l):@sum(matrlsupplant(i,j,k):alpha(i,j,k,l)) +
@sum(matrlsup(i,j):beta(i,j,l)) + @sum(matrlplant(i,k):gamma(i,k,l)) < m(l));

!binary restrictions;
@for(matrlsupplant(i,j,k):@bin(x(i,j,k)));
@for(matrlsupplant(i,j,k):@bin(y(i,j,k)));

!integer restrictions;
@for(matrlsupplantveh(i,j,k,l):@gin(alpha(i,j,k,l)));
@for(matrlsupveh(i,j,l):@gin(beta(i,j,l)));
@for(matrlplantveh(i,k,l):@gin(gamma(i,k,l)));


!import data from the excel file thesis_data_deliverytime;
data:
```

```
matrl,sup,plant,veh =
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','matrl','sup','plant','veh');
capw = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','capw');
capp = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','capp');
LTWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','LTWP');
vcap = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','vcap');
HCW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','HCW');
LTDW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','LTDW');
d = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','d');
TCP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','TCP');
TCWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','TCWP');
HC = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','HC');
LTD = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','LTD');
TCSW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','TCSW');
m = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\Ideal\Test Run - MNEPL - del time.xlsx','m');

!export results to the excel file thesis_data_deliverytime;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','direct') = x;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','whouse') = y;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','veh_direct') = alpha;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','veh_sup_whouse') = beta;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','veh_whouse_plant') = gamma;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','totaltime') = totalleadtime;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\Ideal\Test Run - MNEPL - del time.xlsx','totalcost') = totalcost;


enddata

end
```

LINGO code for NPGP:

```
sets:
matrl;
sup;
plant:capp,LTWP,h;
veh:vcap,m;
source(matrl,sup):C,HCW,LTDW;
demand(matrl,plant):d;
matrlsup(matrl,sup);
matrlplant(matrl,plant);
matrlsupplant(matrl,sup,plant):HC,LTD,x,y;
matrlsupveh(matrl,sup,veh):beta,TCSW;
matrlplantveh(matrl,plant,veh):TCWP,gamma;
matrlsupplantveh(matrl,sup,plant,veh):TCP,alpha;
endsets

!data;
!d(i,k) = demand of material 'i' from plant 'k' (in pallets);
!capw = capacity of warehouse (in pallets);
!capp(k) = capacity of plant 'k' (in pallets);
!vcap(l) = capacity of vehicle 'l';
!C(i,j) = cost per pallet of material 'i' as quoted by supplier 'j';
!HC(i,j,k) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at plant 'k' where HC(i,j,k) = h(k)* C(i,j);
!h(k)is the interest rate of plant 'k' (includes cost of capital, cpst of
physically storing inventory and cost of jobs);
!HCW(i,j) = inventory holding cost of one pallet of material 'i' supplied by
'j' held at the warehouse where HCW(i,j) = hw*C(i,j);
!hwis the interest rate of warehouse (includes cost of capital, cost of
physically storing inventory and cost of jobs);
!TCP(i,j,k,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to plant 'k' using vehicle 'l';
!TCSW(i,j,l) = transportation cost per trip to ship material 'i' from
supplier 'j' to the warehouse using vehicle 'l';
!TCWP(i,k,l) = transportation cost per trip to ship material 'i' from the
warehouse to plant 'k' using vehicle 'l';
!LTD(i,j,k) = lead time for delivering material 'i' from supplier j' to
plant 'k' (in days);
!LTDW(i,j) = lead time for delivering material 'i' from supplier j' to
warehouse (in days);
!LTWP(k) = lead time from the warehouse to plant 'k' (in days);

!variables;
!x(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to plant
'k', 0 otherwise;
!y(i,j,k) = 1 if material 'i' is shipped directly from supplier 'j' to the
warehouse for plant 'k', 0 otherwise;
!alpha(i,j,k,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j'to plant 'k'
!beta(i,j,l) = number of vehicles of type 'l' needed to ship material 'i'
from supplier 'j' to the warehouse;
!gamma(i,k,l) = number of vehicles of type 'l' needed to ship material 'i'
from the warehouse to plant 'k';
```

```
!new objective;
min = (weight1 * devp1) + (weight2 * devp2);

!goal constraints;
[goal1] objective1  + (devn1*ideal1) - (devp1*ideal1) = target1;
[goal2] objective2 + (devn2*ideal2) - (devp2*ideal2) = target2;

!total cost = inventory costs + transportation costs;
objective1 = @sum(matrlsupplant(i,j,k):HC(i,j,k)*d(i,k)*x(i,j,k)) +
@sum(matrlsupplant(i,j,k):HCW(i,j)*d(i,k)*y(i,j,k)) +
@sum(matrlsupplantveh:TCP*alpha)+@sum(matrlsupveh:TCSW*beta)+@sum(matrlplantv
eh:TCWP*gamma);

!lead time;
objective2 = @sum(matrlsupplant:LTD * x) +
@sum(matrlsupplant(i,j,k):LTDW(i,j) * y(i,j,k)) +
@sum(matrlsupplant(i,j,k):LTWP(k)*y(i,j,k));

!inventory costs;
inv = @sum(matrlsupplant(i,j,k):HC(i,j,k)*d(i,k)*x(i,j,k)) +
@sum(matrlsupplant(i,j,k):HCW(i,j)*d(i,k)*y(i,j,k));

!transportation costs;
trans =
@sum(matrlsupplantveh:TCP*alpha)+@sum(matrlsupveh:TCSW*beta)+@sum(matrlplantv
eh:TCWP*gamma);

!original constraints;
!only one option is selected per order plced for material i by plant k;
@for(demand(i,k):@sum(sup(j):x(i,j,k)+y(i,j,k)) = 1);

!capacity at warehouse is limited;
@sum(matrlsupplant(i,j,k):d(i,k)*y(i,j,k)) < capw;

!capapcity constraint at each plant;
@for(plant(k):@sum(matrlsupplant(i,j,k):d(i,k)* x(i,j,k)) < capp(k));

!capacity constraint on each vehicle;
!also gives number of vehicles used;
!shipping directly;
@for(matrlsupplant(i,j,k): d(i,k) * x(i,j,k) < @sum(veh(l):alpha(i,j,k,l) *
vcap(l)));

!shipping via warehouse;
@for(source(i,j): (@sum (plant(k):d(i,k) * y(i,j,k))) <
@sum(veh(l):beta(i,j,l) * vcap(l)));

!shipping from warehouse to plant;
@for(matrlsupplant(i,j,k): d(i,k) * y(i,j,k) < @sum(veh(l):gamma(i,k,l) *
vcap(l)));

!limit on number of vehicls available;
@for(veh(l):@sum(matrlsupplant(i,j,k):alpha(i,j,k,l)) +
@sum(matrlsup(i,j):beta(i,j,l)) + @sum(matrlplant(i,k):gamma(i,k,l)) < m(l));

!binary restrictions;
@for(matrlsupplant(i,j,k):@bin(x(i,j,k)));
```

```
@for(matrlsupplant(i,j,k):@bin(y(i,j,k)));

!integer restrictions;
@for(matrlsupplantveh(i,j,k,l):@gin(alpha(i,j,k,l)));
@for(matrlsupveh(i,j,l):@gin(beta(i,j,l)));
@for(matrlplantveh(i,k,l):@gin(gamma(i,k,l)));


!import data from the excel file data_npgp;
data:
matrl,sup,plant,veh =
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\NPGP\Test Run - MNEPL - npgp.xlsx','matrl','sup','plant','veh');
capw = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','capw');
capp = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','capp');
LTWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','LTWP');
vcap = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','vcap');
HCW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','HCW');
LTDW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','LTDW');
d = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','d');
TCP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','TCP');
TCWP = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','TC_WP');
HC = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','HC');
LTD = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','LTD');
TCSW = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','TCSW');
ideal1 = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test
- MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','Ideal1');
ideal2 = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test
- MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','Ideal2');
target1 = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis -
code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','target1');
target2 = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis -
code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','target2');
weight1= @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test
- MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','weight1');
weight2 = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis -
code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','weight2');
m = @ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test -
MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','m');


!export results to the excel file data_npgp;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL
data\NPGP\Test Run - MNEPL - npgp.xlsx','direct') = x;
```

```
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','whouse') = y;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','veh_direct') = alpha;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','veh_sup_whouse') = beta;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','veh_whouse_plant') = gamma;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','totalcost') = objective1;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','totaltime') = objective2;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','obj1_devp') = devp1;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','obj2_devp') = devp2;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','inv') = inv;
@ole('\\iestudents.ie.psu.edu\ms01\azp148\Desktop\Thesis - code\Test - MNEPL data\NPGP\Test Run - MNEPL - npgp.xlsx','trans') = trans;


enddata

end
```

NOTE: The LINGO codes were linked to an EXCEL spreadsheet for the input and output.