Optimization Tools for the Freight Brokerage Industry

by

Jeffrey L. Silver
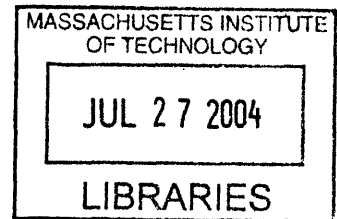A.B., Economics
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Signature of Author_____
Engineering Systems Division
May 9th, 2003

Certified by_____
Cynthia Barnhart
Professor, Civil and Environmental Engineering and Engineering Systems
Co-Director, MIT Center for Transportation and Logistics
Thesis Supervisor

Accepted by_____
Yossi Sheffi
Professor, Civil and Environmental Engineering and Engineering Systems
Co-Director, MIT Center for Transportation and Logistics

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Abstract

The freight brokerage industry in North America was born of the deregulation of the trucking industry in 1982. In the two decades since, the industry has grown from nothing to $50 Billion in revenue. In the beginning, freight brokers used T-card systems to record, track, and bill orders. Technology advances over those two decades have driven many of the operational changes throughout the freight transportation industry as a whole, with shipment data visibility, asset utilization, and supply chain planning leading the way. The use of optimization tools in transportation and supply chain management has proliferated. Network analysis, inventory planning and deployment, fleet routing, and warehouse planning are important examples of areas in which these tools have had a major impact. However, the freight brokerage sub-industry itself has largely ignored the use of these tools.

This research proposes pragmatic uses for optimization techniques in the freight brokerage industry. Three tools are proposed, with justifications for need, mathematical formulations, and exemplary situations and savings described. The three tools are: 1) optimal truckload freight tenders to multiple carriers, 2) optimal LTL consolidation, and 3) optimal matching of loads and trucks.

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1 Introduction

The logistics industry has developed sophisticated software for optimization of asset allocation in supply chain planning and operations. Hundreds of millions of dollars have been invested in the development of these tools and they have been deployed extensively with varying degrees of success. Logistics management firms, consultants, railroads, and some carriers have profited by bringing the operational efficiencies that result from the successful implementation of these tools to their customers. A significant segment of the logistics industry has largely been left behind by this progress.

Freight brokers represent an important element of the third party logistics industry. As the freight brokerage industry has matured over the last two decades, information technology improvements for brokers have mostly focused on developing basic operating platforms and providing shipment status visibility to customers. Little, if anything has been done to extend these systems to help freight brokers capture the benefits of optimization tools for their own critical needs.

1.1 Motivation for Thesis

This research identifies three important areas in which the use of optimization tools will benefit freight brokers. In addition to providing the mathematical formulations for the solutions to these problems, this thesis provides a description of the inbound data requirements for each problem, and the benefits that can be achieved from implementing these solutions. This research will provide the opportunity for further market penetration and more efficient operations to any freight brokerage operation capable of implementing the solutions described herein.

1.1.2 Background

The author of this research was a founder of American Backhaulers, Inc, a freight brokerage company based in Chicago, IL. Over the 16 years he worked at the company before its sale to the world's largest freight brokerage, the author led both its sales effort and its technology development. When the company was sold, its brokerage software was widely recognized as the best in the industry, but lacked the ability to handle even basic optimization. This research is part of an effort to design the next generation of freight brokerage software, including some important practical uses for optimization tools that will allow a brokerage to offer valuable new services to its customers.

1.2 The Freight Brokerage Industry in North America

Freight brokers are but a small part of the overall logistics industry, and even of the long haul, intercity freight transportation industry that is the focus of this paper. There are many other important players providing both service to and competition with freight brokers. Since the birth of the brokerage industry, freight brokers have used the services of the trucking companies and railroads that actually move the freight, and have competed with them. Yet while the brokerage business has grown rapidly over these last two decades, it has been largely ignored by academia and serious technologists alike.

Bowersox[1] provides some insight into the extent to which academia has ignored this segment of the market with his treatment of the topic. In his 700-plus-page book called Logistical Management, the Integrated Supply Chain Process, he offers the following paragraph on freight brokerage:

"Brokers are intermediaries that coordinate transportation arrangements for shippers, consignees, and carriers. They also locate shipments for exempt carriers and owner-operators. Brokers, who must obtain a license from the ICC, typically operate on a commission basis. Prior to deregulation, they played a minor role because of restrictions on their operations. Now, brokers provide more extensive services such as shipment matching, rate negotiation, billing, and tracing."

The rest of the book, with sections on Integrated Logistics, Logistics Resources, Logistics System Design, and Logistics Administration, ignores the existence of brokers, while going into great detail on many of the roles the broker plays and the services it offers.

Yet the industry has grown to some $50 Billion in revenues per year. According to its website, CH Robinson Worldwide handled some $3.3 Billion in revenue in 2002, representing 2.7 Million shipments, with a gross profit of $361 Million.

The table below, taken from Robinson's 2002 Annual Report, shows revenue growth for the last five years. The far right column was added to show the percentage of profit attributable to truck brokerage.

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[1] Donald J. Bowersox and David J. Closs, *Logistical Management – The Integrated Supply Chain Process*, New York: McGraw-Hill, Inc., 1996 page 338

Table 1 - CH Robinson Profit by Mode

	1998	1999	2000	2001	2002	2002 % of Total
Truck	164,186	202,877	313,650	347,991	361,353	88%
Intermodal	6,671	10,738	14,422	16,119	21,111	5%
Ocean	10,215	11,476	16,337	16,345	17,007	4%
Air	3,427	2,858	3,555	2,699	3,068	1%
Miscellaneous	5,298	5,899	7,177	7,286	8,772	2%
Total	189,797	233,848	355,141	390,440	411,311	100%

At these numbers, Robinson is certainly the largest player in the industry. There is a small group of freight brokers around the $50-150 Million range, represented by companies such as Allen Lund Company, claiming $132 Million in annual revenue on 92,000 loads[2], and Stonier Transportation Group, with about $65 Million[3]. However, the majority of freight brokers are much smaller, with a large group in the $10 Million per year range and many at less than $5 Million.

1.2.1 How Freight Brokerage Works

A freight broker is an intermediary between a customer with product that needs to get from point A to point B, and a carrier, a trucking company with an available truck.

A sample transaction is illustrative:

Collegiate Clothing has a distribution center in Chicago. CH Robinson has quoted prices to Collegiate Clothing for shipments from this facility in Chicago to points all over North America. From Chicago to New York City, for a distance of 800 miles, the quoted price is $1,360, or $1.70 per mile.

A shipping clerk from Collegiate Clothing calls CH Robinson with a shipment Monday afternoon to be picked up Tuesday between 7 a.m. and 3 p.m. The shipment will require a 53-foot dry trailer, which is essentially the largest available in North America, since Collegiate Clothing's product is bulky rather than heavy. 53-foot trailers represent about 70% of trailers in use today, the rest being smaller and thus unacceptable to Collegiate Clothing. The shipment is to be delivered to a grocery chain warehouse on Thursday at 4 a.m., so a single driver can handle the shipment. If next day delivery were required, team service would be necessary and a higher price would be used. CH Robinson accepts the order.

Meanwhile, CH Robinson has also been amassing lists of empty equipment from carriers around the continent. These are trucks that will be empty following delivery of the

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[2] From the Allen Lund Company website, www.allenlund.com
[3] From Stonier Transportation Group's website, www.stonier.com

trucking companies' customers' orders. The trucks are scattered throughout North America, with heavy concentrations in some areas and very light volumes in others, depending on many factors such as seasons, production and consumption, population, proximity to export and import facilities, etc.

In Chicago, except during the third quarter, there are typically a reasonably large number of empty trucks available and a decent amount of freight as well. In New York City, however, there is a large population consuming a lot, and very little production. There are many trucks delivering and looking for freight, but very few loads available for those trucks. Therefore, a load from Chicago to New York City is not very desirable, unless a carrier with a truck in Chicago has a need to get a truck to New York to pick up a load for another customer.

The optimal arrangement for CH Robinson is to find a carrier based in or near New York who has just delivered a load in Chicago. Assuming this is true in this example, CH Robinson will likely be able to offer the carrier about $1.30 per mile, or $1,040 to haul the load. If everything goes well, the gross spread on the load will be $320 for CH Robinson.

Often, however, there are no trucks in Chicago willing to go to New York. In such a case, CH Robinson may have to pay a carrier extra to entice him to send his truck out to New York, or pay him extra to deadhead to a better spot after delivering in the city. Or, CH Robinson may have to pay a carrier who needs to get to New York but whose truck is further from the shipping point, empty in Madison, WI, for example, to deadhead to Chicago to come get the load.

In cases like these, margins shrink. In fact, on a small portion of shipments each day, CH Robinson actually pays the carrier more than it charges the customer to move the load, losing money but fulfilling its commitment to its Collegiate Clothing.

Once a deal is struck with a carrier and the driver has delivered his previous load, the driver calls CH Robinson for dispatch. He then goes and picks up the load, reporting back loaded information, intermediate information along the route, any problems as they occur, and delivery information when he has reached New York.

After delivery, the carrier invoices CH Robinson, who in turn invoices the customer. CH Robinson typically pays the carrier in less than 30 days, and is paid by the customer some 15 – 20 days thereafter. Typically, the customer and carrier are prevented from seeing the other side of the transaction, protecting CH Robinson's margin.

2 Review of Current IT Tools for Freight Brokerage

2.1 Description of Common Brokerage Software

In the 1980's, there was very little commercially available freight brokerage software. Those packages that existed emerged either from freight brokerage firms that had developed systems internally that were then marketed to the public, or from trucking company software re-tooled, or sometimes just renamed, to be marketed to freight brokers. Most of these systems were rudimentary order entry systems. The more sophisticated of them had links to commercial mileage look-up software, such as PC*Miler, a product of ALK Associates.

The 1990's brought many more entries, some not much better than their predecessors. The better of these products added more robust order structures and the ability to record and retrieve trucks. Some also added at least minimal web visibility, EDI capabilities, and interfaces with accounting packages.

Common modules in these systems included:

- Order Creation. These modules typically included the ability to create orders, add one or more customers to be billed, retrieve and add shippers and consignees, and set rates.
- Carrier Profile Searches. The modules allowed a broker to maintain profiles on carriers, containing searchable information on desired lanes and equipment capabilities.
- Historical Lane Searches. Here, a broker could find likely carriers for an order in need of a truck by searching historical tables of the carriers used on past loads.
- Carrier Rate Confirmation. The automated, or semi-automated, creation of rate confirmation documents saved time and helped to ensure that carriers charged the broker the correct amount on loads and handled the freight in an appropriate manner.
- Order Tracking. These modules allowed brokers to record, and sometimes expose to the customer via the Internet or reports, the history of events that transpired with an order. Some packages included very robust tracking modules and others merely a spot for free-form notes.

As the Internet rush swooped down upon the industry, hundreds of companies attempted to offer web versions of most of the logistics functions. Web-based freight exchanges promised the disintermediation of freight brokers. And as the bubble burst and most of these disappeared, some of the technology that was developed during the onslaught has found its way into legitimate software, offered both as package based and ASP delivered service.

2.2 Express

In 1999, CH Robinson Worldwide (Robinson) of Minneapolis, MN, the world's largest freight brokerage with some $3 billion in sales, acquired American Backhaulers, Inc, of Chicago, its largest competitor. Until the acquisition, Robinson had used a homegrown system called COSMOS to operate the freight brokerage part of its business. American Backhaulers had also developed a system in house. As a result of the acquisition, Robinson installed the American Backhaulers' Express system in its 135 branches in North America and 15 branches in Europe.

Express was significantly ahead of COSMOS in its functionality. COSMOS was primarily geared at recording transactions after the fact, allowing Robinson's brokers to pass information regarding each completed transaction to the accounting system. Express was an integrated sales tickler system, order processing, matching, reporting, and accounting system. Built in 1998 and 1999, two key goals of the system were to provide unparalleled order visibility to the customer, and to facilitate the entire brokerage operations by automating processes and eliminating redundancies.

Express's order visibility provided SKU level detail. Via the Internet or EDI transmission, a customer could see everything from the weight and number of pieces of each item loaded on a truck, to every check call a driver made along his route while transporting those goods. Through the reporting mechanism, the customer could compare average loading times for one of products across its different plants, or the cost of shipping tomato sauce versus tomato soup into its Western region for a give quarter.

Eventually, customers began to rely on this order visibility and asked American Backhaulers to move freight that it was not brokering through its system. This represented the American Backhaulers' first foray into transportation management. It also represented the effort of brokers with sufficient resources to offer more 3PL services in an attempt to control more freight.

CH Robinson's 2002 Annual Report sites the following use of systems in its efforts:

"We have developed our own proprietary operating systems that help salespersons service customer orders, select the optimal modes of transportation, build and consolidate loads, and select routes, all based on customer-specific service parameters. Systems also make load data visible to the entire sales team as well as customers and carriers, enabling the salespersons to select carriers and track loads in progress, and automatically provide visible alerts to any arising problems. Our proprietary operating systems use data captured from daily transactions to generate various management reports which are available to our logistics customers to provide information on traffic patterns, product mix, and production schedules, and enable customers to analyze their own customer base, transportation expenditure trends, and the impact on out-of-route and out-of-stock costs.[4]"

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[4] CH Robinson Worldwide's 2002 Annual Report

2.3 Use of Optimization in Supply Chain Management and Logistics

While freight brokers were focused on developing operating systems, in the 1990's, some trucking companies and the railroads also began to take advantage of advances in computer technologies. The more sophisticated trucking companies began to use routing optimization programs, well documented in most logistics texts and many papers (see Bowersox and Closs (1996), Chopra and Meindl (2001), and Bramel and Simchi-Levi (1997) for examples). Railroads used resource allocation software to plan routes and schedules. Freight brokers, however, do not manage the assets in the same way as the companies that own them, so these technological advances have only been relevant in that they allow some of these direct suppliers to be more competitive than in the past.

A second group of competitors comprises another important part of the logistics industry. Third party logistics companies, or 3PL's, began to sprout up in numbers in the late 1980's. These companies have offered a wide variety of services: freight bill auditing, the implementation of core carrier programs, private fleet management and leasing, mode selection, and some inventory management to name just a few. The 3PL's have used some of the same routing optimization software, provided by such software companies as i2 Technologies and Manugistics, as the carriers described above. However, the use of these technologies is slightly different when provided by an outside party, with different consequences for the freight broker as well.

In this case, the main issue for the broker in terms of competition with the broader 3PL companies lies within the control over the freight. As explained in the next section, a broker makes money on a transactional basis, when he moves freight for a customer. A 3PL typically charges consulting fees, either flat or as a percentage of savings, to the customer. A freight broker and a third party logistics company selling to the same customer will typically approach the customer in two different ways. The broker will sell price and availability of equipment, while the 3PL will usually sell knowledge and systems. Sometimes, the broker will try to sell systems as well, and sometimes the 3PL will also offer execution. In either case, the result is the desire of the provider to control the freight, either in terms of being able to make money by brokering it, or in terms of being able to claim savings by changing the routing of the freight or the service providers.

Furthermore, as customers began to be faced with the ability and necessity to decide between the use of 3PL's and brokers, they began to demand the alternative services from the other side. So 3PL's began to offer more execution capabilities, and brokers began to look for more ways to offer other 3PL type services.

In fact, Robinson's website now describes the company as "one of North America's largest third party logistics (3PL) companies.[5]" Yet most of the company's profit comes

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[5] CH Robinson Worldwide's website www.chrobinson.com

from brokering freight, while the other services do little more than drive freight into the system or lock customers into using Robinson because of the additional services rendered.

As some freight brokers, like Robinson, begin to sell other 3PL services, they need to understand how to use optimization tools in ways specific to their businesses. One strategy for brokers is to become consultants as well and offer some of the same services as other industry participants do today. The following sections are three examples of common tools implemented by logistics consultants and 3PL's. They are interesting as background, yet none of them directly answers the special needs of a freight brokerage.

2.3.1 Network Analysis

Network analysis is the science of using optimization techniques to help make the tradeoffs involved in determining where to source raw materials, where to place plants and how many to have, where to locate warehouses and distribution centers and how many to use, and which customers to serve from which distribution center. Nearly every book on logistics at least refers to this problem, and many go into much detail

Often, third part logistics companies offer the service of analyzing a customer's network. As an expert, with experience creating and running the models, the 3PL will typically bring one or several tools to bear on the situation, and will charge either a fixed fee, a cost plus, or a portion of the savings created by removing wasted cost from the network.

According to Bramel and Simchi-Levi, network analysis helps a company makes decisions regarding:

"(1) determining the appropriate number of warehouses, (2) determining the location of each warehouse, (3) determining the size of each warehouse, (4) allocating space for products in each warehouse and (5) determining which products customers will receive from each warehouse."[6]

See also Shapiro (2001), who gives a detailed description of the distribution center location model along with examples and optimization spreadsheets in Chapter 4.

Beyond the theory and academic treatments, however, network analysis tools are readily available commercially and in widespread use.

One company, LogicTools, offers a network analysis tool that answers the following business problems:

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[6] Julien Bramel and David Simchi-Levi, *The Logic of Logistics*, New York: Springer-Verlag, 1997

"Manufacturing Network Strategy

Determine the best manufacturing network to maximize asset utilization, minimize total cost and align the manufacturing strategy with the projected business growth/change.

Distribution Network Rationalization

Determine the best network of distribution facilities to serve customers under given parameters of service at minimum cost.

Realignment of Shipping Territories

Optimize the trade-offs between service and cost to determine the best service territory for each DC to improve service levels while reducing cost.

Dynamic Supplier Selection

Optimize the tradeoffs between purchasing, distribution and transportation costs to dynamically determine the supplier for each product to reduce overall network cost.

Service Parts Distribution Strategy

Determine the best network for distributing service parts to customers at minimum cost while maintaining or improving service levels.

Strategic Product Sourcing Strategy

Identify the right product mix and production volumes at each of the plants to replenish distribution centers based on capacities and cost structures for the entire network."[7]

One of LogicTools' competitors, Insight, Inc, offers the following description of its network analysis product:

"SAILS 21, INSIGHT's flagship product, provides the capabilities to help companies design optimal supply chain networks. By minimizing costs, maximizing profits and increasing service levels, SAILS delivers value along the entire supply chain. The software can accurately represent a company's current business practices, from raw materials sourcing to capacity planning through delivery to the end customer. Using cutting-edge optimization technology, SAILS determines the best current network and strategically plans the best future network.

SAILS capabilities include the following:
• Determines the optimal number and size of facilities
• Determines the best locations of facilities
• Evaluates distribution methods and policies
• Examines profitability, seasonality and growth analysis to make production and

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[7] From LogicTools Inc's website, www.logic-tools.com

- capacity decisions
- Analyzes the cost vs. service tradeoff"[8]

Another competitor, Manugistics, offers the following description on its website:

"Manugistics Network Design & Optimization can help you:
- optimize sourcing, storage, manufacturing, distribution, transportation, and retail site locations to minimize costs and increase profits
- make smarter, faster production and distribution decisions
- minimize stock outs and avoid inventory shortages
- reduce customer lead-times through more efficient operations
- optimize distribution plans to most effectively handle promotional events
- minimize transportation costs

Optimize the configuration and use of your network

The Manugistics Network Design & Optimization solution is a comprehensive tool set designed to analyze the variables associated with operating an end-to-end supply network - including costs, capacity, and geography - and optimize the network to help you achieve the lowest possible costs and the highest possible profits, all while maintaining target customer service levels.

Network Design & Optimization leverages the power of linear programming, mixed-integer programming, and meta-heuristic techniques to help you make optimal decisions about the configuration and use of your supplier, manufacturing, distribution, and transportation network. By making it possible to simultaneously optimize millions of costs and constraints, the algorithms give you the ability to solve extremely complex problems. Using graphical building blocks, you can model actual and hypothetical networks to predict the lowest cost and highest profit configuration and use scenarios. Network Design & Optimization takes the complexity out of network design, giving you a distinct competitive advantage by forecasting an optimal solution to a complex problem in minutes or hours, rather than days or weeks."[9]

Several other competitors offer their own solutions. Generally, most of these are mixtures of heuristics and mixed integer linear programming solutions. A sample of how a portion of these problems are solved using the CPLEX solver appears in **Appendix B.**

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[8] From Insight, Inc's website, www.insight-mss.com
[9] From Manugistics' website, www.manugistics.com

2.3.2 Inventory Planning

As with network analysis, there are many explanations of inventory planning problems and solutions in academic literature and in commercial packages.

See *Factory Physics* by Hopp and Spearman (2000) for an in depth discussion of inventory planning issues and mathematical models used to help makes decisions about order sizes and frequencies and where inventory should be kept within a supply chain. See also Bramel and Simchi-Levi (1997), Daganzo (1999), Shapiro (2001), and many others for theory and many examples of implementations.

From a commercial point of view, the following systems are representative:

Logic-Tools' contribution to the inventory planning area is called Inventory Analyst and advertises the following purpose and benefits:

"Business Applications

Inventory Analyst addresses many challenges faced by companies in today's highly competitive and complex business environment.
- Determining the "Push-Pull" boundary (Make-to-Stock vs. Make-to-Order)
- Analyzing Inventory Liability issues
- Designing the appropriate Supply Chain Network with inventory implications
- Selecting between alternate suppliers based on price and service lead times
- Spare parts inventory planning
- Optimally allocating inventory across a retail distribution network

Key Business Benefits
- Improved service levels with reduced inventory
- Reduce excess and obsolete inventory
- Effectively deal with demand fluctuations
- Understand financial implications of servicing customers based on actual cost of goods sold
- Rapid return on investment "[10]

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[10] From LogicTools website, www.logic-tools.com.

Manugistics offers:

"Manugistics Inventory & Allocation solution can help you:
- increase responsiveness to customer demands
- improve accuracy of material and distribution plans
- achieve an optimal product mix
- reduce inventory obsolescence
- improve on-time performance and customer service
- lower inventory levels
- shorten order and cycle times
- cut supply lead times
- increase asset utilization"[11]

2.3.3 Fleet Routing

This may be the most studied of the three problems listed here. Truck fleet routing is an offshoot of the famous traveling salesman problem. The basic problem is, given a single origin and some number of destinations, or customers, what is the least cost way to route a truck or number of trucks to make the deliveries and return to the origin? In most treatments, distance is used as an approximation of cost.

There are many variations considered in the literature.

Daganzo (1999), for example, discusses vehicle routing models with many tours and few tours, identical customers and demand and different customers, cheap and expensive items, low demand and uncertain demand, and several others.

Simchi-Levi illustrates optimization techniques and heuristics for several branches of the problem as well, beginning with what he calls the most basic, the "single-depot Capacitated Vehicle Routing Problem (CVRP). It can be described as follows: a set of customers has to be served by a fleet of identical vehicles of limited capacity. The vehicles are initially located at a given depot. The objective is to find a set of routes for the vehicles of minimum total length. Each route begins at the depot, visits a subset of the customers and returns to the depot without violating the capacity constraint."[12] He then goes on to consider the same problem, but with unequal demands, the UCVRP.

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[11] From Manugistics' website, www.manugistics.com
[12] Julien Bramel and David Simchi-Levi, *The Logic of Logistics*, New York: Springer-Verlag, 1997

Next, he adds time windows for the deliveries, which he calls the "vehicle Routing Problem with Time Windows (VRPTW), and then the Capacitated Vehicle Location Problem with Time Windows (CVLPTW)."[13]

The problem is pertinent to any shipper with a private fleet, and carrier attempting to service a customer with multiple stop loads, and to a logistics company trying to serve either.

There are many commercial packages to handle these problems as well.

One solution is offered by ILOG, the company responsible for the CPLEX solvers.

ILOG describes its tools as such:

> "ILOG Dispatcher's optimization engine powers high-performance vehicle routing applications. Specialized modeling and advanced problem-solving features handle a wide range of routing problems
>
> **Real savings**
> Routing problems can differ greatly depending on the time windows available for visits, vehicle characteristics, and pickup-and-delivery routes. ILOG Dispatcher's flexibility allows companies to consider every facet of a problem, forming optimized solutions that reduce costs and improve customer service.
>
> **Planning and real-time coverage**
> ILOG Dispatcher incorporates ILOG's renowned optimization technology. Superior performance produces efficient planning, while providing the flexibility to respond immediately to last-minute changes."[14]

CAPS Logistics software offers a tool, RoutePro, that handles this problem as well. CAPS offers several case studies on line that describe the benefits of the system. A small one is illustrative:

"Orgill Brothers & Co.
Fixed Sales and Delivery Routes

> **CLIENT**
> Orgill Brothers & Co. is a full-line wholesale hardware distributor. They provide a broad range of hardware, housewares and sporting goods - over 40,000 products in all - to independently owned retail hardware stores, lumber yards and home centers. Orgill Brothers sells directly to customers, dispatching orders from their Memphis distribution center and several redistribution centers in the South and Southwest.

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[13] Julien Bramel and David Simchi-Levi, *The Logic of Logistics*, New York: Springer-Verlag, 1997
[14] From ILOG's website, www.ilog.com

PROBLEM

Adding new accounts and keeping up with changes in routes and existing accounts had become increasingly more complex for Orgill Brothers' distribution management team. They sought help in locating new accounts and identifying unprofitable ones, determining account-to-branch assignments, analyzing salesperson call days and delivery patterns, and creating and modifying fixed delivery routes.

SOLUTION

The logistics analysts at Orgill Brothers & Co. found the ideal integrated distribution network analysis and vehicle routing system for their needs. With CAPS Logistics software they can easily determine the best number and location of redistribution branches to service their accounts and assign accounts to branches. They can also modify route assignments (with or without changing salesperson call days and delivery patterns), modify or eliminate unprofitable routes, and generate new routes for the least efficient branches. In addition, the application interacts with a mainframe for data retrieval and storage, plus generates a variety of assignment and routing reports.

RESULTS

Since using the application , Orgill Brothers has reported significant savings through route consolidation. They have also experienced greater cost avoidance, enabling them to expand their business with minimal route additions."[15]

Beyond these two examples, there are scores of others; such as Caliper Corporation's TransCAD solution offers the following description:

"Vehicle Routing/Dispatching

TransCAD provides a rich set of tools that solve various types of pickup and delivery routing problems. These tools are used to prepare input data, solve the routing problem, and provide tabular and graphical output of the resulting routes and vehicle schedules. The TransCAD procedures can solve many variations on the classic vehicle routing problem, including restrictions on the time when stops can be made, the dispatching of vehicles from multiple depots, and the use of non-homogeneous vehicle fleets. The vehicle routing procedure in TransCAD is also capable of solving problems involving mixed pickup and delivery. Once a solution is found and the results displayed graphically, users can edit the routes interactively by adding or removing stops. Once stops have been added or removed, users can perform a re-optimization of the route so as to minimize time window violations."[16]

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[15] From Caps Logistics website, www.caps.com
[16] From Caliper Corporation's website, www.caliper.com

3 Methodology

Three freight brokerage problems are presented in this paper. First, brokers need a better way to manage the tendering of truckloads to a customer's core carriers when the broker is acting as a transportation management company as well as a broker. Second, brokers need a better tool to consolidate partial shipments into the lowest cost combined truckloads to then be brokered to truckload carriers. And third, brokers need a means of arriving at the best possible combination of trucks and loads at any point in time.

For each of these, this paper first discusses the problem, then presents the system that American Backhaulers, through its Express system, used to deal with the problem, and then suggests a new tool to better answer the problem. The research uses American Backhaulers and its Express system, now used by the world's largest freight brokerage, CH Robinson, as a proxy for the 2003 state-of-the-art in freight brokerage systems.

4 Optimization Tools for Freight Brokers

4.1 Truckload Freight Tendering

By the end of the 1990's, several large customers had begun to rely more and more on American Backhaulers' systems to manage the majority of their freight. This was a new role for American Backhaulers, whose strength had always been in aggregating capacity to cover irregular freight. But as customers pushed the company to handle more of their regular freight, they also began to ask us for other tools that had been promised, and never really delivered, by logistics software vendors or the throng of third party logistics companies that had sprung up in the nineties.

At the same time, many customers had adopted the trend of paring down the number of carriers with which they did business and focusing on a core group of carriers. Often, that meant winnowing down a list of 300 carriers to 30 or so for a nationwide program, often with a company like American Backhaulers or CH Robinson acting either as one of the core carriers, or as a backup. A customer with several plants typically used between 5 and 10 core carriers at a plant, depending on volume, accessibility, and loading hours.

For example, a plant shipping out 100 loads per day, in a location near where many trucks were usually available, with 24-hour per day loading, may have used 5 or 6 core carriers. The same plant in a location far from a good source of trucks and able to load only on first shift might have needed twice that many carriers.

So customers began to ask the company to take over managing these core carrier programs. They saw the shipment visibility and powerful reporting capabilities of the system as key to their own supply chain visibility, and at the same time, immediate and much less expensive than developing the same capabilities in house. They wanted American Backhaulers to take all of their loads, dole them out to the appropriate core carriers, and then monitor them in its system.

4.1.1 Express Auto Tender

Orders came into the system via EDI for these customers, as they did for many other customers. Arriving orders were identified by the customer number, and the origin and destination cities were checked. Next, this combination of customer number, origin, and destination was checked against a customer rate table, which in addition to housing the rate charged the customer for the lane, also had a flag that indicated whether loads coming into the system were to go to the Auto-Tender process.

Next these loads were checked against the carrier cost table. In this carrier cost table were stored costs that a carrier charged a customer for a given lane. A ranking was

maintained within this file that was updated whenever a new cost was added or an old cost changed for a lane for a customer.

For example, for a lane from Chicago to Boston for Collegiate Clothing Corp, if one of the core carriers updated a cost from $1400 to $1450, the ranking for the costs for all of the core carriers in this lane was updated, based almost strictly on cost. The "almost" here referred to a system of penalty and reward that allowed for the addition of cost to carriers with poor service, or reduced cost to reward carriers for good service.

For each customer, for each loading facility, there was a cutoff time and number of days that served as a buffer. Loads arriving to the system within that buffer did not go into the auto-tender system, but were diverted to a group of people handling last minute shipments. If the cutoff for a facility were 2:00 p.m., one day in advance, any load arriving after 2 p.m. the day before the load was set to ship was sent to the problem area.

Next, the load was auto-tendered to the carrier. The carrier was offered the load via EDI, fax, email, or however the carrier's file so designated. The carrier then had a certain amount of time to respond. The first carrier to be offered the load had it for the longest time, spanning from the moment the order arrived into the system up to the point that the primary carrier's "option" expired.

At that point, if the carrier had not committed to the load, the load was taken back from that carrier and the rolling tender would begin. The rolling tender gave each carrier with active costs for the load a half hour to commit to the load. The load went first to the carrier with the second highest costs, and then to the next carrier and so on until there was no carrier left that would commit to the load. If none of the carriers with active costs committed to the load, the load was tendered to the backup carrier, which was usually the brokerage part of American Backhaulers at a higher cost.

The backup cost was negotiated to cover the load in any circumstance. The brokerage took the risk, at that cost, to move the load at whatever price was necessary, at a profit or a loss, with whatever carrier the brokerage could find on the spot market.

This system worked pretty well and effectively saved the customer a fair amount of money. Given the automated system and more efficient labor usage by spreading the costs of employees over several customers, the job was done at less cost and some of those savings were passed on to the customer. Also, many customers found that while their internal routing guides might provide low cost solutions to routing problems, their own employees tend to ignore the routing guides in favor of the last freight salesman who has arrived with pizza or hockey tickets.

Yet while there was clear proof that customers were saving money, there was no answer to their challenges to show that the service was providing an optimal or near-optimal solution.

The other issue that had not been handled was limited capacities. No carrier was willing to provide unlimited capacity to a customer, and carriers usually limited the capacities they provided to a customer to send trucks to a given destination. So a carrier might have been willing to provide 6 trucks to a customer on a given day, but no more than 3 trucks to go to any given destination city, state, or region. Often, there were also a minimum number of loads promised to a carrier, sometimes on an overall basis, sometimes on a given lane, and sometimes both.

4.1.2 The Problem

Begin by assuming that there is a set of the loads that need to be assigned, and a set of only the usable costs. These are the active costs for all of the carriers for all of the loads out of a given facility for a given day. The main software program will be responsible for selecting and exporting the loads that need to be assigned and the relevant carrier costs.

Given that there is at least one active cost by definition for each load, which is the brokerage's backup cost, with infinite capacity, there is a solution to the problem. The upper bound on the cost is obvious; it is the sum of the brokerage's backup cost for all of the loads.

For example, consider the case of the Collegiate Clothing in Chicago, IL.

On a particular day, March 1st, Collegiate needs to ship out 100 loads. The loads are destined for customers in Michigan, Ohio, and Indiana. 50 of the loads are headed to Wolverine Wear in Ann Arbor, Michigan, 30 to Buckeye Blazers in Columbus, Ohio, and 20 to Hoosier Headwear in Bloomington, Indiana.

From the costs table, the brokerage costs are $500 per truckload to Ann Arbor, $600 to Columbus, and $400 to Bloomington, IN. The upper bound on the costs to ship the 100 loads will therefore be:

50 loads x $500 per load + 30 loads x $600 per load + 20 loads x $400 per load = $51,000

Assume also the following, active costs from the other carriers that are servicing Collegiate Clothing:

Table 2 - Carrier Costs for Load Tendering Example

Carrier	Destination	Cost	Destination Minimum	Total Minimum	Destination Limit	Total Limit
Allways	Ann Arbor, MI	$425	1		7	
Allways	Columbus, OH	$550	1	5	6	12
Allways	Bloomington, IN	$375	1		4	
Bestway	Ann Arbor, MI	$450			9	
Bestway	Columbus, OH	$560			7	18
Bestway	Bloomington, IN	$350			5	
Creative	Ann Arbor, MI	$450			10	
Creative	Columbus, OH	$490		20	8	30
Creative	Bloomington, IN	$350			6	
Direct	Ann Arbor, MI	$430			8	12
Direct	Bloomington, IN	$370			6	
Everytime	Ann Arbor, MI	$490	3		6	
Everytime	Columbus, OH	$575	3		8	20
Everytime	Bloomington, IN	$350	3		5	

In the table above, the Destination Minimum is the promised minimum number of loads that Collegiate Clothing has contracted for with the carrier to the specified destination, while the Total Minimum is the total minimum number of loads promised to the carrier. The Destination Limit is the maximum number of loads the carrier will accept to that destination. The Total Limit is the maximum number of loads the carrier will accept from Collegiate Clothing's Chicago facility on a given day.

4.1.3 The Formulation

The objective function here will be to minimize the total cost, or to minimize the sum of the costs of each carrier to each destination multiplied by the number of loads given to each carrier for each destination.

The sets are:

    I   Set of carriers
    J   Set of destinations

The parameters are:

    L_j Number of loads going to destination (j)
    E_i Capacity limit for carrier (i)
    D_{ij} Capacity limit for carrier (i) going to destination (j)
    G_i Minimum guaranteed number of loads for carrier (i)

Q_{ij} Minimum guaranteed number of loads for carrier (i) going to destination (j) c_{ij} cost of each load assigned to carrier (i) for destination (j)

The decision variable will be:

x_{ij} number of loads assigned to carrier (i) for destination (j)

The formulation will be:

$$\text{Minimize} \quad \sum_{i \in I} \sum_{j \in J} c_{ij} \cdot x_{ij} \tag{1}$$

Subject to:

$$\sum_{i \in I} x_{ij} = L_j \quad j \in J \tag{2}$$

$$\sum_{j \in J} x_{ij} \leq E_i \quad i \in I \tag{3}$$

$$x_{ij} \leq D_{ij} \quad \forall i \in I, j \in J \tag{4}$$

$$\sum_{j \in J} x_{ij} \geq G_i \quad i \in I \tag{5}$$

$$x_{ij} \geq Q_{ij} \quad \forall i \in I, j \in J \tag{6}$$

$$x_{ij} \geq 0 \tag{7}$$

$$x_{ij} \in Z^+$$

Note that x_{ij} is constrained to be an integer since shipping partial loads is not allowed in this case.

4.1.4 What's Best Solution

Table 3 - Load Tender Solution

Loads Tendered			
Destination	Loads Required		Assigned
Ann Arbor, MI	50	=	50
Columbus, OH	30	=	30
Bloomington, IN	20	=	20

Minimum Guarantees and Maximum Capacities					
	Minimum		# for carrier		Maximum
Allways	5	<=	12	=<=	12
Bestway	0	<=	18	=<=	18
Creative	20	<=	24	<=	30
Direct	0	<=	12	=<=	12
Everytime	0	<=	19	<=	20
ABH	0	<=	15	<=	1000

Carrier	Destination	Cost	Destination Minimum		Number of Loads		Destination Limit	Cost
Allways	Ann Arbor, MI	$425	1	<=	7	=<=	7	$2,975
Allways	Columbus, OH	$550	1	<=	4	<=	6	$2,200
Allways	Bloomington, IN	$375	1	=<=	1	<=	4	$375
Bestway	Ann Arbor, MI	$450	0	<=	9	=<=	9	$4,050
Bestway	Columbus, OH	$560	0	<=	5	<=	7	$2,800
Bestway	Bloomington, IN	$350	0	<=	4	<=	5	$1,400
Creative	Ann Arbor, MI	$450	0	<=	10	=<=	10	$4,500
Creative	Columbus, OH	$490	0	<=	8	=<=	8	$3,920
Creative	Bloomington, IN	$350	0	<=	6	=<=	6	$2,100
Direct	Ann Arbor, MI	$430	0	<=	8	=<=	8	$3,440
Direct	Bloomington, IN	$370	0	<=	4	<=	6	$1,480
Everytime	Ann Arbor, MI	$490	3	<=	6	=<=	6	$2,940
Everytime	Columbus, OH	$575	3	<=	8	=<=	8	$4,600
Everytime	Bloomington, IN	$350	3	<=	5	=<=	5	$1,750
ABH	Ann Arbor, MI	$500	0	<=	10	<=	100	$5,000
ABH	Columbus, OH	$600	0	<=	5	<=	100	$3,000
ABH	Bloomington, IN	$400	0	=<=	0	<=	100	$0
								$46,530

Running this problem in What's Best yields the following results:

Notice that the broker, American Backhaulers (ABH) is the backup carrier, with its higher rates and capacities large enough to handle any or all of the loads.

So for this simple problem, using the Lindo solver, the cost was reduced from $51,000 to $46,530.

4.1.5 ILOG Solution

While the spreadsheet solution depicted in the preceding section is illustrative, a more robust tool is needed for a real-time application. **Appendix A** at the end of this document shows one solution to this problem as implemented in ILOG, the CPLEX solver software.

Notice that the ILOG solution yields the same result as the Lindo solution.

4.1.6 Real World Challenges

Unfortunately, solving the problem in this way depends on certain unrealistic conditions. First, there is the assumption that all loads are received at the same time. Often, the customer tenders loads into the system either in batches or in a steady stream. The batches may come in minutes or hours apart. Sometimes, the loads come in over many days, as the orders are generated in the customer's system.

The simple way to handle this complexity is to accumulate these loads over time, establish a cutoff date and time, and optimize the group of orders that have been placed as of that time.

The other problem is that while carriers would "commit" to a general level of overall capacity as well as destination specific capacities, the true daily capacities usually differed from the normal conditions.

The problems were also related in that the longer the wait to accumulate the greatest number of loads to optimize, the more likely that actual capacities would be at levels less than those "promised" by the carrier.

Here again, the simple way to handle this would be to simultaneously cutoff the inflow of loads and take a quick poll of remaining available capacity for each carrier. This second part would have to include both a poll of the amount of equipment left at the time, as well as the carrier's willingness to take loads to those destinations to which he will normally go. Often, the actions of another customer change a carrier's willingness to take loads to a given destination. Either another customer has suddenly tendered several abnormal loads to which the carrier has committed bound for the same destination, or the customer from which the carrier normally get reloads near that destination does not have the usual freight available. Finally, another customer may even have important loads that he needs picked up in a different area, so the carrier needs to get his trucks to that area rather than to the normally planned destination.

And even if it were possible to conduct a last minute poll of carrier capacities, by the time the tender actually takes place, both the set of loads and available capacities will likely change.

4.2 LTL Consolidation

LTL is a very profitable service for some freight brokers. Many customers ship not only full trailer loads but partial shipments as well. Not all freight brokers handle partial shipments or have enough volume to combine partials effectively, and even those who have the expertise and the volume rarely have systems tools to help the process of combining shipments.

CH Robinson has the ability to put several partials on a single truck and make even more money than in regular truckload business.

For example, assume that Collegiate Clothing only had a half of a trailer load, or 20 feet, to send to New York. Because of a history of regulated rates in the LTL business, a half truckload does not cost half as much, but rather about 75% of the normal truckload price. In this case, assume a rate of about $1000. Assume also another customer also has a half load, from its plant in Hammond, IN, going to Newark, NJ, with a rate of $900.

CH Robinson sells the load as a two-pick, two-delivery shipment to a carrier, paying him only an additional $25 for each extra stop, and essentially zero extra miles since the points are on the way. In this case, total revenue to CH Robinson is $1,900, while total cost is $1,090, so the margin is $810. While this case is extreme, it is not unusual.

In other cases, for smaller shipments of shippers with higher volumes, CH Robinson passes on higher discounts it receives because of its scale from common, full-service LTL carriers, keeping a few percentage points for itself. Here, it makes much less per load, but does almost no work.

4.2.1 LTL Common Carriers

LTL common carriers move the vast majority of the smaller shipments in North America. Their operations are significantly different from those of most truckload carriers. Most LTL carriers operate hub and spoke pickup and delivery systems in the major markets in which they operate, and link those hubs with linehaul capacity.

For example, an LTL carrier operating between the Chicago area and the East coast will typically have a terminal in Chicago and at least one in Philadelphia or New Jersey. If Collegiate Clothing were to use an LTL carrier to move two pallets of product from Chicago to Pennsauken, NJ, for example, the carrier would take the following steps:

First, a local truck, often with a short trailer to allow for easier maneuvering in a city, picks up the two pallets, along with many other customers' LTL shipments. He brings the freight back to the central warehouse where it is unloaded.

Next, the LTL carrier moves the freight on a linehaul truck to the East Coast warehouse, in Philadelphia for example. Some LTL operations ship a linehaul truck whenever there

is enough freight accumulated to build a load, and others have trucks leaving on regular schedules. When the freight arrives in Philadelphia, it is unloaded at the warehouse.

Finally, another local truck delivers the partial shipment to Pennsauken, NJ.

This method of consolidating freight is very efficient when implemented by some carriers for large volume customers. However, there are opportunities for brokers because of certain characteristics of this type of operation.

The freight is often handled many times. In the example, above, the two pallets were unloaded and reloaded twice, once at the Chicago warehouse and once in Philadelphia. They also moved on three trucks, the pickup, the linehaul, and the delivery. Each time the freight is handled, there is both the opportunity for damage to the product and the likelihood of delay.

In other cases, such as a partial moving from Pennsauken, NJ, to Los Angeles, the freight may be touched several more times, as there may be an intermediate cross dock in Chicago or Denver.

A freight broker, by contrast, is more likely to pick the freight up from a customer, bring it to a consolidation point and then sell it as part of a truckload to a carrier. In some cases, a broker will combine the partials from one or two of its customers' facilities, and then send a truck to load them and deliver them as part of multiple pick-up, multiple delivery load. This method can be faster, with less opportunity for damage, and is often less expensive.

4.2.2 Class Rates

Common LTL carriers are required to charge quotes, somewhat regulated rates for their services. These rates are quoted in tariffs, and are based on the type, or classification, of the freight, and the lane and distance it is traveling. Classifications describe both the relative density of the freight and its value. Light, more valuable products move at higher classifications than denser, lower value items. This rating system allows LTL carriers to charge appropriately based on how much of a trailer a partial shipment uses and to some degree the potential for damages. See Bowersox and Closs (1996) for a complete discussion of class rates.

A freight broker moving into providing transportation management services for a customer will first try to both save the customer money and earn a profit by combining partial shipments into truckloads. Sometimes the most efficient way to do this will be by building several truckloads, and sending some of the less desirable partials by common carrier. The broker may use the customer's LTL carrier or his own, if there is an LTL carrier with whom he has better rates or service.

4.2.3 LTL Consolidation in Express

American Backhaulers' Express system allowed for the combination of multiple orders into a single truckload. A broker could see all of the partials for a given date in a single grid, and sort them by origin or destination. The load merging process, however, was purely manual. A broker could select multiple partial shipments and merge them into a single load. The effort here is to suggest to the broker the right combination of partials.

This problem concerns how best to combine LTL shipments into truckloads when a freight broker governs the process. The broker, acting on behalf of his customer, the shipper, attempts to lower the total combined cost of the LTL partials from the cost a regular, common LTL carrier charges. He can reduce the cost by building some or all of the partial shipments into full truckloads, which can be cheaper than LTL shipments.

Differences from Other, Standard Transportation LTL Optimization Problems

The broker managed LTL consolidation is different from other LTL consolidation problems for several reasons. Unlike a situation in which a carrier performs this function, the broker is not committed to the use of his own assets to move either the partial shipments or consolidated truckloads. This means that he is responsible for neither the efficient use of the equipment that most carriers must watch, nor the final position of each truck and subsequent reload requirements.

Some classical transportation problems, such as the traveling salesman problem, require us to consider the return of the vehicle once it has delivered. In this case, we can ignore that factor.

Another difference is that the broker will achieve the best results by considering the actual costs of each lane. Many transportation problem solutions rely on the substitute use of time or distance as a proxy for cost. In this case, since the transportation broker has a good feel for the cost of different lanes, he should base his solution on that information. For example, he should use the knowledge that the cost of sending a truck from Chicago with two partials, one to Detroit and one to Toledo, will cost $1.65 per mile if Detroit is the final stop and $1.60 per mile if Toledo is the final, even though the distance is about the same either way.

4.2.4 The Problem

In this problem, there is also no assumption of uniform demand, shipment size, or product. Some products, such as carbon black and paper, cannot be shipped in the same truck.

The object is to minimize the total combined cost of the shipments.

This problem considers only palletized freight, with a single pallet being the smallest unit. Some freight can have other freight loaded on top of it. Such freight is said to be OK for bottom loading. Some freight can be loaded atop other freight. Such freight is said to be OK for top loading. Some freight must be loaded on the bottom level with nothing loaded on top of it. For this thesis, only two levels of pallets will be considered.

The problem thus concerns two levels of 24 pallet spaces, or 2 rows of 12 pallets.

The output must therefore describe exactly which spaces are loaded with which freight. For the purpose of this paper, the positions will be described as:

Lower level:

1D	3D	5D	7D	9D	11D	13D	15D	17D	19D	21D	23D
2D	4D	6D	8D	10D	12D	14D	16D	18D	20D	22D	24D

Upper Level:

1U	3U	5U	7U	9U	11U	13U	15U	17U	19U	21U	23U
2U	4U	6U	8U	10U	12U	14U	16U	18U	20U	22U	24U

The pallet positions are labeled as such to allow the problem to be changed to accommodate longer or shorter trailer lengths.

4.2.5 Generating Valid Pairings

For this problem, the pre-optimization process will be very important and rather complicated. The following rules must be considered in generating valid routes.

1. No more than six partials will be allowed in one pairing. For a broker, it is difficult to entice a carrier to accept a load with many stops. Six deliveries is the maximum reasonable number of stops to consider.

2. The total maximum weight of each truckload will be 46,500 pounds. Therefore any set of loads with a total weight of more than 46,500 can be eliminated.

3. The total floor space limit will be 24 pallets. Any set of loads with a total combined pallet count greater than 48 can be eliminated. Also, any combination of loads with more than 24 pallets, where more than 24 pallets have Can Bottom Load = False and the number of pallets in excess of 24 have Can Top Load = False can be eliminated.

4. Any set of partials that generates a total route distance of more than 3,000 miles should be eliminated. This number is set somewhat arbitrarily based on load

combinations that a carrier might accept originating in Chicago. The smaller this number can be, the smaller the set of valid pairings and the easier the problem is to solve. Setting this number depends on the origin of the freight. Loads coming from Boston headed all over the North America might well reach over 3,000 miles, whereas a reasonable limit for a company shipping from Chicago to only points in the Midwest might be closer to 1,000 miles.

5. There are rules governing the distribution of weight throughout the trailer.

6. Some products cannot be loaded in the same trailer as some other products. A table cross-referencing incompatible products will be used to eliminate any set of partial loads with incompatible products.

7. Valid pairings must account for delivery appointments and or windows. After all of the above steps have been completed, this step will handle the delivery scheduling issues.

   a. The distance from the origin to each of the deliveries in the set is calculated.
   b. Using a speed of 50 miles per hour and a maximum of 600 miles per day, and assuming that the truck departs the origin at 17:00 on the ship date, determine whether delivery is possible within the window as scheduled for the closest stop to the origin.
   c. If the delivery is not possible, eliminate this set.
   d. Otherwise, proceed to the closest stop from the previously checked in the same manner. If a subsequent delivery is impossible, retrace one step, test the impossible delivery before the previous delivery, and if this new formation is possible, then recheck the stop that was just realigned. If this is still impossible, discard this set of loads.
   e. If the last delivery is reached within its window, then this aspect of the set is valid.

Other Issues:

- Some products can be bottom loaded, some top loaded, some either, and some neither. This problem ignores the actual vertical dimensions of the freight, assuming that these will be accounted for in the determination of the loading characteristics. In other words, any pallet that can be either top or bottom loaded must be no taller than 48".
- The total cost of the solution must be no higher than the cost of shipping each of the partials via common carrier.

- While there may be some fixed cost involved in the handling of each truck, this paper ignores the number of trucks being loaded, and the availability of trucks at the costs indicated is considered limitless.
- Once all of the invalid pairings have been eliminated, an additional pairing for each load will be added that represents the scenario under which that partial would move by common LTL carrier. This will be a single load pairing, and represents the worst-case scenario. The addition of these pairings will guarantee a feasible solution to the problem.

Shipment Data

Table 4 - LTL Shipment Data

Shipments	Description	Example
Shipment ID	Identifier from main system.	1,400,521
Commodity Code	Identifier from main system.	RAG8100
Commodity Name	Commodity name	Ragu 8oz can
Freight Class	National Motor Carrier Freight Classification	55
Loaded Pallet Weight	Weight per pallet of product and pallet	1,250#
Loaded Pallet Height	Height of pallet plus product	40"
Expected Shipment Weight	Expected weight of all pallets on this shipment	7,500#
Expected Pallet Positions	Total number of pallet positions used	5
Can Top Load Flag	Whether freight can be loaded atop other freight	Y/N
Can Bottom Load Flag	Whether freight can be loaded underneath other freight	Y/N
Temperature Control Flag	Whether freight must be kept within specified temp range	Y/N
Minimum Temperature	Freight must be kept at at least this temperature	35
Maximum Temperature	Freight must be kept at this temperature or below	20
Common Carrier Cost	Cost of shipping this freight by LTL common carrier	$450
Origin Facility Name	Name of shipper	CS Tomato Products
Origin City	City of shipper	Chicago
Origin State	State of shipper	IL
Origin Latitude	Shipper Latitude	41° 59' N
Origin Longitude	Shipper Longitude	87° 54' W
Destination Facility Name	Name of consignee	ABC Markets
Destination City	City of consignee	Detroit
Destination State	State of Consignee	MI
Destination Latitude	Consignee Latitude	42° 25' N
Destination Longitude	Consignee Longitude	83° 1' W
Delivery Available Date	Do not deliver before this date	5/5/2003
Delivery Available Time	Do not deliver before this time	13:00
Deliver By Date	Must deliver by this date	5/5/2003
Deliver By Time	Must deliver by this time	13:00

Freight Rates

Table 5 - Freight Rates from Chicago to All States

To	Cost per M	Minimum	To	Cost per M	Minimum
AL	1.25		NC	1.25	
AR	1.30		ND	1.55	
AZ	1.30		NE	1.45	
CA	1.15		NH	1.65	
CO	1.55		NJ	1.65	
CT	1.65		NM	1.45	
DE	1.65		NV	1.30	
FL	1.55		NY	1.65	
GA	1.25		OH	1.55	
IA	1.50	400.00	OK	1.35	
ID	1.40		OR	1.25	
IL	1.60	350.00	PA	1.60	
IN	1.55	350.00	RI	1.65	
KS	1.45		SC	1.25	
KY	1.40		SD	1.45	
LA	1.30		TN	1.30	
MA	1.65		TX	1.30	
MD	1.65		UT	1.30	
ME	1.65		VA	1.50	
MI	1.65	375.00	VT	1.65	
MN	1.50		WA	1.25	
MO	1.50	400.00	WI	1.55	300.00
MS	1.30		WV	1.65	
MT	1.45		WY	1.50	

4.2.6 Calculating the Costs of the Pairings

The cost of a pairing in this problem is calculated as follows:

The total trip distance is first calculated. This can be handled either through a call to an external distance calculation program, such as PC*Miler, or through the calculation suggested by Bramel and Simchi-Levi (1997).

The distance D_{ab} between two points, a and b, is:

$$D_{ab} = 69\sqrt{(lon_a - lon_b)^2 + (lat_a - lat_b)^2} ,$$

which is then multiplied by a "circuity" factor of 1.3 to account for distance out of the straight line.

The distance is then multiplied by the freight rate from the origin to the final destination of the pairing.

Finally, stop-off charges are added at $30 per intermediate stop if the number of those stops is 1 or 2, and $50 per stop if the number of intermediate stops is greater than 2. This two-tier structure is necessary because it is significantly more difficult for a broker to sell a load with more than three deliveries.

4.2.7 The Formulation

Notation:

L   =   the set of all loads to be covered
R   =   the set of all possible routes
c_j =   the cost of route $j \in R$
x_j =   1 if route $j \in R$ is selected, 0 otherwise
δ_i^j =   1 if load i is part of route $j \in R$

$$\text{Min} \sum_{j \in P} c_j x_j \qquad (1)$$

Subject to:

$$\sum_{j \in P} x_j \delta_i^j = 1 \quad \forall \ i \in L \qquad (2)$$

$$x_j \in \{0,1\} \quad \forall \ j \in R$$

4.2.9 Real World Challenges

In this situation, as in the others presented in this paper, the most difficult implementation problem is the rapidly changing picture. In order to optimize the combination of this set of partials, it is of course necessary to freeze time, to prevent new orders from entering the mix or existing orders from disappearing. In practice, however, orders arrive, change, and cancel constantly. Even in the best possible scenario, with a completely automated process to select the partials to be combined and then send them to the pre-optimization, pairings building process, then combine them, and return the

combinations to the operating system, some time will elapse. During that time, changes may render the solution less useful.

Proposed Extensions

An extension of this work that may add value to the process would be to create a method for understanding the extent to which the original group of partials must change before it is worthwhile to discard the solution and re-optimize, and then to attempt to create a process for re-optimizing based on some of the optimization that had already taken place.

Another extension would be to allow for the combination of non-palletized partials, and to allow for a variable number of layers of freight rather than the two layers stipulated above. These steps would involve work on the pre-optimization process rather than the optimization process itself.

4.3 Matching Trucks and Loads

The most basic function of a freight brokerage business is to find available trucks to transport its customer's loads. Loads, or orders, are accumulated over a period of time leading up to the day on which the loads must ship. Some orders arrive weeks in advance, others a day ahead, and often up to a third on the same day on which they are required to ship. Available trucks are typically posted to the system the day before or the day they will be empty and ready for reloading. These trucks are not dedicated to the use of the freight brokerage; the carrier's own dispatch as well as other freight brokers is concurrently searching for freight for the trucks.

Carriers offer their trucks to freight brokers usually to fill empty, or deadhead, trips, either back to the carrier's loading point or onward to another point at which the carrier can find freight for the trucks. The carrier will usually inform the broker as to the expected empty date, time, and location of the truck, its desired destination or destinations, the trailer size and type, and any pertinent information such as the existence of empty pallets or other packaging materials in the trailer.

The broker also maintains the following pertinent information on its customers' orders: date, time, and location of pickup and delivery requirements, and trailer size and type requirements.

Trailer requirements include the following information:

- Type of trailer, which will typically be van (normal trailer), reefer (refrigerated trailer), or flat bed. Some products can be shipped on any of these trailer types. Others, such as produce, can only be shipped in reefers. Products such as empty plastic bottles require the largest available vans, since reefer trailers have thicker walls and therefore provide less interior room.
- Length. This will typically be either 48' or 53' if the entire trailer will be used, but can be anything from 4' to 53' if a partial shipment will be shipped as a full. In Texas, 57' trailers are also legal as of 2003.
- Width. Always either 96" or 102"
- Height. This will usually range from 96" to 110"

Traditionally, brokers match their customers' loads with their carriers' trucks one at a time. As the broker's employees take orders from their customers, the employees search for trucks scheduled to be empty near the load's origin wanting to head to a destination near the load's destination. For the smaller broker, who may only move 15-30 loads per day, this method is probably the best. However, for the broker handling 1,000 to 10,000 loads per day, with truck postings in the 10,000 to 15,000 truck range at any given time, a Mixed Integer Linear Program should provide a better or lower cost solution.

4.3.1 Load Matching in Express

Matching trucks with loads was a key goal of the Express system. An automated process used radial searches to locate all of the potential trucks that might be willing to handle a load, as well as suggesting matching loads that would be suitable for a truck in need of freight. Brokers used the results of these processes to conduct their business. The process worked as follows:

Every truck entered into the system was required to have an origin as well as a desired destination. The origin and destination longitude and latitude were stored in the system. Each carrier's file in the system also had acceptable origin and destination deadhead allowance fields, which were defaulted to 200 miles, but editable to reflect the carrier's preferences.

Each load in the system also had an origin and destination, and thus the corresponding longitudes and latitudes. For speed, a "square" search was done first, whereby the system queried the loads table and returned all loads with origins within a certain fraction of a degree of longitude and a certain fraction of a degree of latitude in either direction of the truck, and with certain trailer requirements, empty times, and delivery capabilities. Then, a secondary actual distance lookup reduced the set to those trucks actually within the specified radii.

These tools represented the state of the art in the freight brokerage business. There was some ability to manually combine partial loads into combined loads, but there was no automation or optimization involved. While the system certainly offered strategic advantage to American Backhaulers, fueling its annual 40% annual growth rate during the 90's, and eventually to Robinson as well, Express also stopped short of the use of optimization in load matching, LTL consolidation, and load tendering.

4.3.2 The Data

The following two tables contain the data elements required to create the pairings that should be considered viable pairings for the optimization problem.

Loads Data

Table 6 - Shipment Data for Load Matching

Shipments	Description	Example
Shipment ID	Identifier from main system.	1,400,521
Expected Shipment Weight	Expected weight of all pallets on this shipment	7,500#
Trailer Type	String of allowable trailer types (eg V, R, VR, F, VF, etc)	VRF
Trailer Length	Minimum length of trailer required (in feet)	48
Trailer Width	Minimum width of trailer required (in inches)	102
Trailer Height	Minimum height of trailer required (in inches)	108
Temperature Control Flag	Whether freight must be kept within specified temp range	Y/N
Origin City	City of shipper	Chicago
Origin State	State of shipper	IL
Origin Latitude	Shipper Latitude	41° 59' N
Origin Longitude	Shipper Longitude	87° 54' W
Ship Date	Date load must be shipped	5/2/2003
Shipping Cutoff Time	Time by which driver must arrive at shipper	16:00
Destination City	City of consignee	Detroit
Destination State	State of Consignee	MI
Destination Latitude	Consignee Latitude	42° 25' N
Destination Longitude	Consignee Longitude	83° 1' W
Deliver By Date	Must deliver by this date	5/5/2003

Trucks Data

Table 7 - Trucks Data for Load Matching

Trucks	Description	Example
Truck ID	Identifier from main system.	1,536,478
Carrier ID	Carrier's identification code from the main system.	JBHUNT
Maximum Shipment Weight	Maximum weight this trailer can haul.	46,500
Trailer Type	Trailer type	R
Trailer Length	Trailer length (in feet)	48
Trailer Width	Trailer width (in inches)	102
Trailer Height	Trailer height (in inches)	108
Origin City	City of shipper	Chicago
Origin State	State of shipper	IL
Origin Latitude	Shipper Latitude	41° 59' N
Origin Longitude	Shipper Longitude	87° 54' W
Empty Date	Date trailer should be empty	5/3/2003
Empty Time	Time trailer should be empty	14:30
Destination City	City of consignee	Detroit
Destination State	State of Consignee	MI
Destination Latitude	Consignee Latitude	42° 25' N
Destination Longitude	Consignee Longitude	83° 1' W

Carrier Costs Data

Carrier cost data can be slightly more complicated to obtain than the other data. The simple method for accumulating the data is to ask for state to state rate matrices from the carriers. The problem with this method is that carriers approach this type of request as a quoting process, and will tend to quote as if they are attempting to compete for new business rather than load trucks on their backhauls. An alternative means of accumulating this data is to build historical tables of average prices that have actually been paid to carriers. A further difficulty comes from seasonal pricing issues. When produce runs from the South, for example, carriers are paid significantly more than they are paid the rest of the year for their trucks emptying in the produce growing area.

The recommended approach would be to begin with quoted rates from each state to each state, allowing for different rates to apply to different periods of the year. These rates could then be altered when historical records differ significantly.

Table 8 - Carrier Costs Data for Load Matching

Carrier ID	Description	Example
Carrier ID	Carrier's identification code from the main system.	OUTB
Origin State	Origin State	IL
Destination State	Destination State	IN
Cost per Mile	Cost per mile, quoted first, but updated if necessary	$ 1.50
Flat Minimum	Flat minimum rate, quoted at first, but updated if necessary	300
Quoted Cost per Mile	Cost per mile as quoted at first. Not updated	$ 1.45
Quoted Flat Minimum	Flat minimum rate as quoted at first. Not updated	300
Effective Date	Month and Day on which this rate takes effect	1-Mar
End Date	Month and Day on which this rate stops	1-Jun

4.3.3 Generating Valid Pairings

With millions of pairings possible if load requirements were ignored, discarding any pairings that would be impossible is the first step in solving this problem. Prior to the pairings being sent to the optimization process itself a pre-optimization process will select valid pairings.

Invalid pairings would include:

- Pairings with trucks due to be empty after the loads required shipping time and date.
- Pairings between a load and a truck with inconsistent equipment. An example of such a pairing would be a van truck on a load requiring a reefer or a flatbed.

- Pairings in which the load origin and the empty location of the truck are too far away. It is important to avoid being overly constrictive here, as trucks will sometimes deadhead from the bottom of Florida up to the middle of Georgia to find a load going to California when produce is not running in Florida. One way to implement this restriction in a helpful but not overly restrictive way is to set the top distance to either 1200 miles, which would preclude attempting to match a truck in Los Angeles with a load in Chicago. Another way is to set the origin deadhead distance limit to the same numbers as the loaded miles. While this may exclude one or two possible combinations in every 100,000, this limit may be more helpful.
- Pairings in which the empty time and location of a truck preclude its ability to arrive at the shipper by the shipping cutoff time, given an average deadhead travel time of 50 miles per hour, and a minimum of two hours from empty time to shipping cutoff time.

In addition to the valid pairings that result from this process, an additional, phantom pairing should be created for each load. This should be an expensive, non-existent truck that represents the ability of the broker to buy and outbound truck from some carrier at a very high price. Typically, this price should be about $3.00 per mile, with a $600 minimum.

The purpose of these phantom pairings, which should have the following data form, is to guarantee a feasible solution to the problem, as well as an upper bound on the total cost.

Table 9 - Phantom Pairings for Load Matching

Trucks	Description	Example
Truck ID	Identifier from main system.	1,536,478
Carrier ID	Carrier's identification code from the main system.	OUTB
Maximum Shipment Weight	Maximum weight this trailer can haul.	50,000
Trailer Type	Trailer type	VRF
Trailer Length	Trailer length (in feet)	53
Trailer Width	Trailer width (in inches)	102
Trailer Height	Trailer height (in inches)	110
Origin City	For the phantom, this should be the load origin city	Chicago
Origin State	For the phantom, this should be the load origin state	IL
Origin Latitude	Shipper Latitude	41° 59' N
Origin Longitude	Shipper Longitude	87° 54' W
Empty Date	For the phantom, this should be the load shipping date	5/3/2003
Empty Time	For the phantom, this should be 2 hours before the cutoff	12:30
Destination City	For the phantom, this should be the load destination city	Detroit
Destination State	For the phantom, this should be the load destination state	MI
Destination Latitude	Consignee Latitude	42° 25' N
Destination Longitude	Consignee Longitude	83° 1' W

4.3.4 Calculating the Costs of Pairings

In order to calculate the costs for the pairings, this solution suggests using the carrier's cost per mile or flat minimum, based on the total distance from the expected empty location of the truck to the load origin to the load destination to the truck's desired destination.

Again, the trip distance and the deadheads can be calculated as in section 4.2.6 above.

4.3.5 The Formulation

Notation:

L	=	the set of all loads to be covered
T	=	the set of all trucks to be covered
P	=	the set of all possible pairings
c_j	=	the cost of pairing $j \in P$
x_j	=	1 if pairing $j \in P$ is selected, 0 otherwise
δ_i^j	=	1 if load i is part of pairing $j \in P$
γ_k^j	=	1 if truck k is part of pairing $j \in P$

$$\text{Min} \sum_{j \in P} c_j x_j \qquad (1)$$

Subject to:

$$\sum_{j \in P} x_j \delta_i^j = 1 \quad \forall \ i \in L \qquad (2)$$

$$\sum_{j \in P} x_j \gamma_k^j \leq 1 \quad \forall \ k \in T, j \in P \qquad (3)$$

$$x_j \in \{0,1\} \quad \forall \ j \in P$$

Constraint (2) ensures that each load is part of one and only one selected pairing, and constraint (3) ensures that each truck is used at most once in the set of selected pairings.

4.3.7 Real World Challenges

As with the other problems addressed in this paper, one significant problem here is the need to freeze time while the optimal matching process takes place. While it is possible to take a snapshot of all of the loads to be covered and the available trucks and generate a very good set of matches, both the set of loads and the set of trucks will have changed by the time the procedure has finished.

Furthermore, to implement this process in the real world, most brokers would likely need to change their organizations and operating processes.

For example, at American Backhaulers, the brokers responsible for matching the loads and the trucks were compensated largely with commissions. Commissions were based on an internal market mechanism that created incentives for the brokers to cover the same freight consistently and sell it to carriers with whom they had relationships for the least possible cost while maintaining good service. A mathematical optimization program would render that system largely obsolete, or at the least, force major changes to it.

Also, some loads are considered more desirable than others. The desirable loads, or easy loads, are covered quickly, while the less desirable loads require much more work, and frequently, a sort of horse-trading with carriers. Carriers are given some of the more desirable loads in exchange for accepting some of the less desirable loads. The need to cover these less desirable loads is critical, and might not be met by the optimization process as described above.

Additionally, some of these more difficult loads are moved by increasing the price offered to carriers until a carrier accepts them.

4.3.8 Proposed Extensions

Modifying the optimization process to promote horse-trading might improve the solution. This could be done by first rating the loads in the main operating system. A scale from 1 to 5 might be sufficient, with "1"s being the easiest or most desirable loads, and "5"s being the most difficult. Then, the optimization process might be changed to promote a solution in which loads that are "1"s be offered to carriers that have also been offered loads that are "5"s. While a solution with this type of constraint may be more expensive than the solution described above, it may be more practical and still less expensive than the non-optimized solution currently in place.

Another extension might be to return, along with the result set, shadow prices for each suggested booking. These would be an indication of how much higher than the standard cost within the system the broker might offer the carrier to handle the load before it would make sense to offer it to another carrier.

A final extension would involve allowing for the consideration of more than one desired destination for each truck. Often, a carrier would be happy with a truck going to one of several destinations, such as the home base, the location of a good customer, or any place that the carrier may have a planned load to pick up.

The solution above accommodates only a single destination. A better solution would be able to incorporate any number of potential desirable destinations for a single truck or for all of the trucks posted by a carrier.

5 Conclusion

With few exceptions, the freight brokerage industry has ignored the use of optimization tools. This thesis presents three tools that can help brokers deliver better service to their customers and compete with other types of logistics service providers for the right to control their customers' freight.

The tools suggested in the paper are fairly easily implemented, if the broker has a good load management and operations software system. As pointed out throughout, the difficulties arise in the fleeting nature of using optimization tools in a rapidly changing operational environment.

In practice, an argument can be made that much of the fleeting nature of the scenario is a result of the broker's reactive rather than analytical approach to the problems. In the load tendering and LTL consolidation situations, a customer reaping the benefit of an optimized solution might exert more effort to communicate orders to the service provider in ample time to execute the proposed solutions. The customer may even have a better understanding of the cost of changing orders when optimizations have already been run.

In terms of the third solution proposed in this thesis, matching trucks with loads, much of the current industry approach has been a result of its inability to implement an optimal solution. With the tool suggested, the broker would be well served to consider the operational changes required to make the solution work. However, even without these operational changes, this tool would benefit a broker in providing a snapshot optimization to be used as an indication of the best loads to offer to each carrier. While this recommendation would be short-lived, valid for maybe thirty minutes, it would likely result in many good matches and increased profitability, and could be repeated as necessary.

Bibliography

1. Donald J. Bowersox and David J. Closs, *Logistical Management – The Integrated Supply Chain Process*, New York: McGraw-Hill, Inc., 1996
2. Sunil Chopra and Peter Meindl, *Supply Chain Management – Strategy, Planning, and Operation*, Upper Saddle River, NJ: Prentice-Hall, Inc., 2001
3. Julien Bramel and David Simchi-Levi, *The Logic of Logistics*, New York: Springer-Verlag, 1997
4. Jeremy Shapiro, *Modeling the Supply Chain,* Pacific Grove, CA: Duxbury, 2001
5. Wallace Hopp and Mark Spearman, *Factory Physics*, New York: McGraw-Hill/Irwin, 2000
6. Carlos F. Daganzo, *Logistics Systems Analysis,* Springer-Verlag, Heidelberg, Germany, 1999

Appendix A - Load Tender Implementation with CPLEX

Model:

```
enum Carriers ...;
enum Destinations ...;

int+ DestinationLoads[Destinations] = ...; //number of loads to each destination
int+ DestinationCapacity[Carriers,Destinations] = ...; //capacity of each carrier to each
destination
int+ CarrierCapacity[Carriers] = ...; //capacity of each carrier
int+ DestinationMinimum[Carriers,Destinations] = ...; //min loads to each carrier for
each destination
int+ CarrierMinimum[Carriers] = ...; //minimum loads to a carrier
float+ Costs[Carriers,Destinations] = ...;

var float+ loads[Carriers,Destinations]; //array of how many loads assigned to each
carrier for each destination

minimize
   sum(c in Carriers, d in Destinations) Costs[c,d]*loads[c,d]

subject to {
 forall(c in Carriers, d in Destinations)
    sum(c in Carriers) loads[c,d] = DestinationLoads[d];

 forall(c in Carriers, d in Destinations)
    sum(d in Destinations) loads[c,d] <= CarrierCapacity[c];

 forall(c in Carriers)
    sum(c in Carriers, d in Destinations) loads[c,d] >= CarrierMinimum[c];

 forall(c in Carriers, d in Destinations)
    loads[c,d] <= DestinationCapacity[c,d];

 forall(c in Carriers, d in Destinations)
    loads[c,d] >= DestinationMinimum[c,d];

};
```

Data:

Carriers = {Allways, Bestway, Creative, Direct, Everytime, ABH};
Destinations = {AnnArbor, Columbus, Bloomington};

DestinationLoads = [50, 30, 20];
CarrierCapacity = [12, 18, 30, 12, 20, 1000];
CarrierMinimum = [5, 0, 20, 0, 0, 0];

Costs = [
    [425 550 375]
    [450 560 350]
    [450 490 350]
    [430 999 370]
    [490 575 350]
    [500 600 400]
];

DestinationCapacity = [
    [7 6 4]
    [9 7 5]
    [10 8 6]
    [8 0 6]
    [6 8 5]
    [200 200 200]
];

DestinationMinimum = [
    [1 1 1]
    [0 0 0]
    [0 0 0]
    [0 0 0]
    [3 3 3]
    [0 0 0]
];

Solution

Optimal Solution with Objective Value: 46530.0000
loads[Allways,AnnArbor] = 7.0000
loads[Allways,Columbus] = 4.0000
loads[Allways,Bloomington] = 1.0000
loads[Bestway,AnnArbor] = 9.0000
loads[Bestway,Columbus] = 5.0000
loads[Bestway,Bloomington] = 4.0000
loads[Creative,AnnArbor] = 10.0000
loads[Creative,Columbus] = 8.0000
loads[Creative,Bloomington] = 6.0000
loads[Direct,AnnArbor] = 8.0000
loads[Direct,Columbus] = 0.0000
loads[Direct,Bloomington] = 4.0000
loads[Everytime,AnnArbor] = 6.0000
loads[Everytime,Columbus] = 8.0000
loads[Everytime,Bloomington] = 5.0000
loads[ABH,AnnArbor] = 10.0000
loads[ABH,Columbus] = 5.0000
loads[ABH,Bloomington] = 0.0000

Appendix B - Warehouse Location with CPLEX

Warehouse Location

Warehouse location is another typical integer-programming problem. Consider a company that is considering a number of locations for building warehouses to supply its existing stores. Each possible warehouse has a fixed maintenance cost and a maximum capacity specifying how many stores it can support. In addition, each store can be supplied by only one warehouse and the supply cost to the store differs according to the warehouse selected. The application consists of choosing which warehouses to build and which of them should supply the various stores in order to minimize the total cost, i.e., the sum of the fixed and supply costs. The instance used in this section considers five warehouses and 10 stores. The fixed costs for the warehouses are all identical and equal to 30. Table 13.3 depicts the transportation costs and the capacity constraints. The key idea in representing a warehouse-location problem as an integer program consists of using a 0-1 variable for each (warehouse, store) pair to represent whether a warehouse supplies a store. In addition, the model also associates a variable with each warehouse to indicate whether the warehouse is selected. Once these variables are declared, the constraints state that each store must be supplied by a warehouse, that each store can be supplied by only an open warehouse, and that each warehouse cannot deliver more stores than its allowed capacity. The most delicate aspect of the modeling is expressing that a warehouse can supply a store only when it is open. These constraints can be expressed by inequalities of the form

```
supply[w,s] <= open[w]
```

which ensures that when warehouse w is not open, it does not supply store s. This follows from the fact that open[w] = 0 implies supply[w,s] = 0. In fact, these constraints can be combined with the capacity constraints to obtain

```
forall(w in Warehouses, s in Stores)
    sum(s in Stores) supply[s,w] <= capacity[w]*open[w];
```

This formulation implies that a closed warehouse has no capacity.

Table 13.3 - Instance Data for the Warehouse-Location Problem

	Bonn	Bordeaux	London	Paris	Rome
capacity	1	4	2	1	3
store1	20	24	11	25	30
store2	28	27	82	83	74
store3	74	97	71	96	70
store4	2	55	73	69	61
store5	46	96	59	83	4
store6	42	22	29	67	59
store7	1	5	73	59	56
store8	10	73	13	43	96
store9	93	35	63	85	46

store10	47	65	55	71	95

Statement 13.11 describes an integer program for the warehouse-location problem, and Statement 13.12 depicts some instance data.

```
range Boolean 0..1;
int fixed = ...;
enum Warehouses ...;
int nbStores = ...;
range Stores 0..nbStores-1;
int capacity[Warehouses] = ...;
int supplyCost[Stores,Warehouses] = ...;

var Boolean open[Warehouses];
var Boolean supply[Stores,Warehouses];

minimize
  sum(w in Warehouses) fixed * open[w] +
  sum(w in Warehouses, s in Stores) supplyCost[s,w] * supply[s,w]
subject to {
  forall(s in Stores)
    sum(w in Warehouses) supply[s,w] = 1;
  forall(w in Warehouses, s in Stores)
    sum(s in Stores) supply[s,w] <= capacity[w]*open[w];
};

display open;
{Stores} storesof[w in Warehouses] = { s | s in Stores : supply[s,w] };
display storesof;
```

Statement 13.11 - A Warehouse-Location Model (warehouse.mod).

```
fixed = 30;
nbStores = 10;
Warehouses = {Bonn Bordeaux London Paris Rome };
capacity = [1,4,2,1,3];
supplyCost = [
  [20 24 11 25 30]
  [28 27 82 83 74]
  [74 97 71 96 70]
  [ 2 55 73 69 61]
  [46 96 59 83 4]
  [42 22 29 67 59]
  [ 1 5 73 59 56]
  [10 73 13 43 96]
  [93 35 63 85 46]
  [47 65 55 71 95]];
```

Statement 13.12 - Data for the Warehouse-Location Model (warehouse.dat).
The statement declares the warehouses and the stores, the fixed cost of the warehouses, and the supply cost of a store for each warehouse. The problem variables

```
var Boolean supply[Stores, Warehouses]
```

represent which warehouses supply the stores, i.e., supply[s,w] is 1 if warehouse w supplies store s and zero otherwise.

The objective function

```
minimize
  sum(w in Warehouses) fixedCost * open[w] +
  sum(w in Warehouses, s in Stores) supplyCost[s,w] * supply[s,w]
```

expresses the goal that the model minimizes the fixed cost of the selected warehouses and the supply costs of the stores.

The constraint

```
forall(s in Stores)
  sum(w in Warehouses) supply[s,w] = 1
```

states that a store must be supplied by exactly one warehouse. The constraint

```
forall(w in Warehouses)
  sum(s in Stores) supply[s,w] <= capacity[w]*open[w];
```

expresses the capacity constraints for the warehouses and makes sure that a warehouse supplies a store only if the warehouse is open.

For the instance data depicted in Statement 13.12, OPL returns the optimal solution

Optimal Solution with Objective Value: 383

```
open[Bonn] = 1
open[Bordeaux] = 1
open[London] = 1
open[Paris] = 0
open[Rome] = 1
storesof[Bonn] = { 3 }
storesof[Bordeaux] = { 8, 6, 5, 1 }
storesof[London] = { 9, 7 }
storesof[Paris] = { }
storesof[Rome] = { 4, 2, 0 }
```