Designing business logistics networks using model-based reasoning and heuristic-based searching

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Abstract

This article describes an intelligent system called LogNet that provides advice on how to design business logistics networks. It implements its capabilities by utilizing model-based reasoning techniques. In addition, it utilizes heuristic-based searching to guide an end-user toward more effective network designs.

The network design problem studied in this article addresses the warehouse facility location problem: how many warehouses are needed in a network and to which customer markets should they be assigned? LogNet enables end-users to incrementally create and test a logistics network design by using a graphical user interface. LogNet employs model-based reasoning procedures that analyze the structure of the current network design in order to offer recommendations on how to consolidate or decentralize a network. The overall goal of LogNet is to provide a flexible user interface that is capable of supporting this design task.

Keywords: Model-based reasoning; Heuristics; Business logistics networks; Graphical user interface; Intelligent systems

1. Introduction

LogNet is an intelligent system that provides interactive advice to end-users on how to design cost-effective logistics networks. It implements its capabilities by utilizing a class of AI techniques known as model-based reasoning. These techniques solve problems by analyzing the structure and function of a system, as described by a symbolic model (Kunz, 1987). Unlike rule-based expert systems, which reason from 'canned' rule-based associations (IF-THEN rules), systems employing model-based reasoning contain a model simulating the structure and function of a system. In LogNet, we model business logistics networks and reason about their structure in order to offer end-users advice on how to design these networks more effectively.

Much of the previous research in model-based reasoning has focused on fault diagnosis of physical devices, such as the research work of Davis (1984) and Davis and Hamscher (1988) in which they looked at troubleshooting simple electronic circuits. The goal of their research was to generate the candidate components of a simple electronic circuit, which could plausibly be responsible for an observed malfunctioning of the device. To accomplish this, they constructed a model of the device (i.e. a schematic of how the components were interconnected to one another). They then reasoned from this schematic to determine if there was a component that could be responsible for the inconsistent state of the device. Using the schematic, they asked: Is there any way one component alone could be broken to produce the symptoms noted? In other words, they start with an observed malfunctioning of a device, and work backwards to determine which underlying component might be the cause of the failure.

The use of model-based reasoning techniques has not been limited to fault diagnosis of physical devices. Patil (1988) explore the artificial intelligence techniques used for diagnosing diseases in medicine. Of particular relevance to model-based reasoning is their experimental program called ABEL. ABEL’s knowledge base attempts to capture the underlying causal mechanisms of disease processes. ABEL views diagnosis as a process of building detailed causal models that explain a patient’s illness. Such models ‘allow the program to reason with the details of the disease process, to recognize how one disease can alter the presentation of another, and to sort out component elements due to each disease’ (Patil, 1988, p. 373). Patil discusses many types of...
traditional approaches, as opposed to model-based reasoning, used to diagnose diseases: the use of clinical algorithms, flowcharts, pattern recognition, probability theory, and decision analysis. Each of these approaches, as Patil notes, suffers from serious weaknesses when applied to the broad and complicated domain of medical diagnosis. For one, these approaches cannot account for new situations—for instance, the outbreak of a new or rare disease. For another, these approaches are difficult to update and maintain. For example, a flowchart can become so large as to become unmanageable with the specification of each new disease.

In more recent years there have been a proliferation of applications using model-based reasoning techniques. To name a few: Milne, Nicol, and Trave-Massuyes (2001) discuss TIGER, a system that is used to perform fault diagnosis of industrial gas turbines used for power generation; Montani et al., (2003) present an intelligent system for managing type 1 diabetic patients, which, in part, utilizes model-based reasoning techniques; Wotawa (2000) describes a model-based reasoning system that is designed to locate software bugs in VHDL programs; and De Koning, Bredeweg, Breuker, & Wielinga (2000) describe a model-based diagnosis system that helps to monitor and diagnose learner behaviors for an automated tutoring system. In many cases, these systems incorporate a variety of techniques (Torasso, 2001) such as case-based reasoning, temporal reasoning, and probabilistic reasoning, suggesting that model-based reasoning techniques, more and more today, are embedded within intelligent systems.

We have employed model-based reasoning techniques in a novel way to solve a class of design problems in business logistics management. The Council of Logistics Management defines business logistics management as

“...the process of planning, implementing and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods, and related information from point-of-origin to point-of-consumption for the purpose of conforming to customer requirements.”

(Ballou, 1992)

The coverage of this area is broad, encompassing business problems that concern customer service, traffic and transportation, warehousing and storage, plant and warehouse site selection, inventory control, order processing, procurement, material handling, and demand forecasting, to name some of the major areas of study within the field (Lambert & Stock, 1993). The selection of business logistics network design as the application domain was intentional, since there are many problems in logistics strategy planning that could benefit from a model-based graphical visualization. Moreover, there is a paucity of research in business decision-making problems utilizing model-based reasoning techniques, since most of the research is focused on the diagnosis of malfunctioning physical devices.

LogNet attempts to design the most cost-effective network satisfying a certain customer service level. It addresses the facility location problem: How many warehouses are needed in a logistics network? Where should these warehouses be located and to which customer market(s) should they be assigned? Also, which factory should supply each warehouse? Unlike a diagnosis problem that typically works backwards from a symptom to determine what component might be responsible for the faulty behavior, LogNet instead works in a forward direction and looks at a variety of network designs, evaluating each one in order to recommend which among them is the most effective (more about how different logistics network are evaluated later).

2. Description of LogNet

At the heart of LogNet is the network model. One way to view and model a logistics environment is as a network of nodes interconnected by transportation links. The problem of specifying the model would be one of specifying the network structure through which manufactured goods flow. To model this environment, three general types of nodes are considered: first, the factories, where the products are manufactured; second, the warehouses, which receive the finished products from the factories for storage and possibly for further processing; and third, the customer zones (or markets), which place orders and receive the desired products from the assigned warehouse(s). Product moves through the logistics network via different transportation options (e.g. rail, trucking, shipping, air), which are represented by the connections or links between the nodes. There are two types of transportation links: inbound links move products from factories to warehouses, and outbound links move products from warehouses to customers. See Fig. 1 below for an example of a logistics network model created using LogNet. Squares represent factories, circles represent warehouses, and triangles represent customer zones.

Spatial reasoning on the network model is possible to the extent that LogNet contains information about distances between two nodes for all transportation links. See Table 1 for a sample of a five-node system of selected US cities. Distances are road miles between two cities. Whenever an end-user connects two nodes, the system will automatically update the distance-between-nodes attribute for that transportation link, via a look-up from a table containing road mileage between two cities.

LogNet enables end-users to build, directly manipulate, and inspect components of the network model. Different network configurations can be created, and such benchmarks as network costs and customer service level can be obtained. In addition, end-users may modify different input assumptions (such as inventory rates and transportation...
rates) and see how these modifications will affect network benchmarks.

2.1. Network benchmarks

LogNet calculates benchmarks in order to evaluate different network models, and provide intelligent advice on which network designs perform best on these benchmarks. Two main benchmarks are considered: total cost of the network and customer service level.

2.1.1. Network costs

The total cost of a given network configuration consists of three components, transportation costs, warehousing costs, and inventory carrying costs.

Transportation costs are dependent on the volume transported between the two nodes and the distance between the nodes. There are two types of transportation costs: inbound (factory to warehouse) and outbound (warehouse to customer zone). Transportation costs, for a given transportation link, are given by the following functions:

If inbound:

\[
\text{Inbound Rate} \times \text{no. of units in 1000's} \times \text{distance between nodes}
\]

If outbound:

\[
\text{Outbound Rate} \times \text{no. of units in 1000's} \times \text{distance between nodes}
\]

Inbound Rate and Outbound Rate are input parameters that can be set by the end-user. They are expressed as the dollar rate per 1000 units per mile. Total transportation cost is the sum of the inbound costs and outbound costs.

Warehousing costs are a combination of fixed costs (a cost that is set by the end-user) and variable costs (e.g. handling costs per unit). Warehousing costs for a single warehouse, are obtained by the following function:

\[
\text{fixed costs} + (\text{no units stored} \times \text{variable handling rate})
\]

Fixed costs and variable handling rates are input parameters that can be set by the end-user.

Inventory carrying costs depend on the average inventory maintained at a warehouse (in-transit inventories are not considered). In LogNet, we consider only the cost of the money tied up in inventory, or the capital cost of inventory. Other inventory costs such as stock-out costs, inventory service costs, and risk are not considered. In LogNet, inventory carrying costs are estimated, based on the square root rule. (The square root rule simplifies inventory consolidation, but is a useful principle nevertheless. More accurate functions may be found to estimate the cost savings achieved by consolidating inventories.) This rule can be used to estimate the cost of inventory when consolidating a number of stocking points, \( n \). It states the following:

\[
\text{Consolidated Inventory} = \frac{\text{Decentralized Inventory}}{\sqrt{n}}
\]

For example, if previously a network utilized three stocking points of $500,000 each for a total inventory investment of $1,500,000, after consolidation the inventory investment is given by:

\[
1,500,000/\sqrt{3} = 866,025.
\]
Inventory carrying costs, based on the square root rule, are decreased by $1,500,000–866,025 = $633,975. Hence, the unit cost of inventory decreases when the number of warehouses in a logistics network is reduced. The rationale behind this rule is that the more consolidated the logistics network becomes (i.e. the fewer warehouses there are), the greater the inventory per warehouse. Because of this consolidation, the unit cost decreases due to economies of scale. LogNet calculates inventory-carrying costs based on a square root function:

\[
\text{Inventory Carrying Cost} = \sqrt{\frac{\text{Monthly Demand}}{1000}} \times \text{Inventory Rate}
\]

For example, if the monthly demand of a warehouse is 5000 units per month, and the inventory rate is $10,000, then the inventory carrying costs are given by:

\[
\sqrt{5} \times 10,000 = 22,361
\]

Inventory rate is an input parameter that may be set by the end-user.

To summarize, the following are the input parameters, set by an end-user, that determine network costs:

<table>
<thead>
<tr>
<th>Network Cost</th>
<th>Input Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbound Transportation</td>
<td>Inbound Rate per 1000 units</td>
</tr>
<tr>
<td>Outbound Transportation</td>
<td>Outbound Rate per 1000 units</td>
</tr>
<tr>
<td>Warehousing Cost</td>
<td>Warehouse Fixed Cost</td>
</tr>
<tr>
<td>Warehousing Cost</td>
<td>Warehouse Handling Rate</td>
</tr>
<tr>
<td>Inventory Carrying Cost</td>
<td>Inventory Rate for 1000 units</td>
</tr>
</tbody>
</table>

### 2.1.2. Customer service level

In the real world, customer service is a complex and multi-faceted benchmark. To simplify matters, we assume that the logistics decision maker would like to locate a warehouse stocking point as close to customers as possible in order to improve customer service. Hence, LogNet determines customer service in terms of how close the customer zones are to the warehouses. LogNet calculates the weighted customer-to-warehouse average distance over each customer zone \( i \):

\[
\frac{\sum_i (\text{Monthly Demand}_i \times \text{Distance between customer zone and warehouse}_i)}{\sum_i (\text{Monthly Demand}_i)}
\]

If a warehouse is located in every city in which there are customers, then perfect customer service is attained—i.e. average distance between customer and warehouse is 0.

### 2.2. Visual interactive modeling

LogNet was designed so that end-users can directly specify a business logistics network via a direct manipulation, graphical user interface. This means that end-users can interact with a graphical object model and perform such actions as adding a node, deleting a node, connecting two nodes, and disconnecting two nodes to create a network design. The advantage of visual interactive modeling is that it enables end-users to incrementally build and test a network design. At an end-user’s request, the system can evaluate the network design by calculating the benchmarks. Such interaction with the objects of a network model gives end-users the feeling of directness, and empowers them to specify, incrementally modify, and iteratively test a network design until they are satisfied that (1) the network design meets a suitable cost, and/or (2) the network design satisfies a given customer service level.

An example of a logistics network design problem follows. Fig. 2 depicts a completely decentralized logistics network: all customer zones are assigned to a warehouse located in the same city. In this example, five customer zones are assigned to five warehouses. These warehouses, in turn, are sourced by a single factory (located in Dallas). The numbers above the nodes represent the number of units that flows through that node. Because the network is completely decentralized, the customer service level (or average customer-to-warehouse distance) is a perfect 0.

Network benchmarks can be requested at any point during the formulation of a network design. This enables the end-user to modify a network design and immediately observe the effect of the modification on the network benchmarks. Fig. 2 displays the benchmarks for the network model specified by Fig. 1. We assume that the following input parameter assumptions are in effect:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbound Rate (per 1000 units per mile)</td>
<td>10</td>
</tr>
<tr>
<td>Outbound Rate (per 1000 units per mile)</td>
<td>20</td>
</tr>
<tr>
<td>Warehousing Fixed Cost (per warehouse)</td>
<td>50,000</td>
</tr>
<tr>
<td>Warehousing (Variable) Handling Rate (per unit)</td>
<td>5</td>
</tr>
<tr>
<td>Inventory Rate (per 1000 units)</td>
<td>1000</td>
</tr>
</tbody>
</table>

This screen contains information about network costs, as well as customer service levels. Outbound transportation costs are zero—because the network is perfectly decentralized.

Warehousing fixed costs are $250,000, because there are five active warehouses at $50,000 each. As expected, average customer-to-warehouse distance is 0 miles.

Visual interactive modeling, then, allows the end-user to create many different network designs easily and obtain network benchmarks to judge which of several network designs is most desirable. An end-user may directly compare two network designs by performing the following sequence of steps: (1) create the first network design;
(2) request benchmarks; (3) create a second network design (which might entail a number of changes to the first network design); and finally, (4) request the network benchmarks a second time. By performing these steps, the third column of Fig. 2 would display how the before and after network designs are different for each of the benchmarks (Fig. 3).

3. Model-based reasoning

Up to this point, the specification of LogNet, as described in the previous section, does not contain the intelligence necessary to guide an end-user toward better network designs. The decision maker engaged in visual interactive modeling is still limited to trial-and-error and ‘eyeballing’ techniques to test different network configurations and to inspect the costs and customer service levels that result from each. Such techniques may work reasonably well for simple problems, but model-based reasoning (i.e. reasoning from a model or schematic) can be employed to create a more intelligent system capable of solving more complex problems, both more consistently and more systematically.

For purposes of this discussion, we break down the network design problem into two basic types of actions: consolidation of a network (combining two or more warehouses into one) and decentralization of a network (adding a warehouse to a network design). We consider the main tradeoffs involved in consolidating and decentralizing a network. The goal of the logistics decision maker is really to balance these tradeoffs so that network costs are minimized, while maintaining a certain customer service level.

3.1. Consolidation of a network

Why would a network need to be consolidated? It may be the case that the current network is too decentralized (i.e. the network contains too many warehouses) leading to excessive inventory carrying costs, and larger warehousing costs. If this is the case, the end-user will want to eliminate a warehouse and reassign all of its customers to another existing warehouse. By doing so, consolidation will lead to reduced inventory carrying costs because economies of scale are gained as several locations’ inventories are combined.
into one. In addition, warehouse fixed costs are decreased with the elimination of each warehouse. On the negative side, consolidation will lead to increased outbound transportation costs (since the customers, formerly assigned to the eliminated warehouse are now located farther away) and may lead to increased inbound costs as well; also customer service levels are decreased because average distance between warehouse and customer is increased. If deterioration of customer service level is of no concern to the logistics decision maker, LogNet will assess these cost tradeoffs and recommend the consolidation that will result in the greatest cost savings. Later on, we consider a refinement to LogNet’s procedures when customer service level also need to be considered.

LogNet employs model-based reasoning to analyze the structure of the current logistics network, and evaluates all possible consolidation opportunities between two warehouses. The model-based algorithm considers consolidations for each active warehouse in the network (an active warehouse is defined as a warehouse having customers assigned to it, or a warehouse that has at least one customer zone connected to it).

For any two active warehouse $W_i$ and $W_j$:

1. Merge warehouse $W_i$ into warehouse $W_j$.
   1a) Disconnect all customer zones currently connected to warehouse $W_i$.
   1b) Connect all customer zones formerly assigned to warehouse $W_i$ to warehouse $W_j$.
2. Assess the new benchmarks (transportation costs, inventory costs, and warehousing costs, and customer service level) for the proposed consolidation $W_i$ into $W_j$.

LogNet will consider all possible mergers between two active warehouses on the network. For example, if there are...
three active warehouses in the current network model—W<sub>1</sub>, W<sub>2</sub>, and W<sub>3</sub>—the following consolidations are considered:

\[
\begin{align*}
W_1 & \rightarrow W_2 & W_1 & \rightarrow W_3 \\
W_2 & \rightarrow W_1 & W_2 & \rightarrow W_3 \\
W_3 & \rightarrow W_1 & W_3 & \rightarrow W_2
\end{align*}
\]

A total of six possible mergers are considered, taken two at a time (later one, we consider consolidations taken three at a time, and more generally, n at a time). For the consolidation W<sub>1</sub> into W<sub>2</sub>, for instance, all customer zones connected to W<sub>1</sub> are disconnected and re-connected to W<sub>2</sub>, so that W<sub>1</sub> is shut down. In general if there are n active warehouses, n*(n-1) consolidations are considered.

If the end-user wishes to decreases network costs, he or she can request that LogNet determine which consolidation will result in the largest cost savings. Alternatively, LogNet can rank-order the candidate consolidations in terms of the cost savings that results from each. The consolidation rule that LogNet uses to make a consolidation recommendation is:

**Consolidation 1.** If the cost savings (inventory carrying costs + warehousing fixed costs) is greater than the increase in transportation costs resulting from the consolidation of two or more stocking points then suggest the consolidation as a candidate to the end-user

3.2. Decentralization of a network

Whereas consolidation involves the elimination of a warehouse, decentralization involves the addition of a warehouse to the network, and reassigning all customer zones that are closer to the new warehouse than they are to their current warehouse assignment. Adding another warehouse is beneficial to the extent that the outbound transportation cost savings resulting from an additional warehouse (i.e. customers are now located closer to the new warehouse) exceeds the increase in inventory carrying costs and the additional warehousing costs (as discussed above). Which warehouse location will LogNet suggest? The end-user can provide LogNet with a number of alternative warehouse locations (e.g. Seattle, Dallas, Atlanta), and LogNet will suggest the location that results in the greatest cost savings (if any such location exists). Hence, the decentralization rule that LogNet uses to make a decentralization recommendation is:

**Decentralization 1.** If the transportation cost savings is greater than the increase in inventory carrying costs and warehousing costs resulting from the addition of a warehouse then suggest the decentralization as a candidate to the end-user

In fact, it may often be the case that no decentralization opportunity exists that will reduce total network costs. However, the primary reason for decentralizing a network is to improve customer service level (or decrease average warehouse-to-customer distance). If the end-user wishes to design a network that improves customer service level, then LogNet will recommend the decentralization that results in the greatest improvement in customer service level, regardless of cost. The second decentralization rule focuses instead on customer service level:

**Decentralization 2.** If the customer service level is improved (i.e. average warehouse-to-customer distance is decreased) as a result of the addition of a warehouse then suggest the decentralization as a candidate to the end-user

LogNet can determine which of the candidate decentralization opportunities will result in the largest improvement in customer service. Alternatively, LogNet can rank-order the candidate decentralization opportunities in terms of the customer service levels that result from each.

3.3. Refinements

The real difficulty facing the logistics decision maker is that he or she must consider a number of tradeoffs at one time in deciding which of several network designs is most suitable. The consolidation problem would be much easier if the only goal was to reduce network costs. If this were the case, we could more easily automate the network-design task. However, the lowest-cost network design is frequently not the one we seek because it results in an unacceptable deterioration of customer service level. Therefore, we require a procedure that recommends a consolidation candidate, which does not degrade customer service level too much. The second consolidation approach was created for this purpose. It suggests the consolidation candidate that results in a network cost savings, but does so with the least damage to customer service level:

**Consolidation 2.** If deterioration of customer service levels is of concern then find the consolidation candidate that results in a network cost savings, but is accomplished with the least damage to customer service levels.

For example, suppose that LogNet generates three candidate consolidations for a given network design: (1) Network cost savings of $120,000 achieved at a deterioration in customer service levels of 20 miles; (2) Network cost savings of $750,000 achieved at a deterioration of 100 miles; and (3) Network cost savings $5000 achieved at a deterioration of 1 mile. Consolidation 2 will recommend the third candidate consolidation because it results in the least damage to customer service levels. Another implementation of LogNet might calculate the ratio cost savings per mile of deterioration (cost savings/deterioration), and recommend the consolidation candidate that results in the highest cost savings per mile of deterioration. If this criteria were used to make the recommendation, LogNet would recommend the second candidate because it has a cost savings per mile of...
deterioration of $7500—compared to $6000 for the first candidate, and $5000 for the third candidate.

Like the consolidation problem, the decentralization problem involves tradeoffs between customer service level and network costs. The logistics decision maker will most typically wish to decentralize a network whenever a higher customer service level is desired. Decentralization 2 will suggest the decentralization candidate that results in the largest improvement in customer service level. However, the logistics decision maker may wish to balance customer service level against network costs, because the best decentralization candidate (in terms of customer service level) may turn out to be excessively costly. Hence the third decentralization approach will suggest the decentralization candidate that still offers an improvement to customer service level, but accomplishes this at the lowest possible additional cost.

**Decentralization 3.** If total network cost is of concern then find the decentralization candidate that results in an improvement to customer service level at the lowest possible additional cost.

Suppose that a network design will result in three candidate decentralizations: (1) improvement in customer service level of 10 miles achieved at an additional network cost of $10,000; (2) improvement in customer service level of 20 miles achieved at an additional network cost of $40,000; and (3) improvement in customer service level of 5 miles achieved at an additional network cost of $7500. Decentralization 3 will recommend the third candidate because it costs the least. We may also wish to calculate the ratio additional network cost per mile of improvement (additional cost/improvement in customer service level), in which case LogNet would choose the first candidate because it has the lowest ratio—$1000—compared to $2000 and $2500 for the second and third candidates, respectively.

### 3.4. Problem-solving using LogNet

Table 2 summarizes the five model-based procedures used by LogNet to make an appropriate consolidation or decentralization recommendation. The five procedures can be invoked by an end-user at any point during the creation of a network design. If the primary goal of the end-user is to reduce total network costs, the end-user can invoke Consolidation 1, Consolidation 2, or Decentralization 1. Consolidation 1 is a more aggressive consolidation, suggesting the consolidation opportunity that will reduce network costs, regardless of deterioration to customer service levels. On the other hand, if the primary goal is to improve customer service level, the end-user can invoke Decentralization 2 or Decentralization 3. Decentralization 2 is the more aggressive version, suggesting the decentralization opportunity that will result in the greatest improvement in customer service levels, regardless of the costs involved.

To illustrate a problem-solving situation, let us return to the example given in Fig. 2. Suppose our goal is to reduce overall network costs. The network is perfectly decentralized, so that the decentralization procedures are irrelevant to this task. Therefore, we are left with either Consolidation 1 or Consolidation 2. We request both to see what LogNet will recommend. Consolidation 1 suggests that we consolidate Warehouse Dallas into Warehouse Houston. By doing so, our total network costs are reduced by $53,104. Our customer service level is reduced by 48 miles. Next we request Consolidation 2. The screen that provides LogNet’s recommendation is given in Fig. 4. Consolidation 2 suggests that we consolidate Warehouse New York into Warehouse Washington DC. Total network costs are reduced by $52,241; however, our customer service levels deteriorate by 1 mile. We decide this is a more acceptable consolidation than that given by Consolidation 1 (cost savings per mile of deterioration is much higher using Consolidation 2’s recommendation). The solution is given in Fig. 5.

### 4. Heuristic-based searching

The astute reader will observe a problem with the model-based procedures discussed above: for a network design with many nodes, the problem could easily become computationally infeasible, because there are so many network design possibilities to consider. Such combinatorial problems are well known in Operations Research and Management Science. One such problem is known as the traveling salesman problem: given a set of cities, find the route that will take a salesperson to each of the cities with the shortest mileage. One possibility is to try all the possible routes and pick the shortest (an exhaustive search through all the possibilities). However, for n cities the number of routes is n!, a number which quickly becomes very large, as the number of cities increases.

If LogNet is to solve a wide variety of problems of increasing complexity, it must employ means other than exhaustive searching. One possibility is to use heuristic-based searching to cut down on the number of possibilities that LogNet considers. Heuristics are defined as “a short cut
The system has determined that the following consolidation will result in a reduction in network costs at the least damage to customer service levels.

Consolidate warehouse NEW-YORK and warehouse WASHINGTON-DC. Inactivate warehouse WASHINGTON-DC and assign all its customers to NEW-YORK.

Total cost savings: -52241

This amount can be broken down into the following components (negative amounts are savings):
- Inbound-transportation costs: 233
- Outbound-transportation costs: 466
- Warehouse fixed costs: -50000
- Inventory-carrying costs: -2940

Change in average customer service levels:
- Before consolidation: 0 miles
- After consolidation: 1 miles

Fig. 4. Consolidation 2 recommendation.

Fig. 5. Solution.
process of reasoning...that searches for a satisfactory, rather than an optimal solution. The heuristic, which reduces the time spent in the search for the solution of the problem, comprises a rule or computational procedure which restricts the number of alternative solutions to a problem” (Hinkle & Kuehn, 1967). In this section we look at some possible ways to reduce the number of possible consolidations and decentralizations to consider.

We noted earlier that LogNet considers \( n^*(n-1) \) consolidations for a network design containing \( n \) warehouses. However, we also pointed out that this number represents only two warehouses merged at a time. It does not consider three warehouses at a time, four warehouses at a time, and so on. Obviously the number of possibilities grows very large with network designs containing many warehouses, especially when we consider all possible mergers of warehouses taken \( n \) at a time. One way to envision the problem is to draw a tree of the possibilities. For example, the possible three-warehouse mergers for warehouse 1 are (1,2,3), (1,2,4), (1,3,2), (1,3,4), (1,4,2), and (1,4,3). We can eliminate (1,3,2), (1,4,2), and (1,4,3) because they are the same as (1,2,3), (1,2,4), and (1,3,4). But even by eliminating such redundancies (i.e. pruning the tree that represents the search space), we have the problem of combinatorial explosion for networks containing a large number of warehouses.

One heuristic that we might use is to consider only consolidations of warehouses that are ‘close’ to one another. In fact, a human logistics decision maker will often eyeball a network design and merge the warehouses that seem close to one another. We might implement this heuristic in LogNet by considering only consolidation candidates of warehouses that are within \( n \) miles of each other (\( n \) could be an input parameter set by an end-user). For example, we might only allow consolidations of warehouses that are within 400 miles of each other. If we return to the logistics network as given by Fig. 2 (where \( 5 \times 4 = 20 \) consolidations, taken 2 at a time, are possible) LogNet would then only consider consolidations between Houston and Dallas and between New York and Washington DC. Along these same lines, another technique we might use is to ‘regionalize’ a network. That is, we might divide a logistics network into separate regions—e.g. warehouses in the Northeast, the South, the West, the Midwest, and so on. (A warehouse’s region would be specified as an attribute of the warehouse). LogNet would only consider consolidations of warehouses within the same region.

Let us consider another heuristic used by logistics decision makers: The most likely sites for warehouses are those that are in or around centers of greatest demand (Ballou, 1989). To implement this heuristic, we could scan our network design for ‘high-demand’ customer zones that are served by a ‘distant’ warehouse. Again we could let the end-user define what high-demand and distant mean. If, for example, high-demand is defined as greater than 10,000 and distant is defined as greater than 500, then LogNet would search for high-demand customer zones that are connected to a warehouse located more than 500 miles away, and would suggest as a candidate decentralization, a warehouse that is closer.

A third heuristic is given by the following: The most expensive customers from a distribution standpoint are those that purchase in small quantities (i.e. low demand customer zones) and are located at the end of transportation lanes (Ballou, 1989). If our goal is to reduce network costs, we would like to scan our network design to search for low-demand customers zones (e.g. lower than, say, 1000-again, an input parameter set by an end-user) that contain a warehouse in the same city or a nearby city. LogNet would then suggest these warehouses as candidates for consolidation with another warehouse.

We have suggested a few possibilities for cutting down on searching through a very large design space. There are many more possibilities, and they will enable us to employ model-based reasoning techniques to solve a wide class of problems in logistics network design, despite the inherent combinatorial nature of the design task.

5. Discussion and conclusions

The warehouse location problem in business logistics management can be tackled using a variety of optimization techniques well-known in the management science and operations research literatures. Such quantitative methods as linear programming, integer programming, and dynamic programming have been successfully employed to find the optimal solution to network design problems. For example, optimization techniques can find the minimum network costs satisfying a variety of constraints (e.g. customer service level must be at least a certain level).

However, these methods, which utilize precise analytical methods to evaluate alternatives, frequently compromise too much in terms of flexibility and realism of the problem-solving situation (Simon, 1996). Because they impose a strong mathematical structure on the problem, they hardly lend themselves to the visual interactive modeling approach discussed in this article. On the other hand, visual interactive modeling and heuristic-based searching are better suited to more open-ended design tasks, because they provide guidelines to reason about a network structure (in an intuitive way), rather than hard-and-fast analytical methods. This approach offers an alternative to optimization methods if one wishes to have more flexibility in terms of problem-formulation and the incremental testing and design of different network design. Their major disadvantage, however, is that they do not guarantee optimal solutions.

We believe that in terms of usability and user acceptance, this approach has major benefits and advantages over more traditional optimization techniques. Studies on usability and problem-solving ability in our research lab have provided...
some promising results (Nakatsu and Benbasat, forthcoming). Participants in our experimental studies have found the advice to be highly effective in designing business logistics networks. Moreover, we have found that participants appreciated having the ability to interact with the lower-level operators of the system, rather than LogNet just telling them what to do. For example, when we provided study participants with the Consolidation 1, Consolidation 2, Decentralization 1, and Decentralization 2 operators they were generally more satisfied with the system than if they were just told what to do. For more difficult and challenging problems participants were also better able to find optimal solutions by requesting these lower-level operators.

LogNet represents a kind of intelligent support system in which the end-user remains very much in the decision-making loop throughout the entire problem-solving process. Rather than relegating decision-making to the computer system, intelligent support systems are meant to serve in an advisory capacity to human decision-making. The end-user always remains behind the steering wheel, directing how the network design process proceeds by incrementally building the network design and requesting advice from the system, when appropriate. In the end, this is really the philosophy behind LogNet: more flexible user interfaces that support less predictable interactions in a complex design task.

References


