# Reducing Logistics Costs at General Motors

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Automobile and truck production at General Motors involves shipping a broad variety of materials, parts, and components from 20,000 supplier plants to over 160 GM plants. To help reduce logistics costs at GM, the decision tool TRANSPART was developed. In its initial application for GM's Delco Electronics Division, TRANSPART identified a 26 percent logistics cost savings opportunity ($2.9 million per year). Today, TRANSPART II — a commercial version of the tool — is being used in more than 40 GM plants.

General Motors Corporation — popularly known as GM — traces its roots to 1897 when the Olds Motors Vehicle Company produced its first automobile. Nineteen years later, GM was incorporated and encompassed four automobile manufacturing operations, a truck marketing firm, and an export company. Today, GM is one of the largest corporations in the world. In 1984, it marketed over forty different vehicle models, sold 8.3 million cars and trucks worldwide and netted $80.5 billion in vehicle sales.

Roughly 13,000 different parts, varying widely in size and value, must be fabricated and assembled to produce a typical vehicle. A massive production and distribution network is required to accomplish this. In 1984, this network consisted of 20,000 supplier plants, 133 GM parts plants, 31 GM assembly plants, and 11,000 dealers in the United States and Canada. GM's 1984 freight transportation cost was $4.1 billion, with about 60 percent for material shipments and the remainder for finished vehicle shipments. In addition,


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INVENTORY/PRODUCTION — APPLICATIONS
TRANSPORTATION — MATERIALS HANDLING
ROUTE SELECTION

GM's 1984 inventory was valued at $7.4 billion (about 70 percent for work-in-process and the remainder for finished vehicles), with much of this inventory being attributable to material and vehicle shipments. The 164 GM facilities are organized into 32 divisions or profit centers.

Because of the size, scope, complexity, and cost of GM's production network, it is imperative that effective decisions be made regarding the shipment of GM materials and vehicles. In the middle to late 1970s, several factors increased the importance of these decisions:
— The deregulation of the freight transportation industry was impending;
— Interest rates and energy costs were increasing rapidly;
— A recession was imminent;
— Overseas competitive pressures in the auto industry were escalating; and
— Just-in-time manufacturing and shipping were emerging as potentially attractive strategies for US industry.

In 1978, to help prepare GM for the materials management challenges ahead, the GM Research Laboratories formed a new research group. The mission of this group is to perform fundamental logistics research that provides an improved scientific basis for GM's logistics decisions (that is, decisions affecting the flow of materials over GM's extensive production network). The authors of this paper were either members of this group or consultants to it.

In 1981, GM's Delco Electronics Division (currently, Delco Electronics Corporation) confronted a problem in shipping its products which was the catalyst for the management science accomplishments reported here. Delco designs and manufactures a variety of vehicle components. Its products in 1981 included
— Electronic control modules produced in Milwaukee, Wisconsin;
— Radios produced in Matamoros, Mexico; and
— Radios, speakers, heater controls, and a variety of small plastic products and electronic sensors produced in Kokomo, Indiana.

The small size and high value of these electronic products play an important role in how they are shipped.

Figure 1 depicts Delco's product shipping network as it was in 1981. Products from Milwaukee and Matamoros were shipped by truck to a Delco warehouse in Kokomo, where they were consolidated with products made in Kokomo. The consolidated production was then shipped by truck directly to about 30 GM vehicle assembly plants in North America. The warehouse served to combine shipments and store production.

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In 1981, the logistics costs associated with Delco's product shipping network were shared by several GM organizations. Specifically, Delco incurred
— Inventory costs at its three plants and its warehouse due to load make-up;
— Freight transportation and in-transit

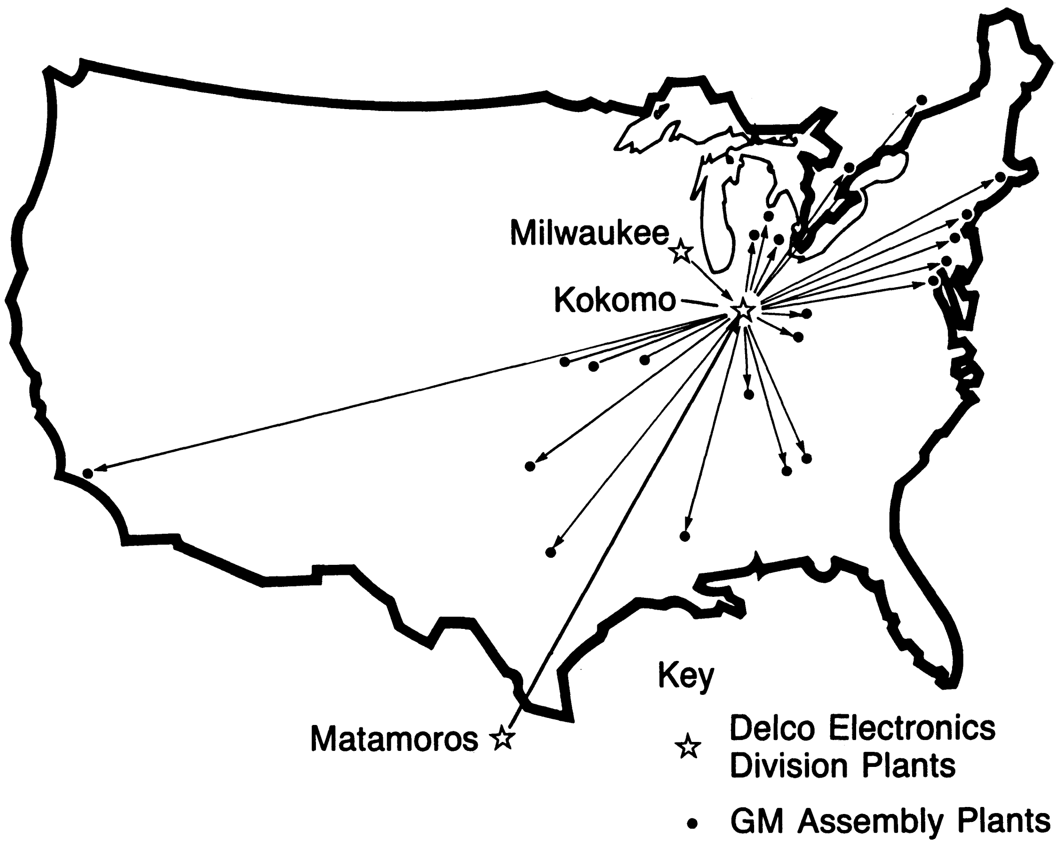


**Figure 1: The Delco Electronics product distribution network in 1981 with its three plants (☆) shipping to about 30 GM assembly plants (•) via the Kokomo warehouse.**

inventory costs on the links to the warehouse; and

— Inventory costs at the warehouse due to material handling time.

In addition, the GM assembly plants incurred

— Inventory costs due to load consumption; and

— Freight transportation and in-transit inventory costs on links from the warehouse.

Delco, like all GM Divisions, was focusing on ways to enhance product quality and reduce product cost. As part of this effort, Delco's manager of material control, Jim Schneider, was responsible for reducing finished product inventory. He recognized that inventory played an important role in allowing Delco to take advantage of the transportation cost efficiencies inherent in large shipments. This is especially important to Delco because its products are small and valuable.

Jim Schneider realized he might be able to reduce inventory by shipping directly from each Delco plant to each GM assembly plant; however, this would increase freight transportation costs substantially, and also affect the share of costs incurred by different GM organizations. While his charge was to reduce inventory, he concluded that he first needed to fully understand the trade-offs in inventory and transportation costs on a network-wide basis.

On June 30, 1981, when Jim visited GM Research, his objective had evolved to one of minimizing the combined corporate cost of inventory and transportation for all Delco products shipped to GM assembly plants. He wanted an analytical tool that would allow convenient and quick evaluation of alternative strategies for shipping Delco's products.

We suspected that several other GM component divisions faced similar challenges and that Delco's situation was a special case of a new and important generic research area for GM. In retrospect, these initial perceptions were correct.

Delco had a complex network that could not be analyzed properly with standard mathematical programming techniques.

Delco had a complex network that could not be analyzed properly with standard mathematical programming techniques. Given Jim's desire to fully understand cost trade-offs and the advantage of using simple, transparent analysis techniques in practical settings, we concluded that there was a need to understand fundamentals and an opportunity to make fresh and original research contributions. We focused on reducing total corporate costs associated with shipping Delco's products and examining the impact different strategies would have on different GM organizations.

**Research**

Transportation costs result from freight charges incurred in shipping products. Inventory costs result from products waiting to be shipped from Delco plants, products in transit to GM assembly plants (including products in the warehouse), and products waiting to be used at assembly plants. Material handling costs at the warehouse were factored into the cost of carrying inventory there. Modeling the trade-off between transportation and inventory costs over the entire network used to ship Delco products became the key to reducing cost.

**Decision Variables**

Shipping strategies are represented by two types of decision variables:

— Shipment sizes (or frequencies) on the network links; and
— Routes over the network.

Shipment sizes affect trade-offs between transportation and inventory costs. Shipping large loads infrequently on a specific link reduces the transportation cost per item because the fixed cost of a shipment can be spread over more items. However, large loads increase the inventory cost per item because of the added time incurred to make-up and use loads of more items. Alternatively, shipping smaller loads more frequently results in a higher transportation cost per item, but reduces the inventory cost per item because the loads can be made-up and used more quickly. Thus, transportation and inventory costs are interrelated, and a trade-off exists between them that depends on shipment size (or frequency).

The route selected for each shipment also affects transportation and inventory costs because it determines the amount of material shipped on each link. Routing options for shipments from each Delco plant to each GM assembly plant include

— Making all direct shipments,
— Making all shipments via the warehouse,
— Making direct shipments between some Delco-assembly-plant pairs, shipping via the warehouse for others, and using a mixture of these two options for yet others, and
— Peddling (that is, delivering items from a Delco plant or the warehouse to several assembly plants in one truck load).

These options result in different allocations of transportation and inventory costs to different GM organizations. While we focused on reducing total corporate costs, we also had to consider the organizational implications of different routing options.

**Research Objective and Approach**

Our research objective was to develop a method that would help Delco determine the best shipment sizes and routes (from a total corporate perspective) for its products. To achieve this objective, we had to develop an improved understanding of

— The way transportation and inventory costs depend on shipment sizes and routes,
— Trade-offs between transportation and inventory costs on complex networks, and
— The sensitivity of costs to system conditions.

In our research, we tried to keep the models and analyses as simple as possible. We accomplished this by first studying the simplest type of network and then gradually considering more complex networks.

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**Transportation and inventory costs are interrelated, and a trade-off exists between them that depends on shipment size (or frequency).**

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**Single Link "Building Block"**

The first step was to develop a model to analyze the trade-off between transportation and inventory costs on a single link and to examine how total link cost depends on shipment size. We developed equations for transportation and inventory costs that reflect the structure of freight charges, the mixture of items that constitute loads, truck capacities in both weight and volume, and total inventory in the system.

Freight charges could have been inferred from freight rate tables that depend on specific plant locations, commodity type, and shipment size (in pounds). However, we found that the freight charges could be approximated exceptionally well by a parameter that depends only on distance. Incorporating this approximation into the equations allowed the optimal shipment size (that is, the shipment size that minimizes total cost) to be determined as a solution to a standard economic order quantity (EOQ) problem [Arrow, Karlin and Scarf 1958; Magee and Boodman 1967].

Sensitivity analyses were performed to see how total cost varied around the optimum as a function of material flow (that is, demand) on the link. The equations assumed constant demand, and sensitivity analyses allowed the cost impact of demand fluctuations to be studied.

**Networks**

The single link results served as a building block for studying networks with several links. They showed that the optimal shipment size on a link increases with the square root of flow. They also showed that the minimum total cost on the link per unit time increases with flow at a decreasing rate until there is sufficient flow to justify full truck loads, at which point cost increases linearly (Figure 2).

The concave relationship between link cost per unit time and flow means that the cost per item shipped on a link decreases with flow. As a result of this scale economy, routing and shipment size decisions for all Delco-assembly-plant pairs are interrelated. This means that minimizing total network cost requires simultaneously determining optimal routes and shipment sizes.

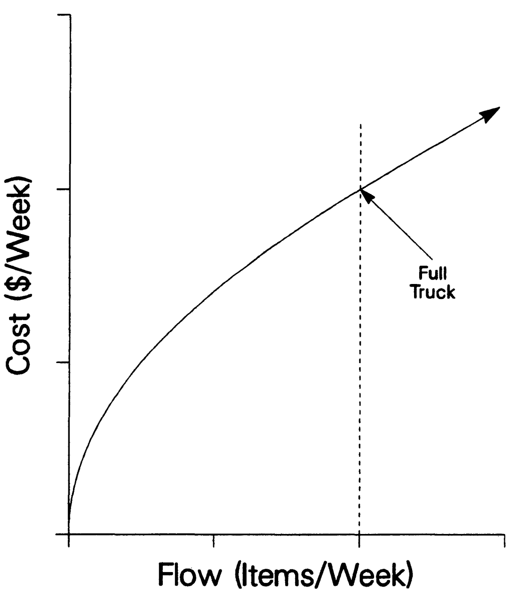


**Figure 2: The concave relationship between cost and flow on a link, showing how the minimum cost per week increases with flow at a decreasing rate, up to a full truck load, and linearly afterwards.**

Because total cost on a link is not a convex function of flow, routing decisions cannot be evaluated with standard mathematical programming techniques. This problem is very complex. Fortunately, because of concavity, we were able to show that only two routing options had to be considered for each Delco-assembly-plant pair: ship all products direct, or ship all products via the warehouse. Routing options that involved shipping some products direct and some via the warehouse for the same plant pair are always more costly. This powerful "all-or-nothing" principle is discussed in Newell [1980].

All-or-nothing routing simplified the problem substantially. However, an enormous number of routing options still remained because the decision to ship direct for one Delco-assembly-plant pair affects total flow through the warehouse and therefore affects costs and routing decisions for other pairs. For the Delco network, there were 90 such plant pairs (three Delco plants and 30 assembly plants). Without accounting for peddling possibilities, there were $2^{90} \simeq 10^{27}$ different routing options.

Attempting to solve Delco's combinatorial problem directly would have involved large-scale computing, with no guarantee of finding a solution. Because we wanted to keep the analyses simple and transparent and provide results in a timely manner, we were motivated to find a simpler

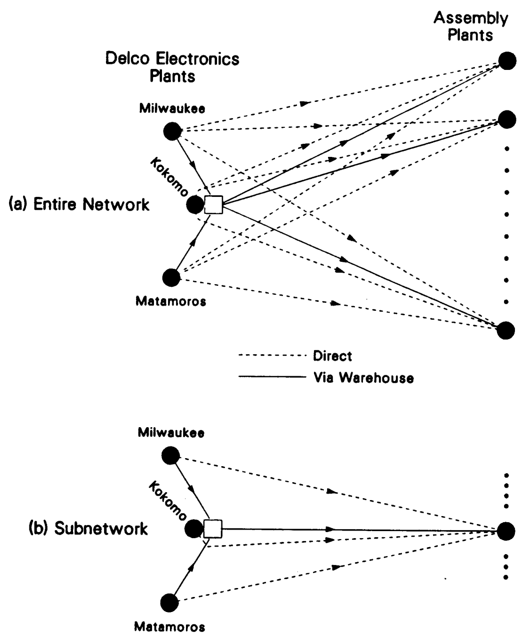


**Figure 3: A schematic representation of the Delco Electronics product distribution network for the entire network and for a subnetwork isolating one GM assembly plant.**

solution technique. We observed that if shipment sizes were fixed (instead of optimal) on each inbound link to the warehouse (that is, from Milwaukee and Matamoros to the warehouse), total cost per unit time on these links would be linear with flow. As a result, we could prove that, for fixed shipment sizes on the inbound links, the total Delco network could be decomposed into independent subnetworks, each involving just one assembly plant (Figure 3) (see the appendix for the proof given in Blumenfeld, Burns, Diltz and Daganzo [1985]). Each subnetwork could then be easily solved by enumerating just four routing options and using the previously described EOQ methods to determine optimal shipment sizes on the links to the assembly plant.

The four routing options on each Delco subnetwork are

— All direct,
— All via warehouse,
— Milwaukee and Kokomo via warehouse, and
— Matamoros and Kokomo via warehouse.

These are the only practical options because the warehouse is located adjacent to the Kokomo plant.

The optimal shipping strategy for the entire Delco network was identified by

(1) Generating a variety of fixed shipment-size combinations on the inbound links,
(2) Determining the optimal shipping strategy on each subnetwork for each shipment-size combination,
(3) Summing the resulting minimum costs on all subnetworks for each shipment-size combination, and
(4) Selecting the combination (and corresponding optimal strategy on each subnetwork) that results in the overall minimum cost.

Since there were only two inbound links, the number of shipment-size combinations to consider was relatively small.

This decomposition method provided a new contribution to network optimization theory. It allowed the optimal shipping strategy (shipment sizes and routes) to be determined quickly and easily for routing options involving a combination of direct and warehouse shipping. This is accomplished using only basic calculus and arithmetic.

In addition to direct and warehouse shipping, our solution technique also applied to peddling (that is, shipping material to several assembly plants in the same load). This was achieved by visually grouping together assembly plants in close proximity to form peddling regions. Each peddling region was treated as a single assembly plant with a total material flow equal to the combined flow to assembly plants in the region. The transportation cost was approximated by the cost to the nearest assembly plant in the region plus the cost of traveling between plants in the region. This additional cost was estimated from the distance traveled on the peddling route and the number of plants in the region. Shipments consisted of a mixture of items (according to demand) destined for each assembly plant.

Having discovered a simple solution technique, a fast FORTRAN-based decision tool was easily developed for Delco's network. This tool was named TRANSPART.

**Decision Tool**

The decision tool TRANSPART was developed to allow Delco to conveniently examine the impact on total corporate cost of different shipping strategies for its products. It contains the model for analyzing transportation and inventory cost trade-offs and the solution technique for determining the minimum cost for the entire network.

> Attempting to solve Delco's combinatorial problem directly would have involved large-scale computing, with no guarantee of finding a solution.

TRANSPART requires the following input data:

— Value, weight, and density of each product;
— Demand for each product by assembly plant;
— Freight charge on each link;
— Transit time on each link;
— Warehouse material handling time; and
— Inventory carrying charge.

Product values are the prices Delco charges assembly plants and are needed in the calculation of inventory costs. Product weights and densities (weight per unit volume) are inferred from packaging data, account for container characteristics, and are needed to ensure their shipment sizes do not exceed truck capacity (maximum weight or volume).

Demands are the number of each product required per week by each assembly plant and are obtained from records of assembly plant production volumes.

Delco produces about 300 different product types grouped into about 40 families of similar products. Each shipment from a Delco plant to a GM assembly plant typically contains a variety of products. To properly reflect this mix, the notion of a *composite product* was developed. A composite product is a proportional mixture of all of the product types shipped together on a link. The value of the composite product is the demand-weighted average of the values of the different products shipped on that link. Composite product weight and density are determined similarly.

The freight charge on each link is the cost of a truck shipment on this link. This charge was modeled as a fixed amount per load, independent of the size or weight of the load. This representation is supported by actual freight rate data and the fact that a carrier's operating expenses are nearly the same whether the transportation equipment travels empty or full. The freight charge was taken to be the full-truck-load rate, available from freight rate data. This means, for example, that shipping trucks half full (to reduce inventory costs) results in a transportation cost per item that is double that of full-truck shipments.

Transit times (days per shipment) were obtained from historical data on truck shipments. An estimate of the average warehouse material handling time was provided by Delco. As a first approximation, this time was assumed to be independent of the total flow of material through the warehouse.

Delco no longer had to speculate about the merits of alternative strategies.

The inventory carrying charge reflects the cost of holding products in inventory. It is expressed as a percentage of product-value-per-unit time. An estimate of this percentage was provided by Delco for its product inventory. This estimate reflects the opportunity cost of money and the cost of insurance, material handling, storage space, and obsolescence.

The FORTRAN program written for TRANSPART uses the network decomposition solution technique described above to evaluate the costs of alternative shipping strategies. This program provides as output the routes and shipment sizes that minimize total corporate cost for Delco's network. It also provides a breakdown of cost by link. This allows the costs of shipping products from each Delco plant to be accounted for separately and identifies which costs are paid by Delco and which by other GM divisions. This organizational impact is important when implementing results. Finally, for each link, the tool analyzes the sensitivity of total cost to changes in shipment size around the optimum. This is important in identifying links for which shipment size has a big influence on cost.

**The Results for Delco Electronics**

The research results, network model, computer program, and data allowed Delco to answer questions regarding

— Trade-offs between transportation and inventory costs,
— Costs associated with alternative shipment frequencies and routes,
— Cost differences between the optimal (that is, minimum cost) routing strategy and routing strategies that are simpler and easier to manage (for example, all direct shipments or all warehouse shipments),
— The sensitivity of results to changes in key parameters such as warehouse material handling time, inventory carrying charge, and freight rates, and
— The impact of different routing strategies on the shipping costs of Delco products incurred by different GM organizations (for example, individual Delco plants, the warehouse, and GM assembly plants).

We feel that providing Delco with the

knowledge to answer such questions properly was more important than the immediate dollar savings. Delco no longer had to speculate about the merits of alternative strategies. It could evaluate them objectively instead. Delco was also in a position to adjust its shipping strategy as conditions changed (for example, as inventory carrying costs changed with changes in interest rates). In fact, we believe that Delco had the opportunity to reduce product shipping costs in 1981 primarily because conditions had changed substantially since the company decided to build its warehouse in the late 70s. Between 1979 and 1981, the freight industry was deregulated, and interest rates increased significantly.

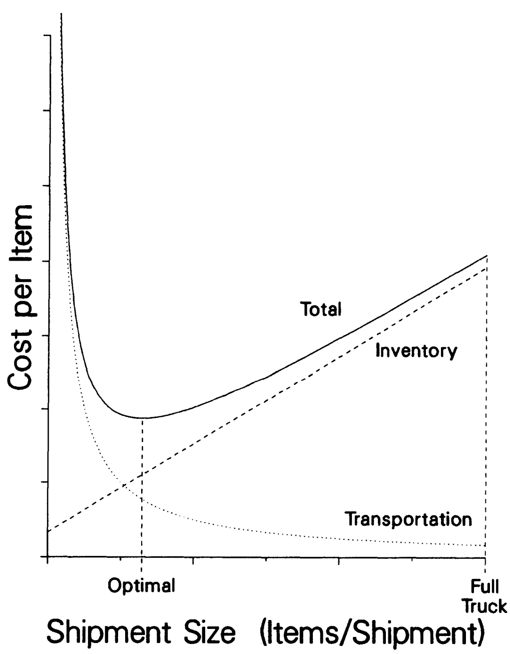


**Figure 4: The economic order quantity (EOQ) relationship between cost and shipment size on a link, showing the trade-off between transportation and inventory costs for shipments from Delco Electronics' Milwaukee plant to GM's Baltimore assembly plant.**

**Single Link Results**

Because we focused on trade-offs and provided graphical answers, the usefulness of our work and the merits of various strategies could be illustrated easily. Figure 4, for example, was used to demonstrate the effect of shipment size on direct shipments between the Delco plant in Milwaukee, Wisconsin and the GM Assembly Plant in Baltimore, Maryland. While this figure presents a standard economic order quantity (EOQ) relationship, showing it graphically is enlightening. At a glance, one can see that transportation and inventory costs need to be managed together and that myopically pursuing one objective (for example, minimizing transportation costs) can result in radically higher total costs. One can also tell that a wide range of shipment sizes result in costs close to the minimum. Finally, the penalty incurred by shipping direct in very small quantities to meet just-in-time delivery objectives can be inferred. Such graphical representations of the trade-offs would later prove to be very important in attaining corporate-wide use of our research results.

**Network Results**

Presenting trade-offs graphically was also effective in evaluating Delco's entire product shipping network (Figure 5). Results are presented for shipping full loads, routing all shipments direct, and routing all shipments through the warehouse, because these strategies are relatively easy to control and manage. Results are also presented for shipping optimal load sizes, using a combination of direct and warehouse routing, and peddling, because Delco had no means of

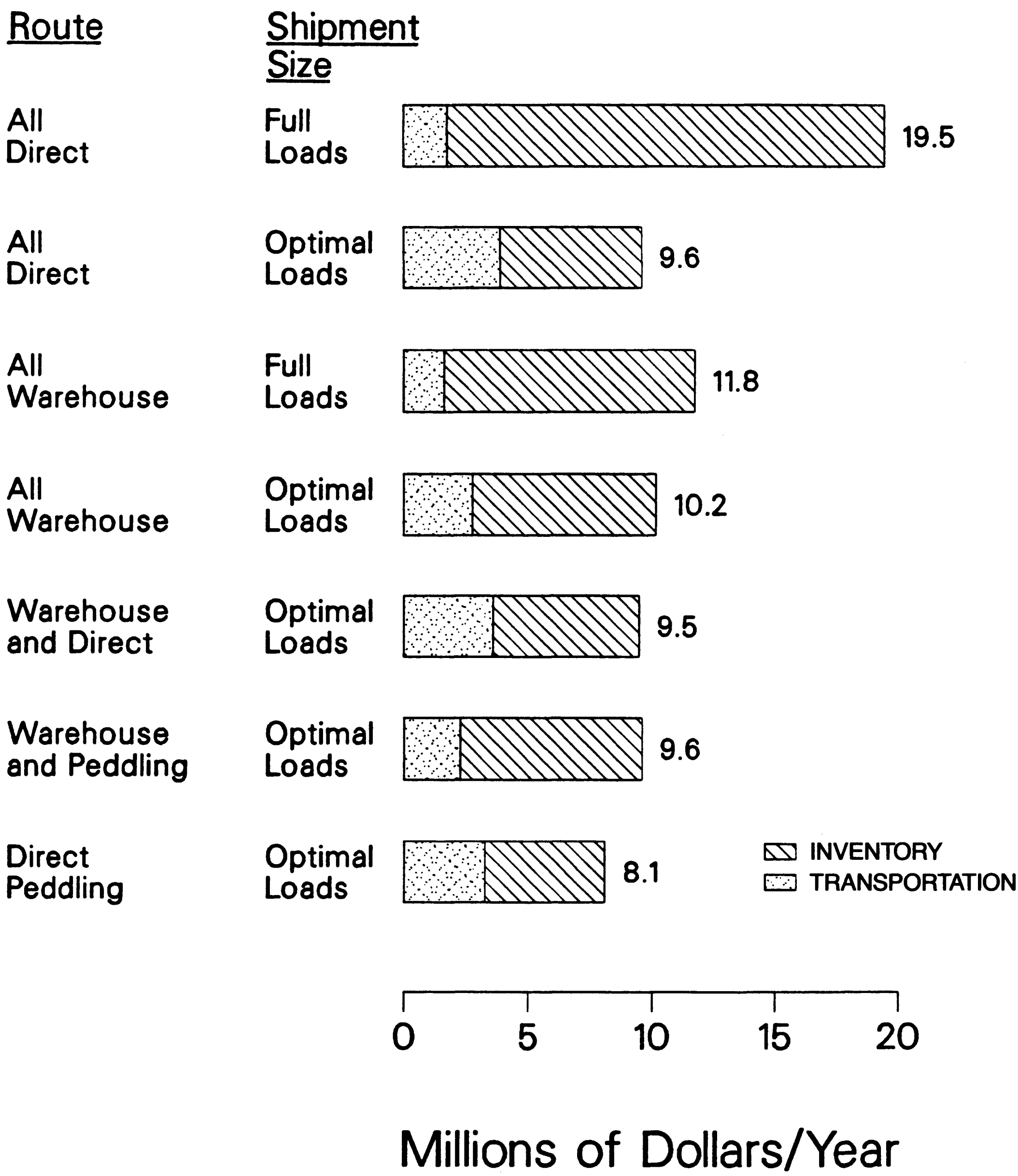


**Figure 5: Trade-offs between total transportation and inventory cost estimates for various shipping strategies over Delco Electronics' entire North American product distribution network.**

evaluating these more complex strategies prior to our research.

Figure 5 reveals that

— Delco's decisions regarding shipment sizes and routes were highly interrelated. As an example, the attractiveness of the all-direct and all-warehouse strategies depends on the extent to which optimal load sizes are used. Using optimal shipment sizes is not as important for the all-warehouse strategy because consolidating flows on links reduces the sensitivity of link costs to shipment size.

— The best mixture of direct and warehouse routing (without peddling) was only one percent less costly than the simpler all direct strategy. This best mixture had 56 percent direct routings.

— Peddling direct was significantly less costly than the other routing strategies considered. (This strategy defined nine peddling regions based on the geographical proximity of GM assembly plants. These regions varied in size from one to five plants.)

**Sensitivity Analyses**

In 1981, Delco was routing all shipments through the warehouse. GM's cost accounting methods made it difficult to isolate actual transportation and inventory costs for Delco's products for a given set of conditions. We therefore had to estimate a range of potential savings. We knew Delco shipped full loads on some (but not all) warehouse links. As such, an upper bound on their 1981 cost was $11.8 million per year (all full loads) and a lower bound was $10.2 million per year (all optimal loads). This suggested a potential savings of 21 percent to 31 percent ($2.1 million to $3.7 million per year) by peddling direct from each Delco plant. Our best estimate of the overall savings is the middle of this range, 26 percent or $2.9 million per year. This estimate is the total corporate savings, accounting for the cost impact on both Delco and GM assembly plants.

We were delighted by the results. Peddling direct, which only recently had become attractive because of trucking industry deregulation, offered significant freight consolidation advantages without a high inventory cost and without the additional transportation cost of routing via the warehouse. However, before concluding that Delco should begin peddling direct from all of their plants, we wanted to better understand the sensitivity of our results to changes in key parameters. Two parameters were especially important: inventory carrying cost and warehouse material handling time.

Inventory carrying cost is difficult to estimate precisely. In addition to the opportunity cost of capital, carrying cost depends on insurance, handling, storage, and obsolescence costs of holding inventory. Furthermore, because interest rates

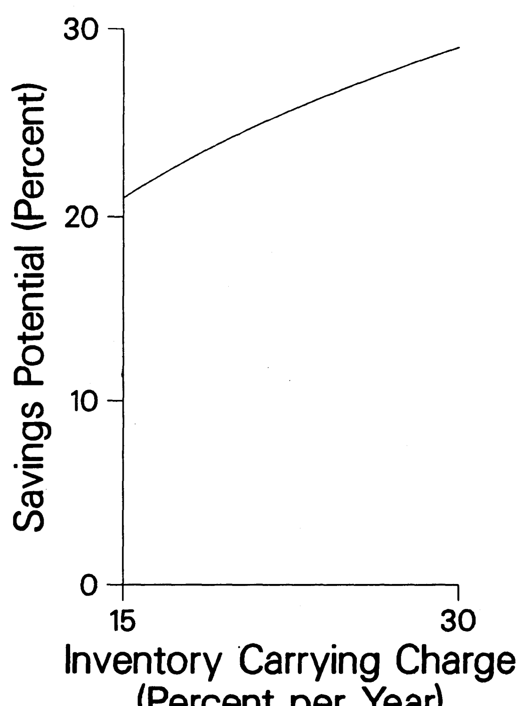


**Figure 6: The cost savings potential from the direct peddling strategy, showing a significant savings opportunity for a broad range of inventory carrying charges.**

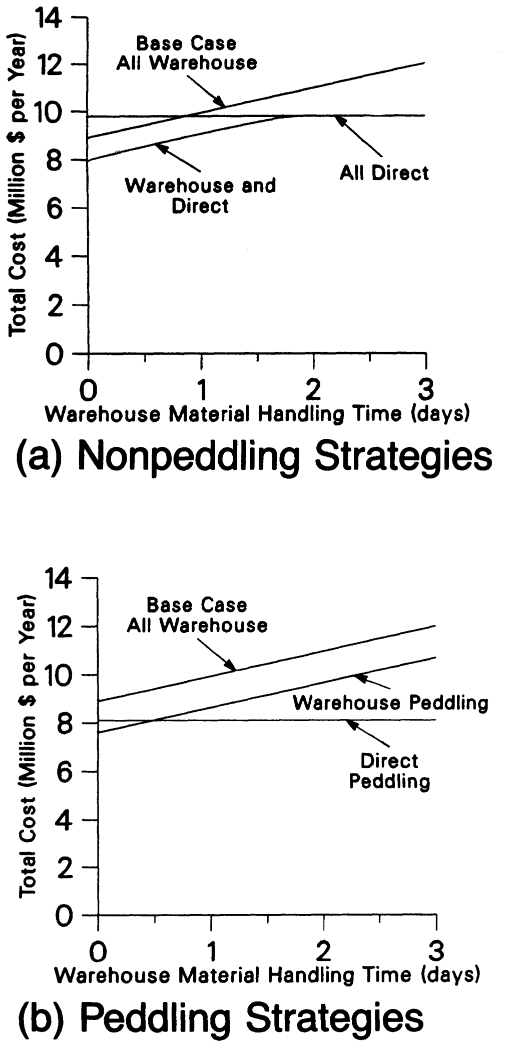


**Figure 7: The effect of warehouse material handling time on total network cost estimates for different shipping strategies.**

had been increasing rapidly, we were convinced that carrying cost would continue to fluctuate.

As shown in Figure 6, the savings potential associated with direct peddling (relative to the previously discussed base case) varies from 21 percent to 28 percent as the carrying charge doubles from 15 percent to 30 percent per year. Thus, a significant savings opportunity existed for a broad range of carrying charges. This sensitivity analysis was far simpler than precisely measuring the carrying charge for Delco's products, and it increased our confidence in the merits of direct peddling.

Warehouse material-handling time directly affected the attractiveness of the warehouse-routing strategies. Embarking on an effort to reduce handling time may have been the most cost-effective way to reduce Delco product shipping costs.

Figure 7 illustrates the sensitivity of results to warehouse material-handling time. Delco's best estimate of this time in 1981 was two days. Figure 7a pertains to nonpeddling strategies and Figure 7b pertains to peddling strategies.

We learned from Figure 7a that without peddling, the base case all-warehouse strategy is less costly than the all-direct strategy with optimal loads when handling time is less than a half day. Furthermore, as would be expected, the warehouse/direct strategy is always better than either all-direct or the base case. The cost difference here is about $1 million per year for handling times ranging from zero to two days. Finally, we learned that reducing material handling time from two days to a half day would reduce base case costs by about $1 million per year. Certainly, making an effort to do this was one viable strategy for Delco.

We learned from Figure 7b that peddling direct and peddling from the warehouse are less costly than the base case for all-warehouse material-handling times. Also, warehouse peddling becomes less costly than direct peddling when warehouse handling time is below a half day. Again, attempting to reduce material-handling time appeared to be a key option for Delco. More importantly though, peddling (while somewhat more complex than the direct or warehouse strategies) appeared to offer a promising opportunity for a broad variety of conditions.

Given that peddling looked promising, we decided to examine its impact on products shipped from each Delco plant. It turned out that 66 percent of the total savings accrued to products shipped from the Milwaukee plant. These products accounted for only 16 percent of the total products shipped by Delco. This suggested that a major savings might be realized by changing only the routes for products shipped from Milwaukee.

The preceding results made it clear that Delco could use a variety of strategies to reduce their product distribution costs. They could attempt to change shipping routes, ship optimal load sizes, reduce warehouse material-handling time, or renegotiate freight rates. By adjusting shipment sizes and routes alone, costs could be reduced by $2.9 million per year (26 percent). More important though, Delco was now in a position to evaluate a wide spectrum of strategies under a wide variety of conditions objectively. For example, because routing and shipment size decisions are short term in nature, the model can be applied to quickly respond to fluctuations in demand, which are characteristic of the auto industry.

**The Impact on Delco Electronics**

In April 1982, Delco began applying the model on their own and pursuing strategies to reduce costs. Initially, they decided to continue their all-warehouse strategy (but use optimal shipment sizes) and to try to reduce warehouse material-handling time. These options offered immediate savings without having to adjust routes. However, because of congestion in the warehouse, Delco concluded that material-handling time could not be reduced significantly without reducing the amount of material flowing through the warehouse. This gave them an added incentive to use routing strategies other than the all-warehouse strategy.

Delco's next step was to begin shipping direct from Milwaukee since this was the plant that offered the largest savings from changing routes. This also reduced warehouse congestion for the remaining products routed through the warehouse. Delco used a combination of direct shipping and peddling from Milwaukee, depending on the relative proximity of assembly plants. They continue to do this today.

Since 1982, Delco has applied the model to address several changes and to explore new strategies. Examples of how it continues to use the model include determining

— The best shipping strategy for a new Delco product manufactured in Hillsdale, Michigan — the Delco/Bose sound system,
— The best use of foreign trade zones for products shipped from Mexico,
— When electronic control modules should be shipped to distant assembly plants by air,
— Whether to use sea or air transportation for products from Singapore,

— The merits of combining Delco's Milwaukee products with other GM freight from Milwaukee in "collecting" routes to assembly plants, and
— The best route for speaker components purchased from a Japanese supplier.

**Corporate-Wide Implementation**

The success at Delco motivated us to implement our research throughout the corporation. We suspected that our results might apply in some form to almost every material shipment made to GM's component and assembly plants. This included opportunities to shift modes (truck, rail, sea, air), adjust shipment sizes, or change routes. It was an exciting and timely endeavor because of the rising popularity of just-in-time delivery strategies and because of new shipping strategies growing out of freight deregulation.

How could we effectively, efficiently, and quickly get our results disseminated and used throughout GM? We sent reports that documented the research, data and computer program, and results underlying our experience at Delco to all of the transportation (traffic) and materials management executives in GM. We also hosted a one-day workshop with representatives from each GM division. This sparked interest, but did not lead to rapid, corporate-wide implementation. Several impediments existed: (1) data were not readily available for most divisions, (2) the FORTRAN computer program written for Delco was tailored to its operation and was not user-friendly, and (3) our reports and workshop used equations which several potential users found difficult to apply.

We needed to overcome these impediments. One option was to work toward a new corporate information system that provided computer access to required data and a general computer program that applied to all divisions. We were concerned that this would be costly and require a long lead-time. While we were seeking an alternative to this top-down, centralized approach, an idea surfaced from a potential user, Jerry Spencer, Assistant Traffic Manager at the Chevrolet Flint Engine Plant. He had read one of our reports and was looking for a way to apply our findings without having to manually stick numbers in formulas. He began experimenting with using our research results on his personal computer to solve problems confronted by his engine plant.

> At a glance, one can see that transportation and inventory costs need to be managed together and that myopically pursuing one objective can result in radically higher total costs.

Personal computers were just becoming available in GM. When Jerry shared his idea with us, a light went on! We did not fully recognize it at the time but, in retrospect, Jerry's idea was the key that opened a door to an exciting new approach to decision-support-system development and implementation in GM. We proceeded to develop a prototype of a user-friendly personal computer decision tool on an IBM-XT, which captured key features of the Delco model and presented solutions graphically. Our prototype, which focused on transportation/inventory cost trade-offs for direct routing, took about three days to develop.

We then developed a more user-friendly prototype that took advantage of color graphics and incorporated several additional analysis options. This second prototype was programmed by one systems analyst in about three months.

Next, pilot tests were performed at five GM plants. At that time, GM had created a new management science activity that is currently called the Decision Technologies Division (DTD) of Electronic Data Systems (EDS). Its objective was to gain widespread use of decision analysis tools throughout GM.

Decision Technologies viewed our decision tool as one of several around which they could begin building their organization. Greg Herrin of Decision Technologies, and Tom Matwiejczyk, then of GM Logistics Operations and now of the GM Truck and Bus Group, took the lead in pilot testing our prototype to refine it and to ascertain its value under a variety of settings.

The pilot tests were encouraging and useful. GM plants provided suggestions that made the tool easier to use and more general. Decision Technologies finalized the software and now had evidence that TRANSPART would be a valuable product to market widely. The pilot tests also identified several savings opportunities for the plants involved. Greg Herrin and Bob Lawson of Decision Technologies marketed the final product throughout GM and provided support for its use.

Decision Technologies' product, called TRANSPART II, is used today in over 40 GM plants and is being considered for sale outside GM. The following quotes describe the kinds of effects it has had:

With the aid of the TRANSPART system, GM of Canada saved approximately $157,000 on carrier selections in four months. Currently we're very active in developing an inventory control system that lends itself to the "just-in-time" concept. Our traffic department uses TRANSPART in all transportation-inventory analyses. The system has helped us complete our transportation-inventory studies in a more efficient and timely manner.

— *Jeff Abbott, Supervisor of GEEM and Expedited Services, Oshawa Traffic Department, GM of Canada*

We've known all the variables in inventory costs for a long time. But before TRANSPART we never had a way to consider all the variables in time to make decisions about inventory levels. I used TRANSPART over a period of four weeks to analyze the total costs involved in setting our maximum in-plant inventory level. I discussed my proposed changes with Production Control to make sure they made sense. The adjustments we agreed upon are saving us over $35,000 per year.

— *Wayne Starr, General Supervisor of Inventory Management, Pontiac Motor Division (now with Chevrolet-Pontiac-Canada Group)*

TRANSPART was very effective in helping us make rail vs. truck carrier comparisons for our [Astro/Safari] Van project in Baltimore. In Logistics, we're always dealing with transportation costs and shipping frequency. Trying to come up with an optimum strategy considering those factors individually — plus inventory costs — is almost hopeless without a computer. TRANSPART takes this complex situation and handles it for you. It ties into "just-in-time," the name of the game today. Once you've seen how TRANSPART can help you, it's obvious you should use it. Eventually we want to integrate TRANSPART into our whole materials scheduling system. Now that's a big project. TRANSPART is a bandwagon we're going to jump on right now!

— *Larry Lamon, Senior Administrator, Central Office Logistics, GM Truck and Bus Operations*

A key ingredient in the successful and rapid evolution of TRANSPART II was the decentralized approach to system development and implementation offered by personal computers. This approach provides many independent users with the autonomy (from the standpoint of both system support and budget) to apply tools on their own and in the privacy of their own offices. As a result, they can take full responsibility and credit for their use of a tool. They do not need to seek approval or wait for priority. And, they are not dependent on the results and schedules of others.

**More Complex Networks**

We also had an opportunity to extend our research to solve problems for more complex networks. This included networks with many supplier plants, several consolidation terminals (including warehouses), and many destination plants. It also included collecting and peddling (that is, making pick-ups from more than one supplier per load and deliveries to more than one destination per load) on networks with hundreds and even thousands of suppliers and destinations.

Our research in dealing with more complex networks followed two paths. The first extended the solution technique developed for Delco. This extension identifies optimal routes for networks with over 1,000 suppliers and on the order of 30 destinations (or vice versa); and one or more consolidation terminals [Hall 1984; forthcoming]. The routing decision on such networks is a minimum-cost, multicommodity flow problem with concave cost functions [Zangwill 1968]. This important class of problems has received much less attention than network flow problems with linear or convex cost functions. The solution method developed here finds optimal routes graphically and is sufficiently efficient to be programmed on a hand calculator or personal computer.

This extended tool has been applied successfully by the GM Warehousing and Distribution Division to identify a significant savings opportunity. This division has a network of about 1,000 suppliers, seven consolidation centers, and about 40 distribution centers. The application involved evaluating routing strategies for shipping sheet metal parts from one of its main suppliers to the distribution centers. The network decomposition technique described previously allowed the evaluation to be performed properly without the need for information on other suppliers. The division selected this technique over several others it considered because it was the only one that correctly accounted for freight scale economies and because it required minimal data.

The second path used methods from geometric probability to develop formulas that help identify optimal collecting and peddling strategies when hundreds or even thousands of suppliers or destinations exist. These methods have been published in Daganzo [1984a, 1984b, 1985]; Burns, Hall, Blumenfeld and Daganzo [1985]; and Hall [1985]. They focus on the spatial densities of suppliers and destinations, and the distributions of production volumes and demands, rather than precise data on each individual location. This simplifies the analysis of logistics problems by eliminating the need to specify a detailed network and corresponding flows. It also results in formulas that allow cost trade-offs to be understood clearly, rather than in mathematical programming techniques that, in their pursuit of optimization, tend to obscure trade-offs.

The formulas for collecting and peddling costs are useful for practical applications and require only estimates of a few easily measurable parameters. For example, in 1983 the collecting formulas were used to evaluate shipments from a large number of suppliers to a GM warehouse in Westland, Michigan. This application identified an opportunity to save 44 percent of transportation and inventory costs for these shipments. The formulas have also been applied in planning material shipments to GM's Buick City Plant in Flint, Michigan. Finally, the collecting formulas are incorporated in TRANSPART II.

**Summary of the Effects on General Motors**

The research, decision tool development, and implementation described here have had a number of major effects on GM:

(1) GM has a new proven approach to decision support systems development and implementation. It is decentralized, expedites implementation benefits, and avoids large-scale system development costs. It involves

— Focusing on simple, transparent decision models that require minimal data, highlight trade-offs, and present results graphically;
— Rapid prototyping, using personal computers and involving potential users (to create a sense of user ownership);
— Pilot testing in real settings to obtain quick prototype refinement and documented savings; and
— Providing widespread corporate exposure by disseminating descriptive brochures, users' manuals (with real examples from pilot tests), and diskettes.

(2) GM has new and simple techniques for analyzing and solving large, complex network problems. They are based on decomposing a network into much simpler subnetworks and using analytical formulas to evaluate shipping strategies. The techniques are original research contributions to network theory and have been published in refereed journals. They are used in GM to reduce logistics costs and plan logistics operations, and they allow GM to solve network problems that it could not solve before.

GM can now also resolve the conflicting objectives that result in logistics networks due to organizational boundaries. These occur because shipping materials typically results in ownership changes, and traffic and material control departments sometimes function independently. The techniques focus on trade-offs and therefore help bridge organizational boundaries.

(3) GM has an improved understanding of the implications of just-in-time manufacturing on freight transportation costs. GM Divisions can now evaluate freight consolidation strategies, such as collecting and peddling, as means of attaining just-in-time delivery objectives (that is, frequent, small loads) without changing supplier locations or increasing freight transportation costs significantly.

(4) Delco Electronics has a new computerized decision tool for evaluating its product shipping strategies. It is used on a regular basis and allows Delco Electronics to properly adjust strategies to changes in conditions and thus avoid cost increases that could result from these changes.

(5) Delco Electronics has implemented strategies that have an estimated product shipping cost reduction of 26 percent ($2.9 million per year). They are based on extensive sensitivity analyses Delco Electronics performed using the decision tool.

(6) GM has a new personal computer decision tool (TRANSPART II) that is currently in use at over 40 GM facilities. The savings at different facilities vary widely with documented examples ranging from $35,000 to $500,000 per year per application.

(7) GM Warehousing and Distribution Division can now effectively evaluate product-routing strategies over its vast network. It is using the decision tool extension for large networks to consider substantially more routing options than it could consider previously. This technique is the only one the division could find that uses minimal data and properly captures freight scale economies.

These examples demonstrate the widespread use of the management science tools we developed for logistics decisions in GM. Many decision makers are applying these tools in their everyday work because they are easy to use and understand. Furthermore, our tools and their implementation have greatly enhanced the image of management science within GM.

**Management Science Lessons**

As a result of our experience, we learned several management science lessons, which should increase the likelihood that decision tools will be used and decrease the time for their implementation.

First, regarding management science research, we learned that it is worthwhile to pursue results that allow simple decision models and principles to be developed. Formulating models that are simple functions of a few key parameters with clear physical interpretations help make decision tools transparent and meaningful to potential users. Transparency is important because decision makers justifiably want to understand the logic underlying decision tools.

Second, regarding decision tool development, we learned that tools evolving from the rigor of management science methods are more likely to be used if they do not require users to have sophisticated skills. Such tools should focus on quantifying trade-offs between key variables, using a minimal amount of data, facilitating sensitivity analyses, and presenting ranges of solutions graphically. They should aid in evaluating several options and highlighting the implications of decisions that are practical alternatives to optimal solutions. In this way, if for practical reasons an optimal solution cannot

By adjusting shipment sizes and routes alone, costs could be reduced by $2.9 million per year (26 percent).

be implemented, the user can identify numerous options that are feasible in practice and nearly optimal.

Third, regarding decision tool implementation, we learned that it is imperative that users share a sense of ownership in a tool. A decentralized approach to decision tool implementation facilitates this because it frees individual decision makers from having to accept the findings of a central group. Instead, it encourages them to generate their own findings, take pride in their individual accomplishments, and monitor the implications of their own decisions.

Fourth, regarding both decision tool development and implementation, we learned that personal computers are a powerful medium. They can reduce system development time, "front-load" system benefits, reduce costs, and enhance the chances of a system being used.

Finally, regarding management science in general, we learned never to forget that people make decisions, not models or computers. Management scientists must therefore be exceptional listeners and view potential users as their most important resource. This certainly was the case for us, as evidenced by the contributions of Jim Schneider and Jerry Spencer. Jim's willingness and ability to clearly communicate Delco's challenge was instrumental in specifying research objectives. Jerry's initiative and foresight in proposing that TRANSPART be programmed on a personal computer was the key to gaining corporate-wide implementation.

In summary, our experience in reducing logistics costs at General Motors taught us several lessons for successful management science. These lessons are not unique to our experience. They reinforce lessons others have learned in the past, and reflecting on them can enhance the chances that future management science endeavors will have significant impact in practice.

**Acknowledgments**

The accomplishments described here would not have been possible without the contributions of a large team of people. Clearly, Jim Schneider and Jerry Spencer played critical roles. In addition, listed by their affiliation at the time of their contributions, are

— Delco Electronics Division: Don Collins, Bob Costello, Tom Endres, and Brian Plante;
— Decision Technologies Division of Electronic Data Systems: Frank Babel, Greg Herrin, Bob Lawson, and John Lucas;
— GM Logistics Operations: Jerry Bodrie, Don Griffin, and Tom Matwiejczyk;
— GM Assembly Division: John Martin and Ray Taylor;
— GM Warehousing and Distribution Division: Dave Hansen;
— GM Research Laboratories: David Diltz, Tom Morrisey, Dick Rothery, and Bill Spreitzer.

Finally, most important are the users of the tools described here. Their contributions throughout this effort assured the acceptability of our tools.

**APPENDIX: Proof that the network decomposition method identifies the optimal shipping strategy.**

Consider a network of two origins and many destinations and a corresponding subnetwork for one destination (Figure 8).

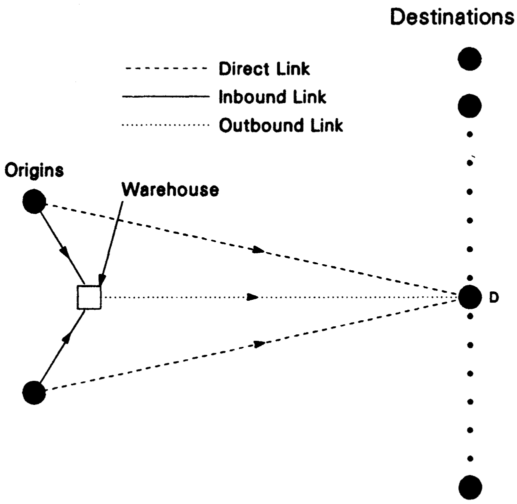


**Figure 8: Subnetwork links for direct and warehouse shipping strategies.**

Let

$D$ = destination on subnetwork,

$C_D^{DIR}$ = cost per unit time on a direct link to $D$,

$C^{IN}$ = cost per unit time on an inbound link to the warehouse,

$C_D^{OUT}$ = cost per unit time on an outbound link from the warehouse to $D$,

$C_D^{SUB}$ = cost per unit time on subnetwork, and

$C^{TOT}$ = cost per unit time on entire network.

The subnetwork in Figure 8 consists of two inbound links, two direct links, and one outbound link. Therefore, the cost per unit time on all links to $D$ is

$$\sum_1^2 C^{IN} + \sum_1^2 C_D^{DIR} + C_D^{OUT}, \qquad (1)$$

where $\sum_1^2$ denotes summation of costs over two links. (Equation (1) assumes $C_D^{OUT}$ includes the inventory cost due to material handling time at the warehouse.)

The direct and outbound links are different for each destination, but the two inbound links are common to subnetworks for all destinations. Therefore $C^{TOT}$ is given by

$$C^{TOT} = \sum_1^2 C^{IN} + \sum_D \left[ \sum_1^2 C_D^{DIR} + C_D^{OUT} \right], \qquad (2)$$

where $\sum_D$ denotes summation over all destinations.

Consider one inbound link. The cost per part, $C$, on this link is [Blumenfeld, Burns, Diltz, and Daganzo 1985].

$$C = PR\left(\frac{V}{Q} + T\right) + \frac{F}{V}, \qquad (3)$$

where $P$, $V$, $Q$, $T$, and $F$ are the part value, shipment size, flow, transit time, and freight rate, respectively, on this link, and $R$ is the inventory carrying charge. Therefore, the cost per unit time on this link is

$$C^{IN} = QC \qquad (4)$$

$$= PRV + PRTQ + \frac{F}{V}Q. \qquad (5)$$

For fixed $V$, this cost is linear in flow $Q$.

The flow $Q$ on this link is made up of part demands at all destinations receiving these parts via the warehouse. Therefore, denoting the demand via the warehouse to destination $D$ by $q_D$,

$$Q = \sum_D q_D, \qquad (6)$$

and

$$C^{IN} = PRV + PRT \sum_D q_D + \frac{F}{V} \sum_D q_D. \qquad (7)$$

Hence, for fixed $V$,

$$C^{IN} = PRV + \sum_D \left(PRTq_D + \frac{F}{V} q_D\right) \qquad (8)$$

$$= \text{Constant} + \sum_D C_D^{IN}, \qquad (9)$$

where $C_D^{IN}$ is the cost on the inbound link attributable to $D$.

Therefore,

$$C^{TOT} = \sum_1^2 \left[\text{Constant} + \sum_D C_D^{IN}\right]$$

$$+ \sum_{D} [ \sum_{1}^{2} C_D^{DIR} + C_D^{OUT} ] \quad (10)$$

$$= \text{Constant}$$

$$+ \sum_{D} [ \sum_{1}^{2} C_D^{IN} + \sum_{1}^{2} C_D^{DIR} + C_D^{OUT} ] \quad (11)$$

$$= \text{Constant} + \sum_{D} C_D^{SUB} \quad (12)$$

Thus, for fixed shipment sizes on the two inbound links, $C^{TOT}$ is the sum of a constant and subnetwork costs. It can therefore be minimized by minimizing the costs on the subnetwork for each destination separately.

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