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Integer Programming
Logistics

DEPARTMENT OF ECONOMICS
RESEARCH MEMORANDUM

APPLICATION OF MIXED INTEGER
PROGRAMMING TO A LARGE SCALE
LOGISTICS PROBLEM

J. Ashayeri, A.J. Westerhof,
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Application of Mixed Integer Programming To A Large Scale Logistics Problem

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Time based competition has a direct impact on logistics operations. Today, logistics costs are increasing rapidly, and tools must be developed to improve logistics operations and reduce its associated costs. This paper describes the development, the application and the successful implementation of a mixed integer programming model for a real life logistics problem at NedCar, a car manufacturer in the Netherlands. The model determines the ordering dates and quantities of purchase parts given constraints on demand, transportation, packaging and inventory levels, in order to minimize logistics costs. Special consideration is given to reducing the model complexity.

1. Introduction

The recognition of time-based competition has placed emphasis on the organization's supply chain and its logistics management. Better management of supply chain means that advantages can be achieved both through reduced cost and through faster service. Other developments have also raised the need of focusing on logistics operations, e.g. the increasing demands on flexibility, the continuously increasing ratio between purchase cost and total cost and the continuous pressure on inventories by just-in-time (JIT) deliveries. All of this makes the coordination requirement ever more complex, to secure delivery of the right products in the right quantity and quality, at the right time and place. Logistics takes care of this coordination, so logistics costs are rising and a better control of these costs is a necessity. In practice logistics decision makers often do not use any quantitative approach and rather rely on rules of thumb. Therefore, a more quantitative approach is desirable to reduce logistics decision costs. This paper concerns a decision support system for in controlling logistics costs and can, by minimizing logistics costs, determine the optimal logistics decisions mathematically.

The paper is organized as follows. Section 2 describes NedCar and NedCar Logistics, the environment for which the model is developed. This prepares the ground for presenting the developed model in section 3. In this section we also discuss the ways of reducing the

model complexity. The model is applied to a number of real situations, and their results are presented in section 4. The results show the benefits of implementing the model. In section 5 some important notes on the implementation are discussed. The overall conclusions are drawn in section 6.

2. NedCar Logistics

Netherlands Car BV (NedCar) is a Dutch company that develops and produces passenger cars for third parties. NedCar, formerly known as Volvo Car BV, is founded in 1992. Volvo Car Corporation, Mitsubishi Motors Corporation and the Dutch State are the three shareholders of NedCar. At the moment, NedCar employs over 5,000 people and produces about 100,000 cars of the Volvo 400-series per year. In the near future NedCar will produce both Volvo and Mitsubishi with a doubled annual volume. New car types will be presented in the mid-nineties.

Logistics is a very important activity at NedCar. The task of NedCar Logistics is the control and continuous improvement of material and information flows from the supplier to the production line. At NedCar, logistics products are purchase parts.

To provide an impression of the logistics requirements at NedCar, it worths mentioning that logistics takes care of more than 4,000 purchase parts from 350 suppliers. The total value of these yearly purchases is about 1.5 billion Guilders; purchase costs amounts to 80% of a car costs. Logistics costs are about 80 million Guilders annually. Logistics inventory worths about 50 million Guilders.

Logistics inventories consist mainly of three product-types (note that in-process-inventories are not included in logistics inventory):

- raw materials (mainly steel in the form of coils);
- engines; and
- "other" purchase parts (dashboards, nuts, bolts etc.).

For a number of reasons this paper only considers the last category. These parts represent about 80% of total logistics inventory. Figure 1 illustrates the production process, the flows that logistics is accountable for and the flow that is modeled in this paper.

The logistical flow describes the consecutive logistical activities. It is coordinated by Marketing, Production and Supply. Marketing determines the number of cars that can be sold. The Production and Supply departments determine the number of cars that can be

Figure 1: production process

made (according to the production capacity and the capacity of the suppliers). In a meeting referred to as "Master Planning Conference" the three departments decide how many cars will be produced in different periods. Given this decision and real production orders, the Material Requirements Planning (MRP) system determines the ordering dates and ordering quantities for each purchase part.

The orders are sent to the suppliers (by fax or Electronic Data Interchange (EDI)). Because of the limited number of packaging units in circulation, before dispatching the orders, it is checked if a supplier has sufficient packaging units. When the available number is lower than required, empty packaging units need to be sent to the supplier. Then, the ordered parts can be transported from the supplier to the factory. The Transport department within NedCar determines the best way of transportation (i.e. routing and truck sizes).

The quality and quantity of arrived parts at the factory are examined before being stored. Stock can be placed in the "Logistics Center" LC, a central stock location at the factory, or in the factory, at the production line. When the parts stored in the LC are needed at a production station, they are transported internally from the LC to the station. When the parts are unpacked and placed at the production line, the control responsibility is transferred from Logistics to Production.

Three activities appear to be important in this logistical flow: ordering, packaging and transportation. These activities are controlled by different departments and are defined as follows:

- *Ordering decisions.*

It has to be determined how frequent to order and how much to order. Ordering is needed to prevent shortages. Because ordered products must be packaged and transported, ordering decisions are indeed related to packaging and transportation decisions.

- *Packaging decisions.*

Products have to be packaged to secure their quality and to facilitate transportation and handling. It has to be decided which packaging unit is the best for each product. Available packaging units are for example: pallets, wooden boxes in different sizes and cardboard boxes.

- *Transportation decisions.*

When parts are ordered, they have to be transported from the supplier to the factory. A number of decisions can be made to carry out transportation as efficient as possible. Possible choices are for example: kind of truck to use and number of suppliers to visit with one truck (direct shipping: one supplier is visited with a truck; grouped traffic: several suppliers are visited with a truck).

To integrate these related activities in one model, cost is considered to be key element to combine the subproblems. Figure 2 shows how the activities can be linked using costs as common factor.

Figure 2: cost: the bridge among related decisions

As shown above, all logistics decisions influence the costs in the logistical flow.

Logistics decisions are not the only source of logistics costs. Logistics influential factors, like product features, minimal ordering quantities and supplier choice, also introduce

logistics costs. The logistics costs can be separated in the next six logistics cost-elements:

- *Ordering costs*: the costs of transmitting the ordering decisions (order quantities, delivery dates, etc.) to the supplier.
- *Inventory holding costs*: the costs of keeping stock at LC.
- *Packaging costs*: the costs of packaging the products in different packaging units.
- *Material handling costs*: the costs of receiving, inspection and internal transportation of the delivered products.
- *Transportation costs*: the costs of transporting the ordered products from the suppliers to the factory.
- *Transport-inventory costs*: the inventory costs of products that are property of NedCar, but not ready to be used in production (products on their way from the supplier to the factory and products waiting for inspection).

For the logistical flow, the decisions that are made in this regard and their interactions, and the way to combine them all, a conceptual logistics cost model is provided (see figure 3). *The model must solve the following problem: schedule the logistics decisions (ordering, packaging and transportation) in such a way that total logistics costs are minimized and relations between the logistics decisions are satisfied.* In this concept, the ordering decisions are the central decisions.

Figure 3: the concept of the model

All logistics decisions influence each other, for example: the decision to order sets the need for packaging, but the way products are packed has great impact on the ordering decisions (for example: when a packaging unit contains two weeks of supply, there would be no sense in ordering more than once every two weeks); different packaging units have different sizes, which means that transportation capacity in packaging units varies with the size of the packaging unit. Figure 3 is strongly simplified for illustration purposes, and presents only one purchase part and one period. As mentioned, in reality there are 4000 parts, 350 suppliers and multiple periods, and decisions for one part in one period influence the decisions for many other parts in other periods.

It can be concluded that the decision process is very complex because there are thousands of decisions to make, based on thousands of relations. This complexity makes it impossible to get the total picture and make good decisions manually. The use of a computer based Decision Support System (DSS) is necessary. The next section deals with the development of the mathematical computer model.

3. The model

In this section the development of a mathematical model, which is the foundation of a computer based decision support system, is described. It is shown that the resulting model is very complicated, and attention has to be given to complexity reduction. The used hard- and software will be described briefly in this section.

3.1 The model and its complexity.

The developed model is a Mixed Integer linear Programming (MIP) model. With MIP a large class of problems can be modeled and solved. Converting the concept of the model (figure 3) into a MIP-model leads to the following model (see the detailed model in appendix 1). In order to present the concept clearly, no mathematical notation is used and only the most important parts of the model are discussed below.

Indicator (zero-one) variables

A variable indicating whether an order for each purchase part is placed in each period.

A variable to indicate whether a certain type of packaging unit is used for each part.

A variable indicating whether a certain truck is assigned to a certain supplier .

A variable indicating which transportation route is selected.

Other decision variables (integer)

Quantity to order.

Number of packaging units required to pack the ordered quantity.

Assisting variables

Inventory level per period.

Variables to prevent subtours in selecting the transportation route.

Objective function

Minimize total logistics costs over planning period

Logistics costs are in every period separated into five logistics cost elements (notice that transport-inventory costs are not considered here):

- * ordering costs per purchase part;
- * material handling costs per purchase part;
- * inventory costs per purchase part;
- * packaging costs per purchase part and packaging unit;
- * transportation costs per truck.

Constraints

- (i) Minimal and maximal ordering quantities must be taken into account when an order is placed. If no order is placed, the ordering quantity must be zero.
- (ii) The ordered quantity must be packaged in an integer number of full packaging units.
- (iii) Ordering must prevent stock outs and respect safety stock set for each part.
- (iv) Only certain types of packaging unit can be selected for each part.
- (v) For each part, one of the available alternative packaging units must be chosen for the entire planning period.
- (vi) Limitation on storage-space.
- (vii) Limitation on availability of some packaging units.
- (viii) The ordered quantity must be transported, so it must fit in the selected truck (both in volume and in weight).
- (ix) When a product of a supplier is ordered, a truck must stop at the respective supplier.
- (x) When a truck stops at certain supplier, the truck must stop at exactly two other suppliers, one immediately before and one immediately following that supplier.
- (xi) Subtours must be avoided.
- (xii) Non-negativity of all variables.

The model formulated here is too large and too complicated to solve, even with a very powerful computer. This is caused by a number of reasons, such as:

- the number of parts and the number of suppliers are very large (4000 parts, 350 suppliers);
- the number of different packaging units is large (about 90);
- the planning period is long (20 days = 4 weeks, this planning period is chosen because every 4 weeks a delivery schedule is sent to the supplier);
- the transportation conditions make the model difficult to solve (a full truck routing problem has to be solved for multiple periods in combination with other decisions in the model; truck routing problems are very difficult to solve when taken separately, in combination with many other decisions they cannot be solved within a reasonable time);
- the model is non-linear (but can be linearized).

The non-linearity of the model intensifies the model size problem. Non-linear constraints and non-linearities in the objective function can be linearized by adding constraints and variables to the problem. All this together leads to a model with a few million variables and constraints and increases the computation time exponentially. In the following section we describe how the model complexities are reduced.

3.2 Complexity reduction

Because complexity is often a problem with modeling real world situations, a closer look is taken here for reducing the model complexity. Such a complexity reduction must have two goals:

1. the resulting model can be solved within an acceptable time;
2. the resulting model must be realistic and transparent.

A number of complexity-reducing actions can be taken (see Bradley et. al (1977), Salkin (1975)). These are summarized in table 1.

Rewriting the model
Reducing the number of decision variables
Reducing the number of periods
Some simplifying assumptions
Splitting the suppliers in supply regions
Approximation in the transportation part of the model
Splitting the model in sub-models

table 1: 7 ways to reduce model complexity

- Rewriting the model.

In MIP there are several ways to formulate the same problem. Formulating the model differently using another definition for variables reduced in this case the number of non-linearities and resulted a model with less variables and constraints. Appendix 2 gives a simple illustration of this action.

- Reducing the number of decision variables.

Taking the packaging unit to use for each product as an input instead of a decision variable makes the problem a lot smaller and reduces the number of non-linearities. This also has a practical explanation. The packaging unit that can be considered for a product is closely related to product characteristics. Modeling all possible combinations would make the model very large and difficult to adjust to new products and packaging units. By optimizing the model for some predetermined choices of packaging units, the optimal packaging unit can be found in far less computing time than when the model would determine the optimal packaging unit.

- Reducing the number of periods.

Replacing daily with weekly decisions reduces the number of variables and constraints with 80%. Most of the time a weekly model is sufficient. When a daily model is needed, the planning periods should be restricted to about 5 days.

- Some simplifying assumptions.

- There is enough storage space available (this means that the inventories of the different products do not influence each other, and therefore products can be regarded separately from an inventory point of view).
- There are always sufficient packaging units available (this means that the way a product is packaged does not influence packaging decisions of other products, and therefore products can be regarded separately from a packaging point of view).

- Splitting the suppliers in supply regions.

Because it is unlikely that products of the suppliers who are not in the same region influence on each other's ordering/transportation decisions, from an ordering/transportation

tation point of view, suppliers can be divided into regions of about 6 to 10 suppliers, depending on the type of parts.

- Approximation in the transportation part of the model.

The complete truck routing problem in the model is replaced by an approximation, some aspects of the approximation are described in section 3.2.1.

- Splitting the model in submodels.

This is to devise a hierarchy approach and reduce the model size (see section 3.2.2).

The simplifying assumptions and the splitting of suppliers in regions made it possible to look at only a few suppliers and their products at a time. This and the other actions have reduced the size of the model to about 1000 variables and 1000 constraints (of course this number is dependent on the number of suppliers and products in a supply region).

3.2.1 Approximation in the transportation part of the model

The use of the approximation in the transportation part of the model, which has the most influence on the model, is discussed in greater detail here.

The approximation of (total) local distance (d) travelled in a region is described in Burns et al. (1985), (see also Daganzo (1984), Sheffi et al. (1987)):

$$d = K * \sqrt{\frac{mn}{\rho}} \quad (1)$$

Where:

m : is the number of suppliers that has to be visited in a tour;

K : is a constant (when m is larger than 2 or 3: $K \approx 0.6$);

n : is the number of suppliers in a supply-region;

ρ : is the supplier density (the number of suppliers per square kilometer).

The total distance D_{total} (local distance in the region and the distance from the supply region to the factory) is given by formula (2).

$$D_{total} = D + d = D + K * \sqrt{\frac{mn}{\rho}} = D + K * \sqrt{\frac{n}{\rho}} * \sqrt{m} \quad (2)$$

Where:

D : is the average distance from a supply region to the factory.

D can be determined as follows:

$$D = \frac{1}{\text{number of suppliers}} \sum_{\text{supplier in region}} \text{distance supplier to factory} \quad (3)$$

The number of suppliers that has to be visited in a tour (m in formula (2)) is a decision variable. Only when a product of a supplier is ordered, a truck has to stop at that supplier. Formula (2) is non-linear. To make the model linear, $\sqrt{m}$ has to be approximated. This can be done by partitioning of variables (see Williams (1987)). The linearized function is non-convex, so the use of binary variables is inevitable.

By using the approximation of the travelling distance (and the corresponding transportation costs), the complex truck routing problem in the original model is reduced to only a few variables and constraints in the new model. For example, when no transportation approximation is used, for a region with 10 suppliers about 100 variables are required to handle the transportation part of the model while with approximation only 13 variables would be sufficient.

3.2.2 Splitting the model in submodels.

When a model of solvable size is obtained, the formulation of the model can be changed in order to formulate a good model (in terms of computation time). How this can be done is shown in Nemhauser et al.(1989). But more can be done by taking the computations that are unnecessary to the real optimization out of the model. As such, the computation time and the size of the model can be further reduced, making the model more transparent. In this paper, the global model is split into three models, the first and the third model make the computations that are needed to get the right solution, but are not part of the real optimization which is performed by the second model. The three models are (as shown in figure (4)):

- a net requirement model;
- the real optimization model;
- a reporting model.

By solving the three models successively, each using output of the former model as input, a solution procedure to the original problem is obtained.

The first model determines the net requirement in full packaging units in every week by calculating the net requirement in each week using MRP data (i.e. scheduled receipts, inventory and gross requirement), and rounding this number to full packaging units.

Figure 4: splitting up the global model

The second model determines, by minimizing all controllable logistics costs, when and how much of every product in a supply region has to be ordered. This model uses the output of the net requirement model as input. Because the net requirement model has rounded the net requirement in full packaging units, it is no longer necessary to request an integer number of packaging units in the second model. This model has the longest computation time. When the model is used for many of products or periods, computation time is still too long. In these cases, an approximation is used to speed up calculations. This approximation uses two models that are very similar to the second model:

- model 2a:
in this model the variable that determines whether or not to order is assumed to be continuous for class B- and class C-products and binary for class A-products (this variable should be binary for all products); the rest of this model is the same as the second model.
- model 2b:
in this model the number of transports in each period is an input obtained as output from 2a (this should be a variable in every period); the rest of this model is the same as the second model.

The approximation has the following procedure:

First model 2a is solved. Part of the solution of this model is the number of transports in each period which may be lower than the number of orders. Next model 2b is solved, using the number of transports from the solution of model 2a. With the optimal solution of model 2b, an approximate solution of the second model is obtained. In practice, the approximation appears to perform very good. Tests showed that the approximation provides most of the times the same solution as the "global" second model, in far less computation time.

The third model provides the information required by the user for decision making. This model determines the exact values of all the factors that cause logistics costs and the values of all the components of logistics costs, by using the output of the second model (the optimization).

3.3 Solving the model

This solution-procedure is implemented for repeated use on a VAX computer system, using the OMP computer package. This package can solve MIP-problems (using the Branch and Bound method) up to 5000 variables and 2500 constraints (larger versions up to 30000 variables and 15000 constraints are also available). A special feature of this package is the "Automatic Pilot". The automatic pilot provides the possibility to create menus for solving the model and handling data and solution in a user-friendly manner. In this case, the three models that have to be solved to get the total solution can automatically be solved in the right order, each of them using output of the former model. The computer is connected to a central database. Most of the data to be used in the model are stored in the database, and the automatic pilot is programmed to import the required data from the database. The easy data gathering and user-friendly menus, the solution procedure and the solution presentation make the model easy to use.

4. Application of the model

After validating the model using techniques discussed by Landry et al. (1983), the model was used with real data to see the differences (regarding decisions and associated costs) between the model and the present situation. The influences of some logistics influential factors were also measured with the model. The most important results are discussed in this section.

To perform the above mentioned study a period of four weeks and suppliers in France, Belgium and Luxembourg are considered. These suppliers were divided into three regions, of which two regions were used for simulating several scenarios. In order to arrange results conveniently, the costs are presented per supplier. Because transportation costs are determined per period and not per supplier, they have to be allocated over the suppliers. This is done by a clustering factor, which is for every supplier in a region defined as (weight in kg; volume in m^3 ; based on transportation agreements there is a minimum weight of 300 kg/m^3):

$$Factor(i) = \frac{1}{3} * \left[\frac{distance(i)}{\sum_{j \in region} distance(j)} + \frac{volume(i)}{\sum_{j \in region} volume(j)} + \frac{\max\{weight(i), 300 * volume(i)\}}{\sum_{j \in region} \max\{weight(j), 300 * volume(j)\}} \right] \quad (4)$$

Note that Factor (i) is determined per supplier and distance (i) is the distance of the supplier i to the factory.

In this section the results for some of the suppliers are given. Because of the confidentiality of the data, these suppliers are numbered and not named. To give a clear picture, sometimes the results for only one product or supplier are given. The applications of the model to be discussed are:

- Optimization of the logistical decisions (using the present data).
- Studying the influence of interest rate.
- Investigation of the cost effects of changing the package.
- Analyzing the effects of changing the distance between a supplier and the factory.

4.1 Optimization of the logistics decisions.

The model is applied to a number of real situations, and in general the model realizes savings of about 6% on logistics costs (compared with the original situation). Table 2 illustrates an example for a region of six suppliers, where the average saving is 8.3%. The "original" columns give the present situation; the "model" columns give the solution of the model. The cost-savings are attained by changing ordering frequencies. The negative cost-savings for the fifth supplier are due to the allocation of transportation costs. The last two columns present the number of orders for the original and model solutions. The sum of ordering frequencies is larger than the number of transports to the suppliers, indicated in the last two cells, due to transport grouping. For suppliers which have low turnover, the order frequency is lower, for one supplier with high turnover, order frequency is higher in the optimal solution. The lower ordering frequency for most suppliers can be explained by the large distance of these suppliers to the factory and the low supplier density in France.

supplier	total costs (original)	total costs (model)	savings of model	savings of model in %	number of orders (original)	number of orders (model)
1	247.74	214.03	33.71	13.61%	2	1
2	8098.02	7313.34	784.68	9.69%	4	6
3	1450.42	1390.26	60.16	4.15%	4	2
4	3415.41	2572.92	842.49	24.67%	4	1
5	8298.87	8316.01	-17.14	-0.21%	4	4
6	4582.14	4118.34	463.80	10.12%	4	2
total	26092.60	23924.90	2167.70	8.31%	22	16
total number of transports					13	12

table 2: Solution comparison: model versus original

4.2 The influence of interest.

Holding cost is a function of the interest rate and other factors. Therefore, the interest rate has an impact on ordering decisions. The choice between market rate and opportunity cost and the problems involved in determining the opportunity cost make it difficult to set an accurate interest rate. As such, the influence of varying interest rate is investigated. Minor changes in the interest rate do not have a spectacular impact on ordering decisions, for example a 1.5 or 2 times higher interest rate caused more orders only for a few suppliers.

4.3 Changing the packaging unit.

Because the packaging unit considered for a part is an input, research is carried out to verify the influence of the packaging unit on logistics costs. Often used packaging units are the L-series. These units consist of a wooden pallet, on which a number of wooden segments can be built to make a box. The more segments are used, the larger the box is: a box with 4 wooden segments is twice as large as box with 2 segments (the number of segments is given by the number after the L, see table 3). The larger the size of the box, the higher is the cost of using it. But the cost per volume unit (e.g. m³) declines. This and the fact that one large packaging unit is easier to handle than two small packaging units, make larger units cheaper to use. The model also confirms that larger packaging units means lower costs. An example for one purchase part is given in table 3. Only in a

few situations, the larger packaging unit resulted in less orders, the lower packaging costs do not compensate the higher inventory costs, for example: every week one packaging unit is ordered; doubling the size of the unit means one order every two weeks, so extra inventory has to be kept.

packaging unit	packaging units needed	packaging costs	material handling costs	inventory costs	total costs
L4	84	1489.32	672.00	717.92	4556.13
L6	56	1304.24	448.00	719.58	4148.72

Remark: transportation costs and transport-inventory costs do not change

table 3: the effect of different packaging units

4.4 Changing the location of the supplier.

As pointed out before, the ordering frequency in the optimal solution of the model is very low. This is mainly due to the large distance of the French suppliers to the factory. Table 4 shows that reducing the distance to the factory for one supplier leads to more orders. The supplier in table 4, who is not in a grouped transport with other suppliers in the optimal solution, is set fictively at half the original distance to the factory, making transportation costs half as large. This doubles the ordering (and transportation) frequency.

costs per transport	number of transports	transportation costs	inventory costs	total costs
303.80	1	303.80	654.10	2681.40
151.90	2	303.80	466.41	2493.71

Remark: the other costs do not change

table 4: the effect of the location of the supplier

4.5 Conclusions of the applications

The mathematical model can be a helpful tool in the decision process. Not only can optimal solutions using current values of influential factors (like packaging and tariffs) be determined, but also the influence of changing influential factors can be measured.

Logistics costs using the model are about 6% lower than logistics costs in the current situation. Given the total logistical expenditures of NedCar, this 6% is a substantial amount of money, which makes the use of this model beneficial. The last application, where the influence of the distance is measured, is an example of how (by changing values of influential factors) the model can be used for supplier choice: maybe it is better to purchase at higher costs from a supplier that is closer to the factory, than to purchase at lower costs from a supplier that is far away. These trade-offs between purchase costs and logistics costs can be made with help of the model. The model can easily be used for determining and continuously revising rules of thumb. And even the advantages of modern developments like sequential deliveries and warehousing can be investigated with the model.

5. Implementation

Building a good model is not the end of implementing a quantitative approach in practice, it is only a part. Providing accurate data and convincing the user are also important issues in the implementation.

The quality of the model is largely dependent on the quality of the data. It is therefore very important that data are correct, and data-input is error-free. As such, duplicating databases must be prevented as much as possible. All this together makes a good interface between a dependable database and the model a must. The model developed in this paper is connected with an existing central MRP database, which is very dependable. Using an automatic interface between the model and the database reduces the risk of data-input errors to minimal.

Having a valid model and accurate data does not guarantee that the model will be used in practice. The potential user's skill and attitude are the keys in the actual use of the model. The user must:

1. Be trained to work with the model.

The user must be trained to know to which extent the model can be used. This is important because the user should not follow blindly the output and must use the model with caution. Users always have to interpret the solutions provided by the model and check whether they are obtainable with common sense. The user must also check whether the model conditions are satisfied.

2. Trust the model and want to work with the model.

This can be achieved by involving the user during different stage of model building and by having a user friendly interface.

In our case, the user was involved in the development process of the model and thus trusts the model. He is also trained to work with the model. The automatic interface with the database, the user-menus and the clear presentation of the optimization results were important for attracting the user to work with the model.

6. Conclusions

Given the current trends in Europe and in the world, the importance of logistics is growing faster than ever. This intensifies logistical problems, making the search for further logistical improvement more beneficial. It should be investigated how logistics decisions can be improved. The changing logistics environment gives the need to revise rules of thumb continuously and makes standard solutions not usable in all situations (Cohen and Lee (1989)). A more quantitative approach provides better solutions than current decision procedures. With mixed integer (linear) programming many real-world problems can be modeled. In this paper a MIP model is developed which can minimize total logistics costs by balancing all logistics decisions.

Because of the large number of decisions to make and the large number of relations these decisions are based on, the size of the model quickly gets out of proportion. This is often a problem in mathematical programming. Real world problems are very complex, and modeling them leads to large models that generally have very large computation times. Reducing model size, without making the model unrealistic, is therefore often important. This paper showed how a large scale model can be reformulated by reducing the number of decisions variables, the number of periods, the number of products and the use of realistic approximations.

When model size is reduced, the model can be checked with reality. When a correct, solvable and realistic model is obtained the model building is completed. But model building is not all. Other factors regarding data and the user are at least as important as the model.

When all factors are taken into account, the quantitative approach can have great benefits. The first benefit is that the model leads to significant cost-savings, in our case more than two million Guilders a year. These cost-savings are realized because the model gets a "global" logistics optimum. The second benefit is a more structured and quantitative decision making process. That means the user changes values of influential factors, foresees the change in the solution, runs the model, and then checks whether the solution of the model matches his expectations. There is no problem if the model and the user get the same solution, but when the model and the user get different solutions, the user is forced to ask himself a few questions, e.g. Why did the model provide another solution? Is the solution of the model better? Why is it better? This process makes the decision making more challenging, and more improvement can be realized. And for logistics improvement is essential.

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Appendix 1: The model.

Part of the model as presented in section 3. The use of mathematical notation is avoided as much as possible. Input parameters are in *italic*, decision variables are in normal letters printed.

The following indices are used:

- t = time period;
- p = purchase part;
- u = packaging unit;
- s = supplier;
- r = supplier;
- k = truck.

The indicator (zero-one) variables that are used have the following explanation:

Order(t,p)	Order(t,p)=1, if part p is ordered in period t ; Order(t,p)=0, otherwise.
Packaging Unit(p,u)	Packaging Unit(p,u)=1, if packaging unit u is used for part p ; Packaging Unit(p,u)=0, otherwise.
Truck Stop(t,s,k)	Truck Stop(t,s,k)=1, if truck k stops at supplier s in period t ; Truck Stop(t,s,k)=0, otherwise.
Route(t,r,s,k)	Route(t,r,s,k)=1, if truck k stops at supplier r immediately before supplier s in period t ; Route(t,r,s,k)=0, otherwise.
No Subtour(t,s,k)	continuous help variable.

Objective function:

Minimize $\sum_t \sum_p \{ \text{Ordering Cost}(t,p) + \text{Material Handling Cost}(t,p) + \text{Inventory Cost}(t,p) \}$
 $+ \sum_t \sum_p \sum_u \text{Packaging Cost}(t,p,u) + \sum_t \sum_k \text{Transportation Cost}(t,k)$

For all periods and parts:

Ordering Cost(t,p) = Order(t,p) * *ordering cost per order*

Material Handling Cost(t,p) = $\sum_u$ Ordered Packaging Units(t,p,u) * *handling cost per unit*

Inventory Cost(t,p) = $\sum_u$ Inventory(t,p) * Packaging Unit(p,u) * *inventory holding cost(p,u)*

For all periods, parts and packaging units:

$$\text{Packaging Cost}(t,p,u) = \text{Ordered Packaging Units}(t,p,u) * \text{packaging cost per unit}(u)$$

For all periods and trucks:

$$\text{Transportation Cost}(t,k) = \sum_r \sum_s \text{Route}(t,r,s,k) * \text{distance}(r,s) * \text{distance tariff}$$

Constraints:

(i) For all periods and parts:

$$\text{Ordered Quantity}(t,p) \geq \text{minimal ordering quantity}(p) * \text{Order}(t,p)$$

$$\text{Ordered Quantity}(t,p) \leq \text{maximal ordering quantity}(p) * \text{Order}(t,p)$$

(ii) For all periods and parts:

$$\text{Ordered Quantity}(t,p) = \sum_u \text{Ordered Packaging Units}(t,p,u) * \text{number of parts per packaging unit}(p,u)$$

For all periods, parts and packaging units:

$$\text{Ordered Packaging Units}(t,p,u) \in \{0,1,2,\dots\}$$

(iii) For all periods and parts:

$$\text{Inventory}(t,p) = \text{Inventory}(t-1,p) + \text{Ordered Quantity}(t-\text{leadtime}(p),p) - \text{usage}(t,p)$$

$$\text{Inventory}(t,p) \geq \text{safety stock}(p)$$

(iv) For all periods and parts:

$$\sum_u \text{Packaging Unit}(p,u) = 1$$

(v) For all periods, parts and packaging units:

$$\text{Ordered Packaging Units}(t,p,u) \leq \text{maximal ordering quantity}(p) * \text{Packaging Unit}(p,u)$$

(vi) For all periods:

$$\sum_p \sum_u \text{Inventory}(t,p) * \text{Packaging Unit}(p,u) * m^2\text{-use per packaging unit}(u) / \{\text{number of parts per packaging unit}(p,u) * \text{staple height}(u)\} \leq \text{available space}$$

(vii) For all periods and packaging units:

$$\sum_p \text{Inventory}(t,p) * \text{Packaging Unit}(p,u) / \{\text{number of parts per packaging unit}(p,u)\} + \sum_p \sum_{\tau=t-\text{leadtime}(p)} \text{Ordered Packaging Units}(\tau,p,u) \leq \text{available packaging units}(u)$$

(viii) For all periods and trucks:

$$\sum_s \sum_p \in_s \sum_u \text{Ordered Packaging Units}(t,p,u) * \text{Truck Stop}(t,s,k) * \text{space consumption}(u) \leq \text{capacity of truck } k \text{ in } m^3$$

$$\sum_s \sum_p \in_s \sum_u \text{Ordered Packaging Units}(t,p,u) * \text{Truck Stop}(t,s,k) * \text{weight consumption}(p,u) \leq \text{capacity of truck } k \text{ in } kg$$

(ix) For all periods and suppliers:

$$\sum_k \text{Truck Stop}(t,s,k) \geq \max_{p=\text{product of } s} \{\text{Order}(t,p)\}$$

(x) For all periods, suppliers and trucks:

$$\sum_r \text{Route}(t,r,s,k) = \text{Truck Stop}(t,s,k)$$

$$\sum_s \text{Route}(t,r,s,k) = \text{Truck Stop}(t,r,k)$$

(xi) For all periods, suppliers (s), suppliers (r ≠ s) and trucks:

$$\text{No Subtour}(t,r,k) - \text{No Subtour}(t,s,k) - \{\sum_s \text{Truck Stop}(t,s,k)\} * \text{Route}(t,r,s,k) \leq \sum_s \text{Truck Stop}(t,s,k) - 1$$

(xii) All variables ≥ 0

Note that in constraint set (x), each tour starts and ends at the factory.

Appendix 2: An example of linearization.

Consider the following simple transportation problem:

A load, which is variable in size, has to be transported. For the transportation a choice can be made between a large truck (LT=1) and a small truck (LT=0). There is also a choice between loading a truck full (FT=1) or not loading it full (FT=0). Regarding these choices two constraints have to be satisfied:

1. a small truck must be loaded full;
2. a small truck can always be used, a large truck can not always be used because of road conditions (this is determined by a constant α . If $\alpha \geq 1$: a small or a large truck can be used; if $\alpha < 1$: only a small truck can be used).

With each combination of choices some costs are incurred.

This gives the following non-linear model:

$$\begin{aligned}
 &\text{minimize} && a*LT*FT + b*LT*(1-FT) + c*(1-LT)*FT \\
 & && (= (a-b-c)*LT*FT + b*LT + c*FT) \\
 &\text{subject to} && FT \geq 1-LT \\
 & && LT \leq \alpha \\
 & && LT, FT \in \{0,1\}
 \end{aligned}$$

This model must be linearized. Straightforward linearizing the above model would give the next formulation of the problem:

$$\begin{aligned}
 &\text{minimize} && (a-b-c)*LTF + b*LT + c*FT \\
 &\text{subject to} && LTF \leq LT && (LTF \text{ linearizes the product } LT*FT) \\
 & && LTF \leq FT \\
 & && LTF \geq LT + FT - 1 \\
 & && FT \geq 1 - LT \\
 & && LT \leq \alpha \\
 & && FT, LT \in \{0,1\}, LTF \in \mathbb{R}
 \end{aligned}$$

Now consider the following definition of variables (remark: other formulations are also possible):

$LTF = 1$ if a full large truck is used;

$LTNF = 1$ if a not full large truck is used;

$NLTF = 1$ if a full small truck is used.

With these definitions, the following model can be formulated:

$$\begin{aligned}
 &\text{minimize} && a*LTF + b*LTNF + c*NLTF \\
 &\text{subject to} && LTF + LTNF + NLTF = 1 \\
 & && LTF + LTNF \leq \alpha \\
 & && LTF, NLTF, LTNF \in \{0,1\}
 \end{aligned}$$

This problem has more binary variables (3 instead of 2), but in total results in less variables (continuous and binary) and constraints. The model then can be solved easier by the use of priority branching.

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