Tilburg University

Application of mixed integer programming to a large scale logistics problem
Ashayeri, J.; Westerhof, A.J.; van Alst, P.H.E.L.

Publication date:
1992

Link to publication in Tilburg University Research Portal

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Department of Economics

Research Memorandum

R37

Integer Programming

Logistics
APPLICATION OF MIXED INTEGER PROGRAMMING TO A LARGE SCALE LOGISTICS PROBLEM
J. Ashayeri, A.J. Westerhof, P.H.E.L. van Alst

FEW 586

Communicated by Prof.dr. F.A. van der Duyn Schouten
Application of Mixed Integer Programming To
A Large Scale Logistics Problem

J. Ashayeri , A.J. Westerhof
Department of Econometrics, Tilburg University, The Netherlands

P.H.E.L. van Alst
Department Head Controlling Logistics, NedCar, Born, The Netherlands

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 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
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](image)

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](image-url)
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/transport-
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)):

\[ d = K \sqrt{\frac{mn}{\rho}} \]  

(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: \( K = 0.6 \));
- \( n \): is the number of suppliers in a supply-region;
- \( \rho \): is the supplier density (the number of suppliers per square kilometer).

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

\[ D_{\text{total}} = D + d - D + K \sqrt{\frac{mn}{\rho}} - D + K \sqrt{\frac{n}{\rho}} \sqrt{m} \]  

(2)

Where:
- \( D \): is the average distance from a supply region to the factory.

\( D \) can be determined as follows:
\[ D = \frac{1}{\text{number of suppliers}} \sum_{\text{supplier in region}} \text{distance supplier to factory} \]  

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.
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 m³; based on transportation agreements there is a minimum weight of 300 kg/m³):
\[
\text{Factor}(i) = \frac{1}{3} \left[ \frac{\text{distance}(i)}{\sum_{j \in \text{region}} \text{distance}(j)} + \frac{\text{volume}(i)}{\sum_{j \in \text{region}} \text{volume}(j)} + \frac{\max\{\text{weight}(i), 300 \cdot \text{volume}(i)\}}{\sum_{j \in \text{region}} \max\{\text{weight}(j), 300 \cdot \text{volume}(j)\}} \right]
\] (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.
### Table 2: Solution comparison: model versus original

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

| total number of transports | 13 | 12 |

#### 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.

<table>
<thead>
<tr>
<th>packaging unit</th>
<th>packaging units needed</th>
<th>packaging costs</th>
<th>material handling costs</th>
<th>inventory costs</th>
<th>total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4</td>
<td>84</td>
<td>1489.32</td>
<td>672.00</td>
<td>717.92</td>
<td>4556.13</td>
</tr>
<tr>
<td>L6</td>
<td>56</td>
<td>1304.24</td>
<td>448.00</td>
<td>719.58</td>
<td>4148.72</td>
</tr>
</tbody>
</table>

*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.

<table>
<thead>
<tr>
<th>costs per transport</th>
<th>number of transports</th>
<th>transportation costs</th>
<th>inventory costs</th>
<th>total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>303.80</td>
<td>1</td>
<td>303.80</td>
<td>654.10</td>
<td>2681.40</td>
</tr>
<tr>
<td>151.90</td>
<td>2</td>
<td>303.80</td>
<td>466.41</td>
<td>2493.71</td>
</tr>
</tbody>
</table>

*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.

References
Daganzo, C.F., *The Distance traveled to visit N points with a maximum of C stops per vehicle: an analytic model and an application*. Transportation science Vol. 18, No. 4, 1984.
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:
- \( \text{Order}(t,p) \):
  - \( \text{Order}(t,p) = 1 \), if part \( p \) is ordered in period \( t \);
  - \( \text{Order}(t,p) = 0 \), otherwise.
- \( \text{Packaging Unit}(p,u) \):
  - \( \text{Packaging Unit}(p,u) = 1 \), if packaging unit \( u \) is used for part \( p \);
  - \( \text{Packaging Unit}(p,u) = 0 \), otherwise.
- \( \text{Truck Stop}(t,s,k) \):
  - \( \text{Truck Stop}(t,s,k) = 1 \), if truck \( k \) stops at supplier \( s \) in period \( t \);
  - \( \text{Truck Stop}(t,s,k) = 0 \), otherwise.
- \( \text{Route}(t,r,s,k) \):
  - \( \text{Route}(t,r,s,k) = 1 \), if truck \( k \) stops at supplier \( r \) immediately before supplier \( s \) in period \( t \);
  - \( \text{Route}(t,r,s,k) = 0 \), otherwise.
- \( \text{No Subtour}(t,s,k) \): 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:
- \( \text{Ordering Cost}(t,p) = \text{Order}(t,p) \times \text{ordering cost per order} \)
- \( \text{Material Handling Cost}(t,p) = \sum_u \text{Ordered Packaging Units}(t,p,u) \times \text{handling cost per unit} \)
- \( \text{Inventory Cost}(t,p) = \sum_u \text{Inventory}(t,p) \times \text{Packaging Unit}(p,u) \times \text{inventory holding cost}(p,u) \)
For all periods, parts and packaging units:
Packaging Cost(t,p,u) = Ordered Packaging Units(t,p,u) * packaging cost per unit(u)

For all periods and trucks:
Transportation Cost(t,k) = \sum_r \sum_s \text{Route}(t,r,s,k) * distance(r,s) * 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) * number of parts per packaging unit(p,u)

For all periods, parts and packaging units:
Ordered Packaging Units(t,p,u) \in \{0,1,2,...\}

(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{safe 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_{r=\text{leadtime}(p)} \text{Ordered Packaging Units}(r,p,u) \leq \text{available packaging units}(u)
(viii) For all periods and trucks:
\[ \sum_t \sum_{p \in s} \sum_u \text{Ordered Packaging Units}(t,p,u) \times \text{Truck Stop}(t,s,k) \times \text{space consumption}(u) \leq \text{capacity of truck } k \text{ in m}^3 \]
\[ \sum_t \sum_{p \in s} \sum_u \text{Ordered Packaging Units}(t,p,u) \times \text{Truck Stop}(t,s,k) \times \text{weight consumption}(p,u) \leq \text{capacity of truck } k \text{ in kg} \]

(ix) For all periods and suppliers:
\[ \sum_t \text{Truck Stop}(t,s,k) \geq \max_{p=\text{product of } s} \{\text{Order}(t,p)\} \]

(x) For all periods, suppliers and trucks:
\[ \sum_t \text{Route}(t,r,s,k) = \text{Truck Stop}(t,s,k) \]
\[ \sum_t \text{Route}(t,r,s,k) = \text{Truck Stop}(t,r,k) \]

(xi) For all periods, suppliers (s), suppliers (r ≠ s) and trucks:
\[ \text{No Subtour}(t,r,k) - \text{No Subtour}(t,s,k) - \{\sum_t \text{Truck Stop}(t,s,k)\} \times \text{Route}(t,r,s,k) \leq \sum_t \text{Truck Stop}(t,s,k) - 1 \]

(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 \( \alpha \). 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:

\[
\begin{align*}
\text{minimize} & \quad a^\prime L^T F^T + b^\prime L^T (1-F^T) + c^\prime (1-L^T) F^T \\
& \quad = (a-b-c)^\prime L^T F^T + b^\prime L^T + c^\prime F^T \\
\text{subject to} & \quad F^T \geq 1-L^T \\
& \quad L^T \leq \alpha \\
& \quad L^T, F^T \in \{0,1\}
\end{align*}
\]

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

\[
\begin{align*}
\text{minimize} & \quad (a-b-c)^\prime L^T F^T + b^\prime L^T + c^\prime F^T \\
\text{subject to} & \quad L^T F^T \leq L^T \quad \text{(LTF linearizes the product } L^T F^T) \\
& \quad L^T F^T \leq F^T \\
& \quad L^T F^T \geq L^T + F^T - 1 \\
& \quad F^T \geq 1 - L^T \\
& \quad L^T \leq \alpha \\
& \quad F^T, L^T \in \{0,1\}, L^T F^T \in \mathbb{R}
\end{align*}
\]

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

- \( L^T F^T = 1 \) if a full large truck is used;
- \( L^T N^F = 1 \) if a not full large truck is used;
- \( N^L T F^T = 1 \) if a full small truck is used.

With these definitions, the following model can be formulated:

\[
\begin{align*}
\text{minimize} & \quad a^\prime L^T F^T + b^\prime L^T N^F + c^\prime N^L T F^T \\
\text{subject to} & \quad L^T F^T + L^T N^F + N^L T F^T = 1 \\
& \quad L^T F^T + L^T N^F \leq \alpha \\
& \quad L^T F^T, N^L T F^T, L^T N^F \in \{0,1\}
\end{align*}
\]

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.
IN 1991 REEDS VERSCHENDEN

466 Prof. Dr. Th. C. M. J. van de Klundert - Prof. Dr. A. B. T. M. van Schaik
Economische groei in Nederland in een internationaal perspectief

467 Dr. Sylvester C. W. Eijffinger
The convergence of monetary policy - Germany and France as an example

468 E. Nijssen
Strategisch gedrag, planning en prestatie. Een inductieve studie
binnen de computerbranche

469 Anne van den Nouweland, Peter Borm, Guillermo Owen and Stef Tijs
Cost allocation and communication

470 Drs. J. Grazell en Drs. C. H. Veld
Motieven voor de uitgifte van converteerbare obligatie leningen en
warrant-obligatie leningen: een agency-theoretische benadering

471 P. C. van Batenburg, J. Kriens, W. M. Lammerts van Bueren and
R. H. Veenstra
Audit Assurance Model and Bayesian Discovery Sampling

472 Marcel Kerkhofs
Identification and Estimation of Household Production Models

473 Robert P. Gilles, Guillermo Owen, René van den Brink
Games with Permission Structures: The Conjunctive Approach

474 Jack P. C. Kleijnen
Sensitivity Analysis of Simulation Experiments: Tutorial on Regression
Analysis and Statistical Design

475 C. P. M. van Hoesel
An \( O(n \log n) \) algorithm for the two-machine flow shop problem with
controllable machine speeds

476 Stephan G. Vanneste
A Markov Model for Opportunity Maintenance

477 F. A. van der Duyn Schouten, M. J. G. van Eijs, R. M. J. Heuts
Coordinated replenishment systems with discount opportunities

478 A. van den Nouweland, J. Potters, S. Tijs and J. Zarzuelo
Cores and related solution concepts for multi-choice games

479 Drs. C. H. Veld
Warrant pricing: a review of theoretical and empirical research

480 E. Nijssen
De Miles and Snow-typologie: Een exploratieve studie in de meubel-
branche

481 Harry G. Barkema
Are managers indeed motivated by their bonuses?
<table>
<thead>
<tr>
<th>Page</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>482</td>
<td>Jacob C. Engwerda, André C.M. Ran, Arie L. Rijkeboer</td>
<td>Necessary and sufficient conditions for the existence of a positive definite solution of the matrix equation $X + A X^{-1} A = I$</td>
</tr>
<tr>
<td>483</td>
<td>Peter M. Kort</td>
<td>A dynamic model of the firm with uncertain earnings and adjustment costs</td>
</tr>
<tr>
<td>484</td>
<td>Raymond H.J.M. Gradus, Peter M. Kort</td>
<td>Optimal taxation on profit and pollution within a macroeconomic framework</td>
</tr>
<tr>
<td>485</td>
<td>René van den Brink, Robert P. Gilles</td>
<td>Axiomatizations of the Conjunctive Permission Value for Games with Permission Structures</td>
</tr>
<tr>
<td>487</td>
<td>Pim Adang, Bertrand Melenberg</td>
<td>Intratemporal uncertainty in the multi-good life cycle consumption model: motivation and application</td>
</tr>
<tr>
<td>488</td>
<td>J.H.J. Roemen</td>
<td>The long term elasticity of the milk supply with respect to the milk price in the Netherlands in the period 1969-1984</td>
</tr>
<tr>
<td>489</td>
<td>Herbert Hamers</td>
<td>The Shapley-Entrance Game</td>
</tr>
<tr>
<td>490</td>
<td>Rezaul Kabir and Theo Vermaelen</td>
<td>Insider trading restrictions and the stock market</td>
</tr>
<tr>
<td>491</td>
<td>Piet A. Verheyen</td>
<td>The economic explanation of the jump of the co-state variable</td>
</tr>
<tr>
<td>492</td>
<td>Drs. F.L.J.W. Manders en Dr. J.A.C. de Haan</td>
<td>De organisatorische aspecten bij systeemontwikkeling een beschouwing op besturing en verandering</td>
</tr>
<tr>
<td>493</td>
<td>Paul C. van Batenburg and J. Kriens</td>
<td>Applications of statistical methods and techniques to auditing and accounting</td>
</tr>
<tr>
<td>494</td>
<td>Ruud T. Frambach</td>
<td>The diffusion of innovations: the influence of supply-side factors</td>
</tr>
<tr>
<td>495</td>
<td>J.H.J. Roemen</td>
<td>A decision rule for the (des)investments in the dairy cow stock</td>
</tr>
<tr>
<td>496</td>
<td>Hans Kremers and Dolf Talman</td>
<td>An SLSPP-algorithm to compute an equilibrium in an economy with linear production technologies</td>
</tr>
</tbody>
</table>
L.W.G. Strijbosch and R.M.J. Heuts
Investigating several alternatives for estimating the compound lead time demand in an (s,Q) inventory model

Bert Bettonvil and Jack P.C. Kleijnen
Identifying the important factors in simulation models with many factors

Drs. H.C.A. Roest, Drs. F.L. Tijssen
Beheersing van het kwaliteitsperceptieproces bij diensten door middel van keurmerken

B.B. van der Genugten
Density of the F-statistic in the linear model with arbitrarily normal distributed errors

Harry Barkema and Sytse Douma
The direction, mode and location of corporate expansions

Gert Nieuwenhuis
Bridging the gap between a stationary point process and its Palm distribution

Chris Veld
Motives for the use of equity-warrants by Dutch companies

Pieter K. Jagersma
Een etiologie van horizontale internationale ondernemingsexpansie

B. Kaper
On M-functions and their application to input-output models

A.B.T.M. van Schaik
Produktiviteit en Arbeidsparticipatie

Peter Borm, Anne van den Nouweland and Stef Tijs
Cooperation and communication restrictions: a survey

Willy Spanjers, Robert P. Gilles, Pieter H.M. Ruys
Hierarchical trade and downstream information

Martijn P. Tummers
The Effect of Systematic Misperception of Income on the Subjective Poverty Line

A.G. de Kok
Basics of Inventory Management: Part 1
Renewal theoretic background

J.P.C. Blanc, F.A. van der Duyn Schouten, B. Pourbabai
Optimizing flow rates in a queueing network with side constraints

R. Peeters
On Coloring j-Unit Sphere Graphs
Drs. J. Dagevos, Drs. L. Oerlemans, Dr. F. Boekema
Regional economic policy, economic technological innovation and networks

Erwin van der Krabben
Het functioneren van stedelijke onroerend-goed-markten in Nederland - een theoretisch kader

Drs. E. Schaling
European central bank independence and inflation persistence

Peter M. Kort
Optimal abatement policies within a stochastic dynamic model of the firm

Pim Adang
Expenditure versus consumption in the multi-good life cycle consumption model

Pim Adang
Large, infrequent consumption in the multi-good life cycle consumption model

Raymond Gradus, Sjak Smulders
Pollution and Endogenous Growth

Raymond Gradus en Hugo Keuzenkamp
Arbeidsongeschiktheid, subjectief ziektegevoel en collectief belang

A.G. de Kok
Basics of inventory management: Part 2
The (R,S)-model

A.G. de Kok
Basics of inventory management: Part 3
The (b,Q)-model

A.G. de Kok
Basics of inventory management: Part 4
The (s,S)-model

A.G. de Kok
Basics of inventory management: Part 5
The (R,b,Q)-model

A.G. de Kok
Basics of inventory management: Part 6
The (R,s,S)-model

Rob de Groof and Martin van Tuijl
Financial integration and fiscal policy in interdependent two-sector economies with real and nominal wage rigidity
527  A.G.M. van Eijs, M.J.G. van Eijs, R.M.J. Heuts  
Gecoördineerde bestelsystemen  
een management-georiënteerde benadering

528  M.J.G. van Eijs  
Multi-item inventory systems with joint ordering and transportation decisions

529  Stephan G. Vanneste  
Maintenance optimization of a production system with buffer capacity

530  Michel R.R. van Bremen, Jeroen C.G. Zijlstra  
Het stochastische variantie optiewaarderingsmodel

531  Willy Spanjers  
Arbitrage and Walrasian Equilibrium in Economies with Limited Information
IN 1992 REEDS VERSCHENEN

532 F.G. van den Heuvel en M.R.M. Turlings
Privatisering van arbeidsongeschiktheidsregelingen
Refereed by Prof. Dr. H. Verbon

533 J.C. Engwerda, L.G. van Willigenburg
LQ-control of sampled continuous-time systems
Refereed by Prof. Dr. J.M. Schumacher

534 J.C. Engwerda, A.C.M. Ran & A.L. Rijkeboer
Necessary and sufficient conditions for the existence of a positive
definite solution of the matrix equation X + A\(AX^{-1}A\) = Q.
Refereed by Prof. Dr. J.M. Schumacher

535 Jacob C. Engwerda
The indefinite LQ-problem: the finite planning horizon case
Refereed by Prof. Dr. J.M. Schumacher

536 Gert-Jan Otten, Peter Borm, Ton Storcken, Stef Tijs
Effectivity functions and associated claim game correspondences
Refereed by Prof. Dr. P.H.M. Ruys

537 Jack P.C. Kleijnen, Gustav A. Alink
Validation of simulation models: mine-hunting case-study
Refereed by Prof. Dr. ir. C.A.T. Takkenberg

538 V. Feltkamp and A. van den Nouweland
Controlled Communication Networks
Refereed by Prof. Dr. S.H. Tijs

539 A. van Schaik
Productivity, Labour Force Participation and the Solow Growth Model
Refereed by Prof. Dr. Th.C.M.J. van de Klundert

540 J.J.G. Lemmen and S.C.W. Eijffinger
The Degree of Financial Integration in the European Community
Refereed by Prof. Dr. A.B.T.M. van Schaik

541 J. Bell, P.K. Jagersma
Internationale Joint Ventures
Refereed by Prof. Dr. H.G. Barkema

542 Jack P.C. Kleijnen
Verification and validation of simulation models
Refereed by Prof. Dr. ir. C.A.T. Takkenberg

543 Gert Nieuwenhuis
Uniform Approximations of the Stationary and Palm Distributions
of Marked Point Processes
Refereed by Prof. Dr. B.B. van der Genugten
R. Heuts, P. Nederstigt, W. Roebroek, W. Selen
Multi-Product Cycling with Packaging in the Process Industry
Refereed by Prof.dr. F.A. van der Duyn Schouten

J.C. Engwerda
Calculation of an approximate solution of the infinite time-varying
LQ-problem
Refereed by Prof.dr. J.M. Schumacher

Raymond H.J.M. Gradus and Peter M. Kort
On time-inconsistency and pollution control: a macroeconomic approach
Refereed by Prof.dr. A.J. de Zeeuw

Drs. Dolph Cantrijn en Dr. Rezaul Kabir
De Invloed van de Invoering van Preferente Beschermingsaandelen op
Aandelenkoersen van Nederlandse Beursgenoteerde Ondernemingen
Refereed by Prof.dr. P.W. Moerland

Sylvester Eijffinger and Eric Schaling
Central bank independence: criteria and indices
Refereed by Prof.dr. J.J. Sijben

Drs. A. Schmeits
Geïntegreerde investerings- en financieringsbeslissingen; Implicaties
voor Capital Budgeting
Refereed by Prof.dr. P.W. Moerland

Peter M. Kort
Standards versus standards: the effects of different pollution
restrictions on the firm's dynamic investment policy
Refereed by Prof.dr. F.A. van der Duyn Schouten

Niels G. Noorderhaven, Bart Nooteboom and Johannes Berger
Temporal, cognitive and behavioral dimensions of transaction costs;
to an understanding of hybrid vertical inter-firm relations
Refereed by Prof.dr. S.W. Douma

Ton Storcken and Harrie de Swart
Towards an axiomatization of orderings
Refereed by Prof.dr. P.H.M. Ruys

J.H.J. Roemen
The derivation of a long term milk supply model from an optimization
model
Refereed by Prof.dr. F.A. van der Duyn Schouten

Geert J. Almekinders and Sylvester C.W. Eijffinger
Daily Bundesbank and Federal Reserve Intervention and the Conditional
Variance Tale in DM/$-Returns
Refereed by Prof.dr. A.B.T.M. van Schaik

Dr. M. Hetebrij, Drs. B.P.L. Jonker, Prof.dr. W.H.J. de Freytas
"Tussen achterstand en voorsprong" de scholings- en personeelsvoor-
zieningsproblematiek van bedrijven in de procesindustrie
Refereed by Prof.dr. Th.M.M. Verhallen
556 Ton Geerts
Regularity and singularity in linear-quadratic control subject to implicit continuous-time systems
Communicated by Prof.dr. J. Schumacher

557 Ton Geerts
Invariant subspaces and invertibility properties for singular systems: the general case
Communicated by Prof.dr. J. Schumacher

558 Ton Geerts
Solvability conditions, consistency and weak consistency for linear differential-algebraic equations and time-invariant singular systems: the general case
Communicated by Prof.dr. J. Schumacher

559 C. Fricker and M.R. Jaïbi
Monotonicity and stability of periodic polling models
Communicated by Prof.dr.ir. O.J. Boxma

560 Ton Geerts
Free end-point linear-quadratic control subject to implicit continuous-time systems: necessary and sufficient conditions for solvability
Communicated by Prof.dr. J. Schumacher

561 Paul G.H. Mulder and Anton L. Hempenius
Expected Utility of Life Time in the Presence of a Chronic Noncommunicable Disease State
Communicated by Prof.dr. B.B. van der Genugten

562 Jan van der Leeuw
The covariance matrix of ARMA-errors in closed form
Communicated by Dr. H.H. Tigelaar

563 J.P.C. Blanc and R.D. van der Mei
Optimization of polling systems with Bernoulli schedules
Communicated by Prof.dr.ir. O.J. Boxma

564 B.B. van der Genugten
Density of the least squares estimator in the multivariate linear model with arbitrarily normal variables
Communicated by Prof.dr. M.H.C. Paardekooper

565 René van den Brink, Robert P. Gilles
Measuring Domination in Directed Graphs
Communicated by Prof.dr. P.H.M. Ruys

566 Harry G. Barkema
The significance of work incentives from bonuses: some new evidence
Communicated by Dr. Th.E. Nijman
Rob de Groof and Martin van Tuijl
Commercial integration and fiscal policy in interdependent, financially integrated two-sector economies with real and nominal wage rigidity.
Communicated by Prof.dr. A.L. Bovenberg

F.A. van der Duyn Schouten, M.J.G. van Eijs, R.M.J. Heuts
The value of information in a fixed order quantity inventory system
Communicated by Prof.dr. A.J.J. Talman

E.N. Kertzman
Begrotingsnormering en EMU
Communicated by Prof.dr. J.W. van der Dussen

A. van den Elzen, D. Talman
Finding a Nash-equilibrium in noncooperative N-person games by solving a sequence of linear stationary point problems
Communicated by Prof.dr. S.H. Tijs

Jack P.C. Kleijnen
Verification and validation of models
Communicated by Prof.dr. F.A. van der Duyn Schouten

Jack P.C. Kleijnen and Willem van Groenendaal
Two-stage versus sequential sample-size determination in regression analysis of simulation experiments

Pieter K. Jagersma
Het management van multinationale ondernemingen: de concernstructuur

A.L. Hempenius
Explaining Changes in External Funds. Part One: Theory
Communicated by Prof.Dr.Ir. A. Kapteyn

J.P.C. Blanc, R.D. van der Mei
Optimization of Polling Systems by Means of Gradient Methods and the Power-Series Algorithm
Communicated by Prof.dr.ir. O.J. Boxma

Herbert Hamers
A silent duel over a cake
Communicated by Prof.dr. S.H. Tijs

Gerard van der Laan, Dolf Talman, Hans Kremers
On the existence and computation of an equilibrium in an economy with constant returns to scale production
Communicated by Prof.dr. P.H.M. Ruys

R.Th.A. Wagemakers, J.J.A. Moors, M.J.B.T. Janssens
Characterizing distributions by quantile measures
Communicated by Dr. R.M.J. Heuts
579 J. Ashayeri, W.H.L. van Esch, R.M.J. Heuts
Amendment of Heuts-Selen's Lotsizing and Sequencing Heuristic for
Single Stage Process Manufacturing Systems
Communicated by Prof.dr. F.A. van der Duyn Schouten

580 H.G. Barkema
The Impact of Top Management Compensation Structure on Strategy
Communicated by Prof.dr. S.W. Douma

581 Jos Benders en Freek Aertsen
Aan de lijn of aan het lijntje: wordt slank produceren de mode?
Communicated by Prof.dr. S.W. Douma

582 Willem Haemers
Distance Regularity and the Spectrum of Graphs
Communicated by Prof.dr. M.H.C. Paardekooper

583 Jalal Ashayeri, Behnam Pourbabai, Luk van Wassenhove
Strategic Marketing, Production, and Distribution Planning of an
Integrated Manufacturing System
Communicated by Prof.dr. F.A. van der Duyn Schouten

584 J. Ashayeri, F.H.P. Driessen
Integration of Demand Management and Production Planning in a
Batch Process Manufacturing System: Case Study
Communicated by Prof.dr. F.A. van der Duyn Schouten

585 J. Ashayeri, A.G.M. van Eijs, P. Nederstigt
Blending Modelling in a Process Manufacturing System
Communicated by Prof.dr. F.A. van der Duyn Schouten