Decision Support for Flow Management in a Recycling Network

Ulrich Derigs  
Department of Information Systems and Operations Research, University of Cologne  
derigs@informatik.uni-koeln.de

Stefan Friederichs  
Department of Information Systems and Operations Research, University of Cologne  
stefan.friederichs@uni-koeln.de

Abstract

This paper describes a decision support system which has been developed for a company operating in the area of waste and raw material management. The system consists of two complementary components that help the company to improve its core business of buying recyclable waste materials from waste collection companies that are sold to recycling companies. Upstream, a real-time component for mobile devices supports procurement representatives during price negotiations with suppliers and thus helps to tighten profitable relationships. Downstream, a model-based optimization component maximizes the revenue generated by selling the purchased waste materials to paper mills and hence helps to improve the distribution network. The system has become a vital tool that helps the company to increase profits and trade volume while the duration of the planning process could be cut by more than half.

1. Introduction

During the last decade, the demand and trade of raw materials increased substantially, strongly influenced by the rapidly growing markets in Asia and South America. Hence, the use of secondary raw material and an effective waste and raw materials management received substantial interest by both researchers and practitioners.

High-quality recyclable waste materials are a scarce resource. Due to the growing demand of such waste materials, competition among waste dealers increased steadily during the last years. At the same time, margins dropped dramatically. Now, the main growth potential stems from a raise in trade volume that is only achievable if the company can offer higher bid-prices than its competitors.

Thus, for a waste dealer there are two main problems that need to be addressed: First, the procurement representatives should be supported during price and quantity negotiations with waste collection companies to ensure that only beneficial trades that yield a certain margin are entered and total trade volume can be raised. Secondly, the company needs to “match” the supply from ongoing purchases and the demand from contracts in a way that the total revenue is maximized. Our Decision Support System (DSS) supports flow management for a waste dealer by addressing these issues.

The remainder of the paper is organized as follows: in section 2, the company’s waste trading business and the problem leading to the system development as well as the system requirements will be reviewed. Section 3 gives an overview of the system environment and introduces its architecture, its components and integration with existing systems. In the last section, we review our approach and conclude the paper with some final remarks.

2. The Waste Trading Business

Our industry partner is a leading vendor of raw material management solutions in Europe and deals with waste materials such as paper, plastics and woods. As a waste dealer in the supply chain (Figure 1), the company buys waste materials from waste collection companies and sells them to recycling companies. Additional services such as transportation and packaging are offered, with transportation being conducted by external freight companies.

The quantities of recyclable waste materials offered in the market by waste collection companies are subject to intense fluctuations caused by exogenous factors. Therefore, procurement representatives travel
to numerous waste collection companies during the week and negotiate the quantity and price of different kinds of waste. All purchases are supplied during the following week and have to be picked up at the waste collectors’ loading sites and shipped to the recycling companies’ plants within that week as the company itself does not maintain any warehouses. Note that also the geographical distribution of waste collection sites offering waste differs from week to week.

Downstream, our industry partner enters monthly sales contracts with recycling companies that specify the price and the quantity of waste paper to deliver during the respective month. Sometimes, more than one sales contract is made with a single recycling company. By offering additional sales contracts with varying conditions (usually higher sales prices but lower quantity), recycling companies compete for high quality waste materials available in the market. In some cases, dependencies between the contracts made with one recycling company restrict the delivery to a higher payoff contract unless the other contracts with lower sales prices are fulfilled entirely.

Due to the fact that at the time the contracts with recycling companies are fixed the supply situation during the next month is still uncertain and there may occur a shortage of recyclable waste materials, the quantities specified in a contract are considered as target quantities.

As a result of the uncertain and varying supply situation, transportation has to be planned at the end of each week when the exact quantity and distribution of waste supplied by collection companies in the upcoming week are known.

Transportation is carried out by different external freight companies. Our industry partner maintains a transportation cost catalogue with information on contractual and historical prices for shipments. Here the price for a certain relation depends not only on the start and destination point, but also on the shipping method. Container shipments are usually more expensive than regular truck shipments since the freight company carrying out the transport has to pick up containers at a special container depot.

Before the introduction of our system the procurement representatives did not use any kind of system-based decision support during price negotiations. The only source of information was a printed list of all currently open sales contracts with recycling companies. Thus, setting bid-price accordingly was a task exclusively performed by drawing upon existing knowledge gathered “on the job”.

Likewise, the transportation plan was generated purely manually. The transportation planning process started on Thursday morning and included all purchases made by procurement representatives until Wednesday evening. Transportation orders for the following week had to be transferred to the freight companies around 2 p.m. the same day. Therefore, the maximal duration for planning was about 5-6 h.

3. System Design & Implementation

In this section, we present the concept and some implementation details of the developed decision support system. Figure 2 gives an overview of its components and the interaction with other systems/entities. On a high level view, the system exchanges information (directly or indirectly) with the waste collectors (suppliers) upstream, the recycling companies (buyers) downstream, and the carrier.

Following the DSS architecture proposed by Sprague und Watson [1], we have designed and
implemented a data, a model and a dialog component.

The central data component is responsible for validation, storage, management, and retrieval of all decision-related data in a dedicated (relational) database. The key information relevant for decision making are

- the monthly contracts with recycling companies,
- the transportation costs and the purchase orders made by the procurement representatives for distribution planning and

- the so-called bid prices for the procurement representatives.

The model component can be divided into two subcomponents: an online pricing component that support the procurement representatives during price negotiations and a distribution component that is used to generate the weekly transportation plan from waste collection companies to recycling companies.

The dialog component provides the planning staff with a comprehensive set of functions to run and modify models flexibly for calculation, what-if evaluation and optimization.

Additionally, we had to design and implement an IT-intensive mobile communication component that enables real-time and on-site access to the pricing component during negotiations and facilitates data interchange with external systems/applications via different networks. We will describe the functionality of the three main components pricing, distribution and communication in more detail in the following.

### 3.1 Model Component - Distribution

The planning model incorporated in the distribution component is a specific variant of the classical transportation problem [2] that aims at generating a min-cost plan for the transportation of a homogeneous product from different supply locations (e.g. factories) to different demand locations (e.g. warehouses).

In the past management has used a simple key performance indicator to measure the efficiency of a transportation plan: the average sales price after
transportation costs (ASPT), which reflects minimization of transportation cost as well as maximization of total sales by delivering those contracts with higher sales prices preferred. Let $S$ be the set of supplies from waste collection companies and $C$ the set of contracts with recycling companies. Given the sales price $p_j$ and a discount rate $d_j$ for each contract $j$ in $C$, the transportation costs $c_{ij}$ and the quantity $x_{ij}$ of waste paper shipped from each waste collection site $i$ in $S$ to each contract $j$ in $C$, the ASPT can be defined mathematically as:

$$ASPT = \frac{\sum_{i \in S} \sum_{j \in C} (p_j(1-d_j)-c_{ij})x_{ij}}{\sum_{i \in S} \sum_{j \in C} x_{ij}}$$

To support our industry partner in determining the optimal weekly supply quantity for a contract and thereby maximizing the revenue, the formulation of the classical transportation problem had to be adapted in several ways. One of the design goals was the flexibility to adjust to changing constraints (e.g. contract dependencies) and incorporate strategic considerations in the decision process.

The following simple abstract concepts are a means to provide the planner with such a flexible and interactive system:

**Minimal and maximal values** limit the quantity supplied to a contract. Within these user defined bounds, the solver determines the optimal distribution of the supplied waste paper to the contracts with respect to transportation costs and sales prices. In the course of the planning process, these values can be adjusted by the dispatcher to incorporate strategic decisions. For example, it might be appropriate to deliver less waste paper to a recycling company taking into account upcoming contract negotiations. Nevertheless, a planner needs to consider the maximal deviation from the target quantity at the end of the month. Since the dependencies between base and additional contracts are seldom fixed and specified beforehand, the minimal and maximal values associated with each contract are also used to represent those restrictions.

The system furthermore supports the concepts of **fixations and supply restrictions** to cope with different quality levels and availability of transportation services. The dispatchers have the knowledge about "bad" combinations that resulted in claims from recycling companies in the past. Such a combination may be banned by applying a supply restriction. On the other hand, it might also be necessary to assign waste paper from a particular collection site to a particular recycling company, either due to quality issues or to enforce the transportation over a particular route. Often, the dispatchers already know at the time of planning what shipping routes are fully booked. Fixations and supply restriction can be applied before the optimization process begins. A fixation results in a decrease of the supply quantity available to dispatch by the solver, whereas a supply restriction adds a constraint to the model.

By setting a **capacity constraint** to zero for a transportation arc we can prohibit shipment from a waste collection site not capable of loading containers to the destinations of those contracts requesting containers. Capacity constraints can also be used to restrict the number of units (trucks/containers) sent from a waste collection site to a contract destination.

For the user all these specifications should be easily possible through the dialog component such that strategic evaluations of alternative transportation plans can be performed in flexible what-if runs of the model.

Now the transportation model is as follows: Again, let $S$ be the set of supplies from waste collection companies offering waste paper during the current planning week, and $C$ the set of contracts with recycling companies for the current month that are not yet fulfilled. Each waste collection site $i$ offers a quantity $s_i$ of waste (in units of full truckloads). The quantity delivered to a contract $j$ is bounded by minimal and maximal values $min_j$ and $max_j$

$$\text{max } \sum_{i \in S} \sum_{j \in C} (p_j(1-d_j)-c_{ij})x_{ij}$$

**s.t.**

$$\sum_{j \in C} x_{ij} = s_i \quad \forall i \in S$$

$$\sum_{i \in S} x_{ij} \geq min_j \quad \forall j \in C$$

$$\sum_{i \in S} x_{ij} \leq max_j \quad \forall j \in C$$

$$0 \leq x_{ij} \leq cap_{ij} \quad \forall i \in S, j \in C$$

$$x_{ij} \text{ integer} \quad \forall i \in S, j \in C$$

respectively. On each transportation arc $ij$, flow capacity is restricted by the value of $cap_{ij}$ and costs for the transportation of one unit are $c_{ij}$. Note that the transportation costs are approximated as described in
the next section. The decision variable \( x_{ij} \) determines the quantity, i.e. the number of trucks/containers shipped from waste collection site \( i \) to the destination of contract \( j \). Then, the mathematical formulation of the planning problem is:

The objective function (1) maximizes the difference between total revenue minus total transportation costs and corresponds to a maximization of ASPT. In contrast to the definition of ASPT we omit division by the total number of units shipped. Since this number is a constant during a planning process, optimality of the solution is not affected. Constraint (2) ensures that all supplied quantities are assigned to contracts. Constraints (3) and (4) enforce compliance with the minimal and maximal quantities to be shipped to the destination of a contract. The maximal flow on a transportation arc is restricted by constraint (5) and depends primarily on the combination of supply and contract. The value of \( cap_{ij} \) is set to “0” if

- a) a supply restriction is applied by the dispatcher,
- b) there is no matching entry in the transportation costs catalogue or
- c) the freight combination is invalid (container is requested but cannot be loaded at waste collection side)

Constraint (6) restricts the shipment of fractional units. With one truck/container being a unit in the model, supply and target values given in tons have to be divided by truck/container capacity that is assumed to be 23 tons for both cases.

The optimal solution to the transportation model does not only specify the optimal distribution of material to contacts but additionally provides shadow-prices which measure the potential increase in profit if additional units of material would be available for the different contracts. This information can be used to control pricing of material on the procurement side.

Our model base has been designed under the paradigm of model-solver independence. The transportation model belongs to the class of network flow problems, i.e. special linear programs with the integrality property for basic solutions that can be solved by the Simplex-method for instance. There are thousands of papers describing algorithmic concepts and specific implementations for network flow problems in general and the transportation problem as a specialization. A good survey on network flow models and algorithms is Ahuja et al. [3]. Derigs [4] has shown the near-equivalence of various LP-based primal, primal-dual and dual algorithms as well as combinatorially motivated augmentation approaches for solving network flow problems. Due to the special structure of the bases, simplex-based methods can solve these problems an order of magnitude faster than general Linear Programs. These specialized simplex algorithms rely on the graphical interpretation of the simplex steps and highly efficient data structures and basis-update procedures. The first publications and seminal computer implementations which demonstrated the efficiency of this approach were by Glover et al. [5],[6] and Srinivasan and Thompson [7]. In our model component we have implemented a proprietary solver KLIGLO which is based on the ideas presented in [6] and [7] and which has been developed by the first author (together with J. Offermann ) in 1975.

In Table 1 we report computational tests comparing KLIGLO with the commercial LP-solver CPLEX from ILOG CPLEX [8] and the open source software GLPK (GNU Linear Programming Kit) [9] on a sample of 12 problem instances resulting from 12 weekly planning problems during the third quarter in 2006. Table 1 displays the characteristics of the problem instance such as the number of contracts and the number of supplies as well as the time needed to generate the optimal solution for each solver. All solvers generate optimal solutions in much less than a second, which supports the interactive planning process with the DSS. The fact that KLIGLO is on average at least twice as fast as both standard LP-solvers (GLPK and CPLEX) demonstrates the computational efficiency of the DSS model component.

### 3.2 Model Component - Pricing

When a procurement representative arrives at a waste collection company to enter price and quantity negotiations, he submits the current location and other information such as the material type he wants to buy and the predicted truckload. Then, the online pricing component draws on the received information to generate a list of sales contracts with recycling
companies to which the purchased material could be sold along with the respective maximal bid price.

Having completed negotiations successfully, the user submits a purchase order online by clicking on the target sales contract chosen from the proposal list. This target sales contract is mainly used for performance evaluation and accounting purposes since the final transportation plan is generated by the distribution planning component once a week. This transportation plan might deviate from the plan that would result from the purchase orders since the supply-demand assignment is optimized globally.

Eventually, the pricing component allows to analyze the performance of procurement representatives. A purchase order contains information on the real price negotiated by a procurement representative as well as the maximal price proposed by the system. These values can be compared for different time periods and procurement representatives, allowing management/the controlling department to evaluate the performance of a single representative or a group over a specified time horizon.

By default, the bid-price calculation is performed based on the following simple model:

\[
\text{Bid price} = \text{contract sales price} - \text{approximate transportation costs} - \text{target margin}
\]

As part of the bid-price calculation, the transportation costs from the procurement representative’s current position to all the recycling companies with contracts for the specified waste material and cargo type have to be specified. The system uses three different sources to approximate transportation costs: “real” costs that had to be paid for transportation orders already carried out, “planned” costs that can be obtained from a virtual market place (an internet platform that links shippers and carriers), and “estimated” costs that are calculated based on the great-circle distance between waste collection companies and recycling companies. The accuracy of transportation costs is supposed to be highest for real costs and lowest for estimated costs. Real costs for a particular route are used only if there are at least three entries within the last 6 month and are calculated by taking the average of the last entries. Note that all cost entries can be flexibly adjusted by adding for instance fuel surcharges.

Two reasons make the upper bid price one of the most important factors when negotiating purchase contracts:

### Table 1. Problem instances and solver times

<table>
<thead>
<tr>
<th>Problem</th>
<th>Properties</th>
<th>Solver time (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>number of supplies</td>
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<tr>
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</tr>
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<td>62</td>
</tr>
<tr>
<td>Average</td>
<td>134</td>
<td>54</td>
</tr>
</tbody>
</table>
• On the one hand, a contract might easily lose its value or even result in losses if the upper bid price is surpassed by a small fraction that exceeds the target margin.
• On the other hand, procurement representatives might raise the contracted supply quantity substantially when offering higher prices than the competition.

The maximal bid price is influenced by the sales price of the recycling company it will be shipped to, the transportation costs from the waste collection site to the recycling plant, and a target margin. As mentioned before, by the time a procurement representative buys waste materials, it is not known yet where the purchases will finally be shipped to (distribution planning is only performed once a week to minimize transportation costs). Therefore, the problems of purchasing waste materials and managing their flow strongly influence each other.

The procedure that generates bid price proposals offers a flexible way to influence purchasing decisions centrally by the planning staff. The main adjustment screw is the target margin, and by turning this screw the company is able to implement a revenue management strategy. The system allows to define rules that adjust the target margin depending on a specific region, the kind of waste material to purchase and/or the procurement representative. Additionally, information gained from the weekly transportation optimization (e.g. about waste collection sites whose supplied materials yield the highest returns) may be used to alter the target margin strategically.

The process described above poses special requirements for the support of procurement representatives during price and quantity negotiations: a suitable system must be accessible from anywhere and in real-time, i.e. all relevant information available such as other purchases made during a day or changes of transportation costs influence the maximal bid price and must be considered in its calculation.

### 3.3 Communication Component

To pursue a “decisions everywhere” paradigm and to facilitate the use of the pricing component by procurement representatives everywhere and at any time, we implemented a specific communication component that is responsible for all communication of our system with external entities and resources. Particularly, the communication component grants access to the pricing component from outside the main application. The procurement representatives use a wide range of mobile and stationary end user devices such as smart phones, PDAs, laptops (wired or wireless) and regular personal computers. Consequently, we decided to build a special web application as part of the communication component that gives the procurement representative access to the pricing component on any device equipped with a JavaScript-enabled web-browser. Thus, part of our DSS becomes a web-based DSS. A web-based DSS enables decision makers to access information and the application logic using a “thin client” web browser [10]. Naturally, basic security principles such as the use of firewalls and secured communication channels are applied.

The implementation goal of the web application was driven by two important aspects: the flexibility to render output for different mobile or stationary devices and a role-based security system for the various user groups such as sales representatives, planning staff and people from the controlling department.

The dynamic web pages generated by the system rely on standard .html and JavaScript features that are rendered in the same way on different operating systems and web browsers. The entire user interface was implemented for mobile and stationary devices separately since mobile devices usually have a much smaller screen. Some features such as data maintenance services and the performance evaluation which are only used from desktop computers are not available on the mobile version. The mobile version was specifically designed to cope with small bandwidth connections and the problem of lower data transfer rates in rural areas. Each user interaction such as clicking on a button or a link triggers a server request that forces the web-server to generate and transfer a whole webpage. By minimizing the number of such “round-trips” using standard JavaScript functionality we were able to reduce the amount of data exchanged and make the application respond fast enough even if the internet connection is limited.

Access to the mobile web application is generally restricted to users that are able to validate their identity with the correct combination of user name and
password. Moreover, each user must be assigned to at least one role. A role is connected with a set of policies that define what parts of the application can be used and what actions can be performed by any user assuming the role. For example, the performance analysis component can be accessed by personnel from the controlling department as well as procurement representatives. Yet, the policies defined for the role “procurement representative” allow users that are in this role only to view the performance analysis data for their own purchase orders. Only the controlling department staff may view and compare data from all representatives.

4. Final Remarks

In this paper, we have described the novel concept and implementation of a DSS that tackles a real business problem by managing the waste materials flow in a recycling network. Its two components for decision support – a mobile, real-time pricing component as well as a distribution planning component – form a complementary core that helps to improve management as well as operations of the recycling network of our industry partner.

The organizational implementation of the pricing component has resulted in a dramatic impact on the way procurement representatives are able to conduct their purchase negotiations. Fed with up-to-date information on all relevant revenue, costs and status information, better decisions about the price and quantity of waste materials to buy are facilitated – everywhere and at any time. Besides effectiveness the system contributes to efficiency by rationalizing the whole procurement process. Time consuming tasks such as filling out purchase orders and order confirmations or comparing the procurement representative’s performance can now be carried out almost instantaneously.

The distribution planning component supports the planners in generating an optimal transportation plan from waste collection companies to recycling companies. It has become an integral part in the planning process of our industry partner. The system changed the way of planning and reduced the time for the entire planning process, i.e. the time to generate, evaluate and alter a solution step by step, to less than one and a half hours. Scenarios can be evaluated immediately, helping to analyze the impact of strategic decisions. Additionally, the dual variables guide the planners’ decisions and broaden the understanding of the impact that altered input parameters can have on a solution. Thus, planners can move from generating feasible plans to generating optimal plans that maximize revenues.

During the last months we have extended the distribution model to capture the specification of fixed delivery days and delivery rules for recycling companies. Such a delivery rule for a recycling company could be to deliver a constant quantity for each selected delivery day of a planning week.

According to management the system described in this paper has become a key success factor since its organizational implementation in 2007 because its use lead to standardized, efficient, and transparent processes which in turn increased overall profitability. Due to confidentiality issues, precise information cannot be stated.

Future work is connected to a further integration of the two components pricing and distribution. Ideally, the whole purchase process should be supported by a real-time revenue management component similar to those systems applied at airlines. Yet, extensive field studies are necessary to first identify and evaluate adequate strategies, and second to convince management about the profitability of another system extension. Currently, we collect and evaluate historical data using statistical tests to identify appropriate assumptions for expectations on the geographical distribution and quantity of future purchases. Based on such information we may be able to set some kind of “booking limits” for the contracts over the week. In such a scenario, we can evaluate a “purchase request” by calculating bid-prices on the basis of dual prices obtained from optimizing a reduced transportation problem. Furthermore, we might adapt a revenue management approach for scenarios with limited demand information described by Ball et al. [11].

References


