Technical Memorandum Number 757

Hazardous Waste Disposal: A Waste-Fuel Blending Approach

by

A. Dale Flowers
And
Kevin Linderman

January 2003

Department of Operations
Weatherhead School of Management
Case Western Reserve University
10900 Euclid Avenue
Cleveland, Ohio 44106-7235

Hazardous Waste Disposal: A Waste-Fuel Blending Approach

A. Dale Flowers
Weatherhead School of Management
Case Western Reserve University
10900 Euclid Avenue
Cleveland, Ohio 44106
Phone: 216-368-3825
Fax: 216-368-4776

Kevin Linderman
Carlson School of Management
University of Minnesota
3-235 CarlSMgmt Building
321-19th Avenue South
Minneapolis, MN 55455
Phone: 612-626-8632
Fax: 612-624-8804

Abstract

The disposal of hazardous wastes creates major economic and environmental problems for both developed and developing nations. One productive use of hazardous wastes is to blend them into fuel, which mitigates damage to the environment by recycling waste into fuel and reducing fossil-fuel consumption. Operations personnel face a daunting task of efficiently blending hazardous waste into fuel, while at the same time maintaining environmental regulatory requirements. This research develops a goal-programming approach to the waste-fuel-blending process that considers the diverse objectives of fuel managers. A real-world case study at a cement kiln illustrates the effectiveness of this approach, where the implementation followed principles of team building and quality management.

Keywords: Environmental issues, government regulation, implementation, mathematical programming, waste management, fuel blending, goal programming, cement kiln, microcomputer applications

1. Introduction

The large-scale industrialization of the 20th century produced both positive and negative effects. One of the negative effects was the production of hazardous wastes as a result of manufacturing processes. Preventing, recycling, and disposing of these wastes in an environmentally sustainable manner presents a challenge for the 21st century. The United States alone produces 230 million tons of hazardous wastes per year (see http://www.ckrc.org/about .html) and much of it occurs as a direct result of industrial operations. It follows that practitioners and researchers in operations management would accept the challenge to help solve this problem (Angell and Klassen 1999, Klassen 1993).

Ideally, waste-prevention strategies would make environmental problems go away. In fact, some organizations include pollution prevention in their competitive strategies (Angell and Klassen 1999). For example, 3M implemented a pollution-prevention strategy that saved $827 million from 1975 to 1999 (see http://www.3m.com/about3m/environment/). Russo and Fouts (1997) suggest that it pays to be “green” but Walley and Whitehead (1994) and others argue that win-win strategies between the environment and corporate profits are the exception rather than the rule. Although the relationship between pollution prevention and profits may be symbiotic, one cannot ignore the large volume of wastes generated each year. Hazardous waste disposal, in particular, creates a challenge for organizations because of its special threat to the environment. Three prominent strategies deal with hazardous wastes: landfill, incineration, and use as a fuel.

Valenti (1999) provides a summary of the advantages of incineration over landfill. Lamb, Miller, and Roth (1994) compared the risks of burning coal only versus coal and waste fuel. They performed a comprehensive risk assessment for nine exposure pathways and concluded that there was no significant difference in risks for the two approaches. Hart (1994) studied the fullscale operation of a cement kiln with various percentages of the fuel being provided by waste sources. He concluded that emissions could be reduced when burning waste fuel versus coal. Kemezis (1993) points out that there is still controversy about the process. However, blending waste into fuel is the only option that produces a positive effect for society; that is, it turns a nonproductive form of waste disposal into a productive form of waste disposal. This approach has the added benefit of avoiding fossil-fuel consumption.

This research presents a goal-programming approach to blend wastes into fuel as a means of disposal. The model assumes that managers seek to blend wastes into fuel as efficiently as possible without violating EPA guidelines. In the following sections, we review the relevant literature, present the waste-fuel-blending model, describe a case-study application, and then provide summary observations.

2. Literature Review

The relevant literature in this research is plentiful and diverse. We review research from the important areas of environmental regulations, multiobjective environmental optimization models, and blending models.

2.1 Environmental Regulations

For a particular country, applicable environmental law provides a place to start reviewing the regulatory context of hazardous waste disposal. In the United States, Environmental Protection Agency (EPA) publications provide relevant information. One critical regulation is the Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities (EPA 1999), which governs the operations of such facilities. Another critical regulation is the National Emission Standards for Hazardous Air Pollutants from Hazardous Waste Combustors (EPA 1999), which defines allowable emissions from those facilities. To comply with the latter regulation, furnaces burning waste fuel typically require special monitoring and combustion equipment. The cost of such equipment becomes part of the discussion when waste fuels are considered. Similar laws regulating handling and disposing of hazardous wastes exist in most countries and provide guidance to determine parameters for the model presented in section 3.2, which reflects the regulations in the references cited above.

2.2 Multiobjective Environmental Optimization Models

Another area of relevant work is the application of multi-criteria decision modeling to environmental problems. While a number of applications exist, many more opportunities await discovery. Because the applications reveal considerable diversity, we will present them chronologically.

Charnes et. al. (1976) developed a goal-programming model to support resource-allocation decisions in the U.S. Coast Guard environmental-protection program. In a related project, Charnes et. al. (1979) used chance-constrained goal programming to help Coast Guard managers formulate policies to plan the equipment for containing major pollution incidents. The model included three response stages: offloading, containment, and removal.

Tayi (1985) developed a linear and a polynomial goal-programming model to evaluate quality-control problems, including pollution control. Output, pollutant, and input characteristics are all incorporated in the trade-off analysis. Mohanty and Koay (1988) developed a goal-programming application for process and quality control in waste treatment. They focused on a waste-water-treatment technique called the Upflow Anaerobic Sludge Blanket process, which includes using a bacterial-growth approach. Norman and Naveed's (1990) study compared expert systems and human-operator performance of a cement kiln. They identified the expert system that came the closest to emulating human-operator performance.

Mogharabi and Ravindran (1992) applied goal programming to the liquid-waste-injection process. This process involves pumping liquefied wastes at a controlled rate under controlled pressure into confined forms that have no other potential use. Changchit and Terrell (1993) applied a multiobjective-programming approach to water management in a reservoir.

Moore et. al. (1993) used multicriteria-mathematical-programming models to analyze the U.S. Department of Energy Restoration and Waste Management Program. Shih and Frey (1995) developed a multiobjective, chance-constrained-optimization model for the coal-blending problem in coal-fired plants. Their goal was to optimize the coal-blend for multiple objectives. Chang and Wang (1997) applied fuzzy-goal programming to the problems of planning metropolitan solid-waste-management systems. Penkuhn et. al. (1997) used a nonlinear optimization model to consider production planning, planning of byproducts and residues, and emission taxes for an ammonia-synthesis operation.

Gupta and Isaacs (1997) used goal programming to analyze the trade-offs between technological, economic, and environmental factors for two automotive-body designs. Giannikos (1998) used multiobjective programming to locate treatment sites and route hazardous wastes. He included economic, risk, and equity factors in his analysis. Amouzegar and Moshirvaziri (1999) applied bilevel (hierarchical) programming to determine optimal pollution-control policies from a governmental perspective. Finally, Hobbs and Meier (2000) provide a comprehensive discussion of energy and environmental policy decisions using goal-programming methods. They consider the environmental impact of capacity expansion and facility location on power generation systems.

2.3 Blending Models

The general set of blending problems provides further background for this research, although the set is far too large to enumerate. A few relatively recent applications of blending models will provide a foundation for this research. Rigby et. al. (1995) described the system for gasoline blending that Texaco used. Al-Shammari and Dawood (1997) described the application of a linear-programming-blending model to the production of paints and putties in a chemical-manufacturing process. Vermeer et. al. (1997) described a blend-control system for Sunoco's Sarnia petroleum-refining facility in Ontario, Canada. Mihailidis and Chelst (1998) described an integer-programming model used by a chemical company to reblend out-of-specification material to produce product batches that meet specifications. Finally, Karmarkar and Rajaram (2001) described a nonlinear mixed-integer program that minimizes total grade inclusion, batching, blending, and quality costs in chemical process for wheat- and starch-based products. These examples illustrate the important contributions that blending-optimization models have made.

The development of the model in this paper builds on all three streams of research reviewed above. It uses the EPA references to establish a model that could be applied to any process that employs a furnace that can burn fossil fuel, and could be configured to burn a mixture of fossil and waste-derived fuel. As such, it has great potential for reducing the amount of wastes that are simply incinerated or go into land fills with no residual benefit to society. It is a new example of a multi-objective environmental optimization model in the rich tradition of such models.

3. Waste-Fuel Blending Model Formulation

3.1 Background

Hazardous-waste streams occur in a variety of forms, including used oil, lubricants, and paint thinners. Generators, the waste producers, must dispose of these contaminants and one option is to pay fuel managers to take responsibility of disposal. Fuel managers then blend the wastes into waste fuel, which can substitute for fossil fuels like coal. Waste fuel is ultimately used by a fuel user in this supply chain as illustrated in Figure 1. To understand the logic of the goal programming model in section 3.2, it is necessary to understand how both the generator-to-fuel manager interactions take place, as well as those of the fuel manager-to-fuel user.

---Insert Figure 1---

Wastes produced by generators are typically placed in 5000 gallon capacity tanker trucks. When a truck is filled and its chemical contents are measured, the generator will “shop” the load to various fuel managers to determine which of them will charge the least to accept the load. Fuel managers charge higher prices for higher concentrations of contaminants, but their exact quote is based on their inventory position in terms of its volume and mix. If they have no more room or very limited capacity, they may quote a higher price. More important, however, is the relationship of the contents of the truck to the contents of their inventories. The more *dissimilar* the truck is to their existing inventories, the more they will desire it and the lower the price they can quote. This is because they have reasonable assurance that it can be blended with existing inventories to produce acceptable fuel. If the truck load is (1) similar to their existing inventory and (2) both it and the existing inventory have high levels of EPA controlled contaminants, then it is not desirable since they may not be able to blend it into usable fuel. If they accepted such a load when at or near capacity in their inventory tanks, a disastrous situation could occur where they could not blend any wastes into acceptable fuel.

Further exacerbating this situation for the fuel manager is the uncertainty of availability of future loads from generators, as well as uncertainty about what the contents will be. One uncertainty described above was that the generators “shop” the truck loads of waste to the lowest bidder. In addition, the fuel manager has no knowledge of the production schedules of various products the generators produce, so neither the volume nor the type of waste material can be anticipated. This uncertainty plays an important role in formulating the objective function for the model in section 3.2.

The relationship of the fuel manager to the fuel user also presents some interesting challenges. The fuel manager *pays* the fuel user for using the waste fuel. The price is typically a constant per gallon price. The EPA regulates *both* the waste fuel input to the furnace of the fuel user, as well as the emissions that may be released into the atmosphere from the furnace. Special emissions monitoring equipment must be installed if a facility plans to use waste fuel. Due to the expense of such equipment, the fuel user wants the maximal amount of waste fuel burned in their furnace in order to pay back the cost of the equipment. EPA guidelines allow up to 50% of fuel burned to be waste fuel, so the fuel user would like to get as close to that number as possible.

The EPA guidelines list upper limits on 17 specific contaminants found in industrial waste streams. If a blend of fuel is at or below each of these guidelines, provides the minimum BTU needed to burn, and does not result in a violation of emission limits, the fuel manager may feed the fuel to the furnace at the 50% maximum rate (the rest comes from coal). If a blend is too high on any of the 17 controlled contaminants, the feed rate must be adjusted downward from the 50% limit to meet the emission limits. If the emission limits are violated at any time, the law requires that the waste fuel must be immediately discontinued until the emissions are brought back under control. Note that this is in spite of the references cited earlier that showed that waste fuel burns cleaner than coal; higher emissions are allowed when burning fossil fuel.

Optimization models can help fuel managers determine the appropriate blends. A profit maximization approach could be adopted wherein the blend of fuel created would maximize the difference between the price the fuel manager charged the generator versus the price the fuel manager paid the fuel user to burn the waste fuel. This would be an obvious choice, but it contains an inherent weakness in the volatile market described above. It does not pay attention to the resulting inventory mix in the tanks after a blend is created, so that the flexibility of the fuel manager to bid on the next load may be compromised. An alternative goal is to create a blend with each of the contaminants as close to its EPA upper limit as possible, but without violating the upper limit. This approach controls the remainder of the wastes left in the tanks so that the probability of being able to accept virtually any future load is maximized. In addition, it ensures the maximal amount of fuel meeting EPA guidelines can be input to the furnace. Finally, it has the added advantage of not requiring the record-keeping burden of tracking of the weighted average cost of the contents in each tank.

If transactions between generators and fuel managers, and fuel managers and fuel users, were much more predictable, then a true long-term profit maximization model would be possible. Due to the general correlation between level of contaminant and the price the generator is charged, the goal-programming model below should perform quite well.

3.2 Waste-Fuel Blending Model

Some explanation is provided to help understand the model formulation presented below. Consider that a charge of fuel to supply a furnace for a period of time consists of some target number of gallons. Each of the contaminants regulated by the EPA (there are 17) will have an upper limit on the amount of the contaminant allowed in the target volume. The allowances are expressed in different units of measure, however. For example, the maximal chlorine content is 3%. To both simplify the interpretation of the problem and to minimize potential scaling problems due to substantially different units of measure, the allowances can be normalized.

Consider an example of chlorine in Tank 1 in Figure 1. Assume the percentage of chlorine in the Tank was 4.5%. Normalize this by dividing it by the limit of 3% to determine that the chlorine coefficient for Tank 1 is 1.5. If the target was a 50,000 gallon charge of fuel, and 20,000 were used from Tank 1, then 30,000 gallons of the chlorine *allowance* would have been used. The remaining 30,000 gallons needed to complete the 50,000 gallon charge must not consume more than 20,000 gallons of the allowance. In other words, the balance must average 2/3 or less of the EPA guideline on chlorine or the feed rate to the furnace must be reduced.

The BTU of the waste fuel must be 10,000 or greater, or the feed rate must be lowered. With these concepts and Figure 1 in mind, the model may be developed by using the notation in Table 1. The top part of the Table lists the decision variables, while the bottom part lists the constants.

--- Insert Table 1 ---

The model assumes there are N storage tanks and K+1 EPA guidelines (K to regulate contaminants and 1 to guarantee BTU content). The mathematical formulation follows:

$$\min \sum_{j=1}^{K} (Below_j + M\ Above_j) + M\ Below_{BTU} + Above_{BTU}$$

s.t.

$$\sum_{i=1}^{N} Tank_i = Target \qquad (1)$$

$$Tank_i + E_i = I_i \quad i = 1 \ldots N \qquad (2)$$

$$\sum_{i=1}^{N} \left[CON_{j,i} / EPA_j\right] Tank_i + Below_j - Above_j = Target \quad j = 1 \ldots K \qquad (3)$$

$$\sum_{i=1}^{N} \left[BTU_i / BTUMIN\right] Tank_i - Below_{BTU} + Above_{BTU} = Target \qquad (4)$$

$$Tank_i \geq 0, Below_j \geq 0, Above_j \geq 0, Below_{BTU} \geq 0, Above_{BTU} \geq 0, E_i \geq 0 \ \textit{for all } i, j$$

The objective function seeks to minimize the weighted deviations from the EPA guidelines for the contaminants and the BTU requirement. The weight for being below the contaminant guideline or above the BTU guideline is assigned a value of 1 per gallon. A penalty of M per gallon can then be chosen to penalize contaminant levels above the guideline or a BTU level below the guideline. A higher value of M lessens the likelihood that any EPA guidelines will be violated, thereby reducing the likelihood that the feed rate must be lowered.

Constraint (1) determines the amount of waste required from the *N* storage tanks to create a blend (charge) of *Target* gallons. Constraint (2) guarantees that the amount of waste used from a tank does not exceed its total inventory available. Constraints (3) and (4) determine the penalties for deviating from the EPA guidelines for contaminants (3) and BTU (4).

To illustrate the model in more detail consider a chlorine example for constraint (3). Assume the solution yielded $Tank_1$ = 20,000 gallons and $Tank_2$ = 30,000 gallons. Further assume that chlorine in $Tank_1$ was 4.5% so the coefficient for $Tank_1$ in the chlorine constraint is 1.5, and that the chlorine content for $Tank_2$ was 0.75% yielding a coefficient of 0.25. Then [(1.5)(20,000) + (0.25)(30,000) = 37,500]. Since the Target was 50,000, we are BELOW the limits on chlorine by 12,500. This 12,500 will be added to the deviation value in the objective function (BELOW values on contaminants have a weight of 1). The process works in reverse for BTU, where ABOVE values have a weight of 1.

The simplicity of the proposed model should also facilitate implementation. Recently Hopp et. al. (1997 p.329) conjectured that "one reason for the failure of companies to make use of advanced methods is the difficulty in implementing them." They later proposed guidelines for developing easily implementable solutions (Hopp et. al. 1999 p. 978). Although these guidelines applied to inventory management solutions, they suggested that the guidelines might apply to other real-world systems. Following these general guidelines, the proposed waste-fuel blending model's simplicity should be easy to implement.

4. Case Study: Implementing the Waste-Fuel-Blending Model

Observing the blending model's implementation in a real-world setting helps validate the model, and provides a deeper understanding of implementation issues. The researchers acted as participant-observers during the implementation process. To describe this experience, we will divide this section into three parts: overall situation for the application, technical and managerial implementation details, and implementation results.

4.1 The Situation

The opportunity to apply the model arose when TBN Cemtech, a fuel manager, and Medusa Cement Company, a cement kiln owner, requested our involvement in their problem. The companies had formed a joint venture and the benefits were to be shared in a previously agreed distribution. The fuel manager's responsibility was to provide acceptable fuels to the kiln for its continuous operations. The kiln operated seven days per week, 24 hours per day, except for a roughly six-week shutdown period each year for maintenance. The fuel manager provided waste-derived fuel to be used as a substitute for and in conjunction with coal (fossil) fuel. The waste fuel was produced in other manufacturing processes and the companies that created it (generators) paid the fuel manager for its disposal within the laws governing such processes. The higher the concentration levels of contaminants in the waste, the more the fuel manager charged the generator. The fuel manager paid the cement kiln a constant price per gallon to motivate the cement company to use the waste-derived fuel.

The physical structure of the operation is represented in Figure 2. The connecting pipes in the figure all support two-way flows. The two large blending tanks each had a 60,000-gallon fuel capacity. The waste fuel was mixed in these tanks, then pumped to the kiln furnace for burning. The six tanks in the tank farm each had a 20,000-gallon capacity. The chemical specifications of the contents in these six tanks were known at all times. Typically, the contents of the six tanks were used to create the mixture in one of the blending tanks that would fuel the kiln. While one of the blending tanks was actively feeding the kiln, the others were being filled to take over when the previous tank was empty. Mixing a blend and fueling the kiln from the same tank at the same time wasn't possible so two blending tanks were needed. A 50,000-gallon charge in a blending tank would typically run the furnace for about 24 hours. Tanker trucks, each with a 5,000-gallon capacity, hauled wastes from the generator plants to the fuel-management facility. The fuel manager used some heuristic "receiving" guidelines to decide whether to accept the load. For example, one guideline specified that a load would not be accepted if the chlorine content was greater than 6% (the allowable chlorine limit for "burning" was 3%.). The second decision was to determine into which of the eight tanks (six holding tanks and two blending) a truck's contents should be unloaded. Generally, the operator unloaded the trucks into the holding tank that had enough capacity to accept the load and contained material most similar to the contents of the truck.

---Insert Figure 2---

Before developing the waste-fuel blending model, the operators used a spreadsheet to design a charge of fuel for the cement kiln in a two-pronged trial-and-error process. They reviewed the waste inventories in the six holding tanks, made a guess as to how much from each might make a good blend, and then used the spreadsheet to estimate the final contaminant and BTU level of the blend. If the blend violated any of the EPA guidelines, the operator tried another mix until he was satisfied with the result. Similarly, if the mixture met the guidelines but was well below contaminant guidelines or well above the BTU minimum, the operator adjusted the mixture.

The operators and the general manager agreed that this judgmental process yielded inconsistent results. Different operators had different experience and expertise and each had developed his own approach to designing a blend. Depending on the inventories available in the tank farm, a number of attempts might be required to find an acceptable blend, which frustrated the operators.

4.2 Implementation Details

The implementation details included technical issues, dealing with the model and its computer implementation, and social issues, dealing with making the model work for the people involved. We will use a simple list format to name and explain each of the issues that arose. Technical projects in operations management often involve only managerial and technical personnel, thereby ignoring other members of the work force. In contrast, this implementation team followed a Total Quality Management (TQM) approach that included inputs from representatives of all the major functions. Goetsch and Davis (2000) provide an indepth description of the TQM approach. Scholtes, Joiner, and Streibel (1996) detail running successful teams for problem-solving processes. These general guidelines were followed during the implementation. The implementation team also paid particular attention to involving fuel-blending operators because they were the end users of the system and the most knowledgeable about the operations. TBN Cemtech's general manager, Rob Miller, was a strong supporter of our process and was a major contributor.

4.2.1 Objective-function coefficients

The fuel manager and the cement kiln manager both wanted to use as much waste-derived fuel in the kiln as possible but adamantly wanted to avoid violating the EPA guidelines on contaminants and BTU. If the limits were violated, the fuel feed rate had to be slowed to accommodate the violation and the possibility of problems with the EPA increased. The parties agreed to weight the conditions so that the penalty for exceeding a limit by one gallon for one material had a higher penalty than the sum of the penalties for all gallons for all contaminants that were below the limit.

4.2.2 Constraints

Occasionally, storage tanks from the tank farm were emptied for maintenance as required by law (EPA regulations), which made necessary adding some constraints to the model that gave the operators the option to force the contents of a particular tank into the next blend.

4.2.3 Microcomputer implementation

The fuel-manager used IBM-compatible microcomputers to run the operation and the tank-farm-inventory data were formatted for the Microsoft Excel spreadsheet. The Excel User's Guide (Microsoft Corporation 1996) describes the Solver mathematical-programming capability built into Excel and developed by Frontline Systems Inc. Fylstra, et. al. (1998) and Patterson and Harmel (2001) provide additional information concerning this tool. Excel's capability proved adequate for the algorithmic requirements of the implementation effort, but the application needed to be as user friendly as possible for the operators. To accommodate the two platforms, we developed a graphical user interface using the Visual Basic programming capabilities within Excel, described by Walkenbach (1996). The result was an application that appeared to be an off-the-shelf Windows product. Screen layouts were designed to be familiar to operators and well integrated with the company's pre-existing systems.

4.2.4 Documentation

The programming was completed in a highly modular, well-documented fashion so that the fuel manager could take over software maintenance independent of the developers. In fact, because Excel and Visual Basic are popular, the documentation opened many alternatives for software maintenance, internal and external to the company. In addition to the system documentation, a user's manual was developed, which contains shots of every screen in the system and a complete, real numerical example to illustrate system use.

4.2.5 Training

The developers provided extensive training to the lead operator of the waste-fuel-blending process. During the training session, the operator provided feedback to improve the system. After the developer adjusted the system and the lead operator made a final review, the operator took over training for the other operators.

4.2.6 "Dummy" tanks

Operators had been using heuristic guidelines to decide whether to accept or reject truckloads of wastes and the operators expressed concern about the risk of accepting a load that might lead to violating EPA guidelines. If they accepted a load with very high contaminant levels, they might not be able to blend a load in the tank farm that met EPA guidelines. In response to their concerns, two "dummy" tanks were added to the model to improve the heuristic system. In this situation, if doubt arose about a load's acceptability, the specifications for its contents could be entered into the computer system as a "dummy" tank. Then the model could be run to force the contents of the "dummy" tank load into the next blend. If an acceptable blend could be designed, the load would be accepted. Otherwise, it was a rejection candidate. This truckload-testing part of the model became a regular part of the process: if the load in the "dummy" tank worked well at the computer, it could be the next blend in reality.

4.2.7 A second model is needed

A second model was added after an operator asked whether the software could produce a solution that contained the largest possible volume within the burn and EPA guidelines. He needed to know precisely how to make that blend. Given reluctance to slow the feed rate, smaller-volume blends would be preferable to blends that violated the EPA guidelines. However, the drawbacks to this approach include more work for the fuel manager personnel in order to blend more charges, and that more inventory would be left in the other storage tanks that might prevent accepting new wastes from generators. This request resulted in another goal-programming model, with a new variable z = maximum deviation from guidelines:

$$\max\left\{\sum_{i=1}^{N} Tank_i - M z\right\}$$

s.t.

$$Tank_i + E_i = I_i \quad i = 1 \ldots N$$

$$\sum_{i=1}^{N}\left[\left(CON_{j,i}/EPA_j\right)Tank_i - Tank_i\right] - z \le 0 \quad j = 1 \ldots K$$

$$\sum_{i=1}^{N}\left[\left(BTU_i/BTUMIN\right)Tank_i - Tank_i\right] + z \ge 0$$

$$z \ge 0, Tank_i \ge 0, E_i \ge 0 \text{ for all } i$$

This model determines the maximum amount of waste fuel that can be blended without violating the EPA guidelines, so that the maximum feed rate can be sustained.

4.3 Implementation Results

External costs to develop the goal-programming-decision-support system totaled $19,500. While the company did not keep precise records of the internal costs, the general manager estimated they were much less than the external costs. The total time to complete development and implementation was three months. The gross profit of the fuel-management joint venture in the year preceding the implementation was $950,000. In the year following the implementation, gross profit reached $1.4 million. Of the $450,000 increase, $200,000 represented cost reduction efforts at the facility and were unrelated to model implementation. The remaining $250,000 was due to the goal-programming implementation, thus increasing gross profits by more than 25%.

The fuel manager could accept waste streams with higher contaminant levels for burning as fuel because the model showed how to blend them into acceptable fuel. Comparing loads rejected before and after the model was implemented provides strong evidence that the goal-programming model produced the desired results. In the year preceding the model implementation, 65 loads were rejected; while in the year following, only eight were rejected. That operators could use the "dummy" tanks to evaluate a particularly harsh load was extremely useful. The kiln used record volumes of waste-derived fuels because these extra loads could be accepted. The waste fuels provided 47% of the total needs of the kiln in the year following the implementation of the model, resulting in savings in excess of $1million on coal purchases. These coal savings, of course, cannot be attributed to the goal-programming model but instead to the idea of burning waste fuel efficiently in cement kilns. It also means that the consumption of more than 42,000 tons of coal was avoided.

5. Summary Observations

Ideally prevention strategies would completely eliminate the problem of waste disposal, however given the volume of waste produced each year practitioners can expect to deal with waste disposal well into the future. Academicians can help to understand and predict how operations managers might respond to this problem. This research develops a goal-programming approach to blend waste into fuel. A case study of the model illustrates the effectiveness of this approach and highlights the technical, social, and managerial issues involved in development and implementation.

This research also contributes to our larger understanding of the issues in environmental management; for example, that regulatory specifications matter and can be met. Since fuel managers rely heavily on regulatory specifications as a guide for blending fuel, regulatory agencies need to set precise specifications. If the specifications are set too low, disposal may result in environmental damage; if the specifications are too high, regulators may be encouraging excessive fossil-fuel consumption.

Finally, it is important to consider the validity of this research. Recently, researchers have noticed an academic drift (Corbett and Van Wassenhove 1993) and the growth of *scientism* (Meredith 2001) in modeling based research. Studying real-world problems require that researchers not only consider model verification, but also model validation (Miser 1993, Gass 1993). Meredith (2001 p. 330) notes that "many recently published OR/MS research studies following the realists philosophy seem to pay careful attention to verification test but circumvent the true validation process by conducting the validation testing against the intuitive, assumed phenomenon instead of the real phenomenon in the description phase, thus generating 'ivory-tower prescriptions' instead of real-world knowledge."

The implementation of the model in a real world setting helped validate the research. One year after the implementation effort the firm reported significant improvements in productivity and profitability. This helps confirm the applicability of the model and the quality management approach to develop the model. Productivity improvements occurred by getting as close the EPA specifications as possible with violating them, which simultaneously increased revenue and achieved the maximum throughput rate. We believe that as other organizations seek improve the productivity of their waste disposal processes they will also consider similar approaches.

References

Al-Shammari, Minwir, and Dawood Isaam 1997. Linear Programming Applied To A Production Blending Problem: A Spreadsheet Modeling Approach. Production and Inventory Management Journal, 38, 1, 1-7.

Amouzegar, Mahyar A., and Khosrow Moshirvaziri 1999. Determining optimal pollution control policies: An application of bilevel programming. European Journal of Operational Research, 119, 1, 100-120.

Angell, Linda C. and Klassen, Robert D. 1999. Integrating environmental issues into the mainstream: an agenda for research in operations management. Journal of Operations Management, 17, 575-598.

Chang, NI-BIN, and S. F. Wang 1997. A fuzzy goal programming approach for the optimal planning of metropolitan solid waste management systems. European Journal of Operational Research, 99, 2, 303-321.

Changchit, Chaweng and M. P. Terrell 1993. A multiobjective reservoir operation model with stochastic inflows. Computers & Industrial Engineering, 24, 2, 303-313.

Charnes, A. and W. W. Cooper 1976. A Goal Interval Programming Model for Resource Allocation in a Marine Environmental Protection Program. Journal of Environmental Economics and Management, 3, 4, 347-362.

Charnes, A., W. W. Cooper, K. R. Karwan, and W. A.Wallace 1979. A Chance-Constrained Goal Programming Model to Evaluate Response Resources for Marine Pollution Disasters. Journal of Environmental Economics and Management, 6, 3, 244-274.

Corbett, C. J. and L. N. Van Wassenhove 1993. The natural drift: what happened to operations research?. Operations Research 41, pp. 625-640.

Environmental Protection Agency 1999. National Emission Standards for Hazardous Air Pollutants from Hazardous Waste Combustors. Federal Register, 64, 189, 53038-53070.

Environmental Protection Agency 1999. Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities. Federal Register, 64, 189, 53074-53075.

Fylstra, Daniel, Leon Lasdon, John Watson, and Allan Waren 1998. Design and use of the Microsoft Excel Solver. Interfaces, 28, 5, 29-55.

Gass, S. I. 1993. Model accreditation: a rationale and process for determining a numerical rating. European Journal of Operational Research 66, pp. 250-258.

Giannikos, Ioannis 1998. A multiobjective programming model for locating treatment sites and routing hazardous wastes. European Journal of Operational Research, 104, 2, 333-342.

Goetsch, David L., and Stanley B. Davis 2000. Quality Management, 3rd Edition, Prentice Hall, Upper Saddle River, New Jersey.

Gupta, Surendra M., and Jacqueline A. Isaacs 1997. Value analysis of disposal strategies for automobiles. Computers & Industrial Engineering, 33, 1,2, 325-328.

Hart, John R. 1994. Comparison of emissions from burning hazardous waste in a dry-process cement kiln with emissions from burning conventional fossil fuels. Hazardous Waste & Hazardous Materials, 11, 1, 193-9.

Hobbs, Benjamin F., and Peter Meier 2000. Energy decisions and the environment: a guide to the use of multicriteria methods, Kluwer Academic Publishers, Boston, MA.

Hopp, Wallance J., Spearman, Mark L., Zhang, Rachel Q. 1997. Easily Implementable Inventory Control Policies. Operations Research, Vol. 45, No. 3, 327-340.

Hopp, Wallance J., Zhang, Rachel Q., Spearman, Mark L. 1999. An easily implementable hierarchical heuristic for a two-echelon spare parts distribution system. IIE Transactions, Vol. 31, 977-988.

Karmarkar, Uday S., and Rajaram Rajaram 2001. Grade selection and blending to optimize cost and quality. Operations Research, 49, 2, 271-280.

Kemezis, Paul 1993. EPA gets heat on haz-waste kilns. ENR, 231, 34.

Klassen, Robert D. 1993. Integration of environmental issues into manufacturing. Production and Operations Management Journal, 34, 1, 82-88.

Lamb, C. W., F. M. Miller and A. Roth 1994. Detailed determination of organic emissions from a preheater cement kiln co-fired with liquid hazardous wastes. Hazardous Waste & Hazardous Materials, 11, 1, 201-16.

Microsoft Corporation 1996. User's Guide Microsoft Excel.

Mihailidis, D. and K. R. Chelst 1998. Optimal blending of out-of-specifications substances. The Journal of the Operational Research Society, 49, 5, 458-466.

Miser, H. J. 1993. A foundational concept of science appropriate for validation in operational research. European Journal of Operational Research 66, pp. 204-215.

Mogharabi, Saeed N., and A. Ravindran 1992. Liquid-Waste Injection Planning Via Goal Programming. Computers & Industrial Engineering, 22, 4, 423-433.

Mohanty, R. P., and Jerry C. C. Koay 1988. A Goal Programming Application for Waste Treatment Quality Control. The International Journal of Quality & Reliability Management, 5, 4, 65-77.

Moore, Laurence J., Jack C. Davis, Aubrey E. Harvey, John J. Imholz 1993. Multicriteria models for analysis of the environmental restoration and waste management program. Computers & Industrial Engineering, 25, 1-4, 21-24.

Norman, P., and S. Naveed, S. 1990. A Comparison of Expert System and Human Operator Performance for Cement Kiln Operation. The Journal of the Operational Research Society, 41, 11, 1007-1019.

Patterson, Mike C. and Bob Harmel 2001. Using Microsoft Excel solver for linear programming assignment problems. International Journal of Management, 18, 3, 308-313.

Penkuhn, T., Th. Spengler, H. Puchert, and O. Rentz 1997. Environmental integrated production planning for the ammonia synthesis. European Journal of Operational Research, 97, 2, 327-336.

Rigby, Billy, Leon S. Lasdon, and Allan D. Waren 1995. The evolution of Texaco's blending systems: From OMEGA to StarBlend. Interfaces, 25, 5, 64-83.

Russo, Michael V. and Fouts, Paul A. 1997. A Resource-base Perspective on Corporate Environmental Performance and Profitability. Academy of Management Journal, Vol. 40, No. 3, 534-559.

Scholtes, Peter R., Brian L. Joiner, and Barbara J. Streibel 1996. The Team Handbook, 2nd Edition, Joiner Associates, Inc., Madison, WI.

Shih, Jhih-Shyang, and H. Christopher Frey 1995. Coal blending optimization under uncertainty. European Journal of Operational Research, 83, 3, 452-465.

Tayi, Girikumar 1985. A Polynomial Goal Programming Approach to a Class of Quality Control Problems. Journal of Operations Management, 5, 2, 237-246.

Valenti, Michael 1999. Trash, heat, and ash. Mechanical Engineering, 121, 8, 44-47.

Vermeer, Peter J., Clifford C. Pedersen, William M. Canney, and John S. Ayala 1997. Blend-control system all but eliminates reblends for Canadian refiner. Oil & Gas Journal, 95, 30, 74-79.

Walkenbach, John 1996. Excel For Windows 95 Power Programming with VBA, 2nd Edition, IDG Books Worldwide, Inc., Foster City, CA.

Walley, N. and Whitehead, B. 1994. It's not easy being green. Harvard Business Review, 72, 3, 46-52.

Acknowledgements

We would like to thank TBN Holdings, Inc., the parent company of TBN Cemtech, for supporting this project. Our special thanks goes to Mr. John Miller, CEO and founder of TBN Holdings, whose use of linear programming at an oil company earlier in his career prompted him to involve us in this project. We thank all of the people, who so graciously contributed important ideas to this project.

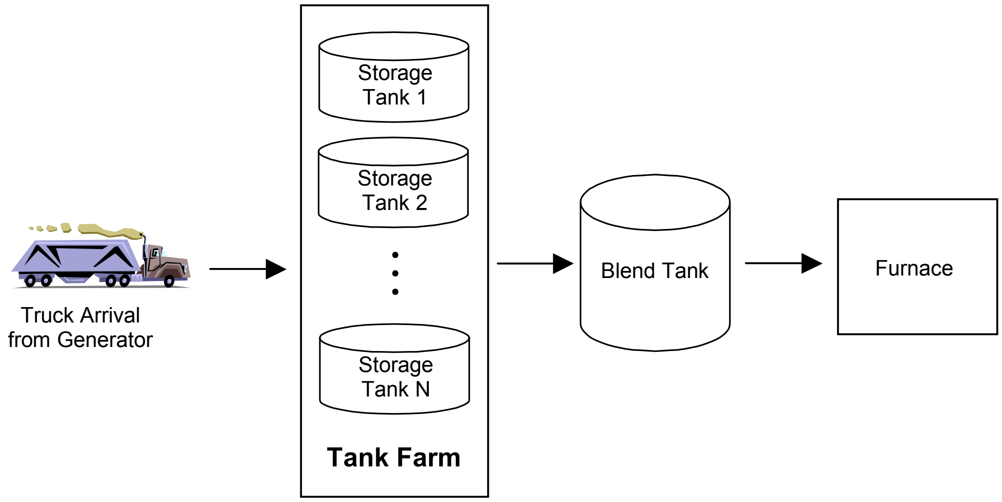

Figure 1: Waste-fuel blend-process flow

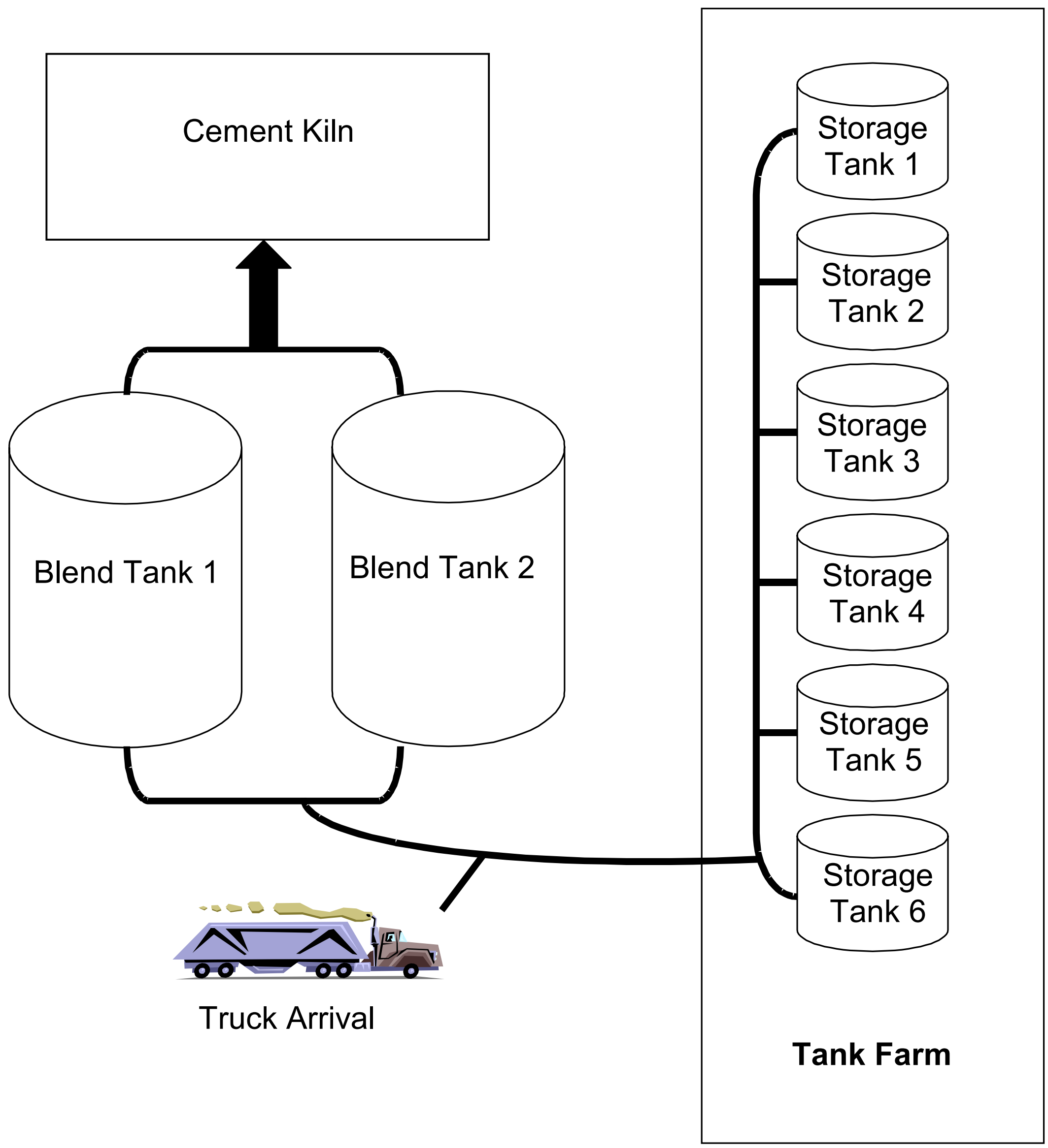

Figure 2: TBN Cemtech Facility Schematic

Variable	Definition
$Tank_i$	Amount of inventory taken from storage tank *i* to blend fuel (gallons)
E_i	Amount of inventory in storage tank *i* not used in blend (gallons)
$Below_j$	Amount of hazardous waste *j* below EPA guideline in gallons
$Above_j$	Amount of hazardous waste *j* above EPA guideline in gallons
$Below_{BTU}$	Amount of BTU below EPA guideline (burn specification) in gallons
$Above_{BTU}$	Amount of BTU above EPA guideline in gallons
Constant	**Definition**
EPA_j	EPA burn specification (guideline) for contaminant *j*
$CON_{j,i}$	Amount of contaminant *j* in storage tank *i*
$BTUMIN$	Minimum BTU burn specification (EPA guideline)
BTU_i	Amount of BTUs in storage tank *i*
I_i	Amount of inventory in storage tank *i* (in gallons)
$Target$	Target amount of waste blended into waste-fuel (gallons)
M	A penalty cost for violating an EPA guideline; typically a large value

Table 1: Notation