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# A Multiobjective Modeling Approach to Locating Incinerators

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# Abstract

The location of hazardous material incineration facilities is an important problem due to the environmental, social, and economic impacts that they impose. The costs associated with the facilities and the risks placed on nearby populations are important concerns as are the distributions of these costs and risks. This paper introduces a mixed-integer, multiobjective programming approach to identify the locations and capacities of such facilities. The approach incorporates a Gaussian dispersion model and a multiobjective optimization model in a GIS based inter-active decision support system that planners can access via the Internet. The proposed approach is demonstrated via a case study in central Portugal where the national government has decided to locate a large facility for the incineration of hazardous industrial waste. Due to intense local and national opposition, construction of the facility has been delayed. The system has been designed so that it can be used by decision makers with no special training in dispersion modeling, multiobjective programming, or GIS.

**Keywords:** decision support systems, HAZMAT location modeling, GIS, multiobjective modeling

# 1. Introduction

This paper presents a geographical information system (GIS) based inter-active decision support system (IDSS) designed to help planners determine the most appropriate locations and capacities for incineration facilities for hazardous materials (HAZMAT). The system incorporates a Gaussian plume model, to model atmospheric emissions from the facilities, and a multiobjective mixed-integer linear programming model to generate alternative siting schemes. Users enter data, and user options and preferences into the IDSS via tables. The web-based IDSS includes a sophisticated algorithm server that automatically constructs the mathematical model, generates the solution, and returns the results to the user in a table. A web graphical interface allows the user to conduct "what-if" analysis and generate additional solutions to consider. The system is demonstrated with a case study in Portugal.

The analysis of technological and industrial hazards has received a considerable amount of attention during the past several decades. In fact, threats to the environment are considered much more seriously in policy making at local, regional, national and global levels than they were only a few decades ago [3]. The location of HAZMAT facilities is a complex and important societal problem as these location decisions impose costs on those who provide and use the facilities, and risks on those who are impacted by them. Due to the fact that these costs and risks are often quite large, such facilities are often provided by governmental entities. In situations where such decisions are not made directly by a governmental entity, they are generally highly regulated by them.

Airborne pollutants are of crucial concern in many HAZMAT location problems, especially those involved with incineration. The emissions of atmospheric pollutants, either continuous or accidental, impose risks to various people. Mathematical programming has been applied to air quality control problems since Teller [52] and Kohn [30] at least. The severity of the risk depends on numerous factors such as the locations of the sources of the emissions, atmospheric conditions (e.g., wind direction), and the location of the people who may be affected. The potential for accidental emissions with very large negative impacts on various subsets of the overall population results in real and/or perceived inequity in the distribution of the resulting risks. As a consequence, issues associated with environmental justice have received considerable attention in recent years from the news media, policy makers, environmental activists, and academic researchers [6], [7].

The Gaussian dispersion, or Gauss plume, model is the most widely used technique for describing the movement and spread of non-reactive pollutants, and for estimating their

impact [7], [54], [29]. Gaussian dispersion models have been linked with mathematical programming for a long time [2], [26], [27], [21], [22]. ReVelle and Ellis [39], and Cooper et al [14], provide excellent surveys of this literature. In spite of this long history, there is a continuing need for additional dispersion based modeling approaches [38], [35].

In addition, the benefits, costs, and risks of HAZMAT facilities typically are dispersed among different individuals. As a consequence, considerable research has been dedicated to analyzing such problems. The use of mathematical programming techniques in HAZMAT facility location dates back to the late 1970s [10], [13]. A special journal issue on the topic appeared in 1995 [5], [18], [34], [55]. Excellent reviews of this literature appear in Erkut and Neuman [23], Schilling *et al.* [48], Murray *et al.* [36], and Moreno-Jiménez and Hodgart [35].

Researchers have been interested in multiobjective location problems for over 25 years [17]. Multi-objective approaches to public facility location [47], [49] and HAZMAT location [13] are among the earliest applications. Total risk, the equity of the distribution of the risk imposed, and dollar costs associated with the location scheme have been three crucial objectives addressed in this literature [34], [55]. Numerous approaches have been taken to address the equity of risk [32], [24], [38]. Minimizing the maximum risk imposed upon any individual [37], [18], [15] or on any region [36] have been important approaches to modeling the equity of risk.

GIS has been used in facility siting analysis since the 1970's. However, the application of GIS to location analysis has intensified in recent years in terms of application areas, and sophistication of interface. This is not surprising given the storage, retrieval, analysis, mapping, and visualization capabilities of GIS. GIS can greatly assist the location modeling and analysis process by helping to gather, structure, filter, and analyze input data and by presenting model outputs in a way that helps decision makers understand their spatial consequences. The interested reader is referred to Church [8] for an excellent review of this literature. There has been also a growing interest in the use of GIS tools to help analyze environmental problems [25]. The use of GIS has great potential to assist in the analysis of HAZMAT facility location issues given the spatial nature of the location decisions and the risks imposed by them [33], [31], [16], [9], [8], [35], [1].

The research presented in this article was generated by a real world HAZMAT location problem in Portugal; specifically, the location of incineration facilities for HAZMAT. Public reaction to initial proposals suggested that a multiobjective approach would be most appropriate. Due to the potential number of options, and the complexity of the tradeoffs among the objectives for them, an interactive decision support system (IDSS)

was developed to assist the decisions makers in the selection of the most preferred option. The proposed IDSS utilizes GIS to integrate a Gaussian plume dispersion model and a multiobjective facility location model.

The remainder of this article is organized as follows. The motivation for the research is given in section 2. The underlying multiobjective facility location model is formulated in section 3. Section 4 discusses the proposed approach to the case study, some of the system's capabilities, and preliminary results. A summary is presented in the last section.

#### 2. Motivation for the research

This research was motivated by the location of a facility for the incineration of hazardous industrial wastes (HIW) in Portugal. During the past two decades, the Portuguese government has addressed the problem of processing HIW produced in the country. A special committee consisting of members from six Portuguese universities was appointed to gather information about the production of industrial wastes in Portugal. A report on the amounts of waste produced by administrative region and by type of industrial source was presented [28]. HIW accounts for 25.36 x 10<sup>4</sup> tons (about 0.9%) of the total industrial waste produced in Portugal yearly (29.2 x  $10^6$  tons). Approximately 48% of this HIW production (12.16 x  $10^4$  tons) results from used oils. Other important HIW sources in Portugal are organic chemicals (32.4 x  $10^3$  tons corresponding to 12.8% of the total) and solvents (28.0 x  $10^3$  tons corresponding to 11.0 % of the total). Figure 1 demonstrates the geographical distribution of HIW in Portugal. To date, there are no processing facilities for this waste in Portugal.

# Insert Figure 1 about here

To address the issue of HIW processing, a decision was made by the central government to establish two co-incineration facilities (at existing cement plants) to process this waste. One was to be in the Lisbon and Tagus Valley (TV) region in Otão (south of Lisbon near Setúbal), and the other in the Center region in Souselas (about 7 kilometers north of Coimbra). This decision created intense debate and strong opposition from environmental groups and the public in general. Demonstrations in front of the Parliament and the official residence of the Prime Minister were frequent. As expected, the populations near the proposed sites were the most active opponents. Souselas is near Coimbra, a city with one of the oldest universities in the world (more than 700 years old) and a population of about 150,000 people including approximately 20,000 university students. Equity of risk

was an important concern to the local population as the Coimbra region produces very little HIW as the service sector accounts for about 75% of its economic activity and its industrial sector (about 20% of local economic activity) produces very little HIW.

The central government's location decisions were based largely on the conviction that co-incineration was the most efficient way to process the HIW as filters in the chimneys would prevent health risks. The local population and the scientific/engineering community were concerned with occasional atmospheric dispersions of pollutants (e.g., dioxins causing cancer and other diseases) resulting from an accident or a malfunction in the chimney filters. No scientific studies analyzing the impacts associated with extraordinary events (e.g., accidents or equipment malfunction) were ever presented to the public by the government.

Due to strong public opposition, construction has not started on either of the two proposed HIW incineration facilities. The purpose of this research has been to develop a decision support system that will facilitate a multiobjective analysis of the HIW siting problem. The underlying multiobjective location model is presented in the next section.

#### 3. Model formulation

At the core of the decision support system is a multiobjective facility location model. The purpose of this model is to identify non-dominated [12], [20] siting schemes for the HIW incinerators. The model determines the number of facilities to be opened, their locations, and their respective shares of the total HIW to be incinerated. This differs somewhat from the government's initial decision to locate a single plant in the northern half of Portugal to process approximately 50% of the total HIW generated in the country. However, it was done to determine if the possibility of multiple facilities would result in a more preferred option. Minimum and maximum processing loads were included for the candidate facilities. The minimum loads reflect the fact that small plants are not economical to operate. Maximum loads were established to facilitate the "sharing" of the risk imposed. These values are inputs to the model and can be varied to see their impacts on the location schemes generated.

The model includes five objectives. The first two of these minimize facility costs: fixed and operating. Two facility cost objectives were included, as these costs will be borne primarily by different entities. That is, the fixed costs will be assumed largely by the European Community and the operating costs will be paid largely by Portugal. The third objective minimizes total risk (measured as average per parish). The last two objectives address the equity of the risk imposed. The fourth objective does this by minimizing the

maximum average risk imposed on any parish and the fifth objective minimizes the maximum risk imposed on any individual. Transportation costs and risks are frequently important in HAZMAT facility siting [18], [15]. However, they were not included in this research due to time and cost constraints on the analysis and the fact that transportation distances are not great and the options are limited given the government's decision to have one facility near Lisbon and one near Coimbra.

Given the following definitions:

- $y_i$  binary variable, 1 if the *i*-th incinerator candidate is opened, 0 otherwise;
- $x_i$  amount (e.g., ton/day) of waste processed in incinerator *i*; real variable;
- *M* maximum average impact on the parishes; real variable;
- *T* maximum impact on an individual; real variable;
- *D* total demand (ton/day); real parameter;
- $I_i$  investment cost for incinerator *i*; real parameter;
- $L_i$  maximum capacity for each incinerator *i*; real parameter;
- $l_i$  minimum amount of waste required to open incinerator *i*; real parameter;
- $E_i$  processing cost for incinerator *i* by month, corresponding to the daily processing of 1 unit (e.g., 1 ton/day); real parameter;
- *N* number of candidate incinerators; integer parameter;
- $n_i$  number of inhabitants in parish *j*; integer parameter;
- *P* number of parishes; integer parameter;

*h* total number of inhabitants in Coimbra region ( $h = \sum_{j=1}^{p} n_j$ ); integer parameter;

- $m_i$  maximum impact on any individual from incinerator *i*, relative to the processing of 1 unit of waste (1 ton/day); real parameter;
- $f_{ij}$  average impact on parish *j* relative to the processing of 1 unit of waste in the incinerator *i* (e.g., 1 ton/day); real parameter;
- $c_{ik}$  impact produced by incinerator k relative to the processing of 1 unit (e.g., 1 ton/day) on the inhabited point (grid cell) of the maximum impact produced by incinerator *i*; real parameter.

The underlying multiobjective mathematical model may be formulated as follows.

The five objectives are:

Min 
$$\sum_{i=1}^{N} I_i y_i$$
 minimize total investment cost; (1)

Min	$\sum_{i=1}^{N} E_i x_i$	minimize total processing cost;	(2)
Min	$\sum_{i=1}^{N} \sum_{j=1}^{P} \frac{n_j f_{ij}}{h} x_i$	minimize total impact (measured as average per person);	(3)
Min	М	minimize max. average impact in the parishes;	(4)
Min	Т	minimize max. impact to an individual.	(5)

The constraints are:

N

$$x_i \leq L_i y_i \qquad \qquad i = 1, \dots, N \tag{6}$$

ensures that the maximum capacity for each incinerator *i* is not exceeded (*N* constraints);

$$x_i \geq l_i y_i \qquad \qquad i = 1, \dots, N \tag{7}$$

ensures that the minimum amount of waste required to open incinerator *i* is assigned to incinerator *i* before it is opened (*N* constraints);

$$\sum_{i=1}^{N} x_i \geq D \tag{8}$$

ensures that the total demand, D, is satisfied (1 constraint);

$$\sum_{i=1}^{N} f_{ij} x_{i} \leq M \qquad j = 1, ..., P$$
(9)

records the average impact on individuals in each parish (P constraints);

$$\sum_{k=1}^{N} c_{ik} x_{k} \leq T , \quad i = 1, ..., N$$
 (10)

records the maximum impact on any one individual (N constraints).

#### 4. Case study analysis

Several factors contribute to the complexity of the decisions involved in this analysis. First, the underlying science of aerial dispersion and its potential impacts is difficult for non-scientists to comprehend. Secondly, facility location problems typically involve a multitude of possible solutions. Third, the complexity of the analysis is greatly complicated by the inclusion of multiple objectives [12].

Interactive decision support systems (IDSS) have been shown to be effective aids in analyzing complex, multiobjective location problems [15], [1]. Consequently, a GIS-based IDSS was developed to assist governmental agencies and the general public in understanding and analyzing the problem at hand. GIS can be a powerful tool in the collection, storage, manipulation, and presentation of relevant data for the analysis as well

as an important tool to present outputs of the analysis to decision makers in a meaningful manner [8], [19]. Various interactive display techniques were included in the IDSS to assist the decision makers in understanding the various options and in analyzing the tradeoffs among them.

As noted earlier, the Portuguese government's initial plan was to locate two HIW incineration plants in Portugal: one in the southern half of Portugal at Otão, south of Lisbon; and the second in the northern half at Souselas, north of Coimbra. This research concentrates on developing a decision support system for analyzing such location decisions. To demonstrate the potential for the IDSS approach, the case study focuses on the northern facility location. The study assumes that the 50% of Portugal's total HIW (i.e., 126.8 x 10<sup>3</sup>ton/year) will be processed north of Coimbra. An additional 12 sites were selected as candidate locations in this area.

The IDSS starts by determining the geographical distribution of the impacts resulting from an accident or filter malfunction at each of the potential locations. These were evaluated for one unit of pollutant emission using the Gaussian dispersion model presented in the Appendix. The model identified the populations affected considering the most frequent wind direction in the region (approximately NW-SE, taken from 10 year wind records) and average wind speed (9m/s). The atmospheric stability class C of Pasquill-Gifford was considered [29]. The aim of this analysis was not to model a particular pollutant or to measure the absolute levels of exposure. Rather, it was to evaluate who would be impacted.

The spatial distributions or these impacts were calculated over a continuous region defined on a digitized map. This resulted in thirteen individual emission concentration distributions based upon one unit of HIW processed at each source. These are graphically represented in Figure 2. The darker the color in each plume, the higher the concentration. Only concentrations above a given threshold are visible. The study region covers 672 km<sup>2</sup> divided into 10 x 10 meter cells. Consequently, Figure 2 represents a 2800 x 2400 matrix of cells. The concentrations are evaluated at the centroid of each cell. In the case of an accident, it was assumed that the amount of emission from each source would be proportional to the quantity of HIW processed at that source. As these quantities are to be determined by the analysis, the Gaussian dispersion model generated per unit dispersion concentrations.

Insert Figure 2 about here

The IDSS uses the multiobjective mixed-integer linear programming (MILP) model presented in the previous section to generate non-dominated solutions to the problem. A solution consists of a set of opened facility locations and the HIW load assigned to each facility.

Model input (e.g., data, user options and preferences) can be entered and edited via four interlinked matrices. For example, Table 1 presents the "Incinerator Input Matrix". The investment cost ( $I_i$  in the MILP) and the processing cost ( $E_i$ ) for each potential facility site (i = A, B... M) are entered in the last 2 columns of this table. This matrix can also be used to force certain facilities to be opened (or not opened) in a solution by writing "Yes" or "No" under "Install" in Column 5 for the appropriate facility. When the user wants the system to "decide" if a facility should be opened at a particular location (which corresponds to a binary variable in the model), a "?" must be entered in the Install column for that facility's row. Similarly, Column 6 can be used to predetermine load allocations to various facilities. These features facilitate "what-if" analyses by the users. In another matrix, the user can define objective function weights and/or establish constraints on the objective function values to generate additional non-dominated solutions [12], [20].

# Insert Table 1 about here

The user submits the four matrices to the algorithm server via the website. The user needs no specialized training in multiobjective mixed-integer linear programming to formulate the model or any specialized software to solve it as the integrated web interface automatically structures the mathematical model from the user's tabular input and links the resulting model to an online MILP solver to generate the solution. In short, the IDSS automatically constructs the mathematical model, calculates the solution, and returns the results to the user in a table. In the case presented in this article, the model consists of 5 objective functions and approximately 200 constraints with over 10,000 entries (coefficients, variables, weights, etc.)

The IDSS employs the weighting method to initially generate ten non-dominated solutions to the multiobjective model. This is done to give the planners a general understanding of the tradeoffs among the objectives. The first five of these optimize the five objectives individually. Very small weights are placed on the other four objectives to identify a non-dominated solution. Objective function values for these five solutions are presented in columns 2-6 of Table 2 (where individual optimum values:  $opt_1$ ,  $opt_2$ ,  $opt_3$ ,  $opt_4$ ,  $opt_5$  are highlighted in bold). Objective 1 (investment costs) and Objective 2

(processing costs) are expressed in monetary units. Objectives 3, 4 and 5 represent pollutant concentrations (all in the same unit: impact/individual). Respectively, these are: average over all the inhabitants in the entire region, maximum average over the inhabitants in each parish, and the maximum over any individual in the entire region.

#### Insert Table 2 about here

Solutions 6 to 8 are "compromise" solutions. That is, they are non-dominated solutions identified via the weighting method [12], [20] using the following "relative" weights: Solution 6,  $(w_1, w_2, w_3, w_4, w_5) = (1/5, 1/5, 1/5, 1/5, 1/5, 1/5)$ ; Solution 7,  $(w_1, w_2, w_3, w_4, w_5) = (1/10, 1/10, 2/10, 3/10, 3/10)$ ; and Solution 8,  $(w_1, w_2, w_3, w_4, w_5) = (1/3, 1/3, 1/3, 0, 0)$ . Solution 6 weights the objectives equally while Solution 7 places a higher importance on the impacts on people (objectives 4 and 5). Solution 8 imposes additional constraints that limit the maximum values of objectives 4 and 5 to 220 and 420 respectively and assigns equal weights to the first 3 objectives. That is, it identifies the best solution for the first 3 objectives given the constraints on objectives 4 and 5.

These relative weights were selected to generate an approximation of the set of non-dominated solutions. The IDSS editing module, readily permits planners to input other weighting schemes based upon their relative preferences among the objectives.

The initial "relative" weights used by the IDSS and those provided later by the decision makers are automatically "scaled" by the IDSS. The actual weights,  $\overline{w}_i$ , used by the IDSS algorithm server to generate non-dominated solutions are based upon the relative weights and the values of *opt*<sub>1</sub>, *opt*<sub>2</sub>, *opt*<sub>3</sub>, *opt*<sub>4</sub>, and *opt*<sub>5</sub>. Specifically,

$$\overline{w}_i = w_i \frac{\sum_{j=1}^{5} opt_j}{opt_i}, \qquad i = 1, \dots, 5$$

The "ideal solution" [56] is a useful benchmark for comparing non-dominated solutions. The values of the five objective functions in the ideal solution are those obtained when each objective was optimized individually (i.e., *opt*<sub>1</sub>, *opt*<sub>2</sub>, *opt*<sub>3</sub>, *opt*<sub>4</sub>, and *opt*<sub>5</sub>). The objective function values for the ideal solution are given in the row labeled "Ideal Solution" in columns 2-6 of Table 2. This solution is not feasible unless a single solution is optimal for all of the objectives. The IDSS also identifies the "anti-ideal solution". The five

objective function values for this solution are the "worst" (i.e., maximum) values for each objective in Solutions 1-5. The objective function values for the "anti-ideal" solution are given in the row labeled "Anti-ideal Solution" in columns 2-6 of Table 2. The "ideal" and "anti-ideal" solutions are used in BAGAL, a graphical display representing solutions in objective space [15]. Solutions 1 through 5 which define the inner and outer boundaries (i.e., the ideal and anti-ideal solutions) of the BAGAL are shown in Figure 3.

#### Insert Figure 3 about here

One way to compare non-dominated solutions is to compare their "distances" from the ideal solution. The "distance" of each solution from the ideal solution is automatically evaluated by the IDSS using two frequently adopted metrics [4], [50]. These metrics are the Rectilinear, or Manhattan (L<sub>1</sub>), distance where  $L_1(x, y) = |x_1 - y_1| + ... + |x_n - y_n|$  and the Chebyshev (L<sub> $\infty$ </sub>) distance where  $L_{\infty}(x, y) = \max \{x_1 - y_1 | ..., |x_n - y_n|\}, x, y \in \Re^n$  (here, n = 5 objectives). The distances of each solution from the ideal solution, represented as a percentage above the ideal are given in columns " $\Delta L_1$  (%)" and " $\Delta L_{\infty}$  (%)" of Table 2.

The IDSS also uses the ideal solution to identify two additional non-dominated solutions using goal programming [51] where the "goals" are the ideal solution value for each objective. Solution 9 measures the relative (normalized) distances from the goals using the L<sub>1</sub> metric and solution 10 measures the distances using the L<sub> $\infty$ </sub> metric. The objective function values for these solutions are given in rows "Goal L<sub>1</sub> (Norm)" and "Goal L<sub> $\infty$ </sub> (Norm)" of columns 2-6 in Table 2 and their distances to the ideal solution are represented in columns " $\Delta$  L<sub>1</sub> (%)" and " $\Delta$  L<sub> $\infty$ </sub> (%)" of that table. For example, according to the data in Table 2, solution #10 would be the preferred solution according to the L<sub> $\infty$ </sub> metric.

The IDSS incorporates numerous graphical tools to help planners generate and compare non-dominated solutions and to determine if additional solutions might be of interest. Although a complete description of the IDSS is beyond the scope of this paper, we present two such tools built into the IDSS. First, various output tables can be generated

automatically. For example Table 3 shows how many facilities are opened (column 2), the load assigned to each opened facility (columns 3-15), the total HIW load for each solution generated to date (column 16) and the solutions obtained (column 17) when the facility capacity constraints are relaxed (i.e., a single facility can process all of the HIW.)

## Insert Table 3 about here

The IDSS also generates BAGALS displaying various solutions selected by the user. For example, Figure 4 displays Solutions 5 and 8 on the BAGAL. The decision makers can readily see that Solution 8 outperforms Solution 5 in terms of Objectives 1, 3, and 4 and is worse than Solution 5 in terms of Objectives 2 and 5. Another major advantage of the IDSS is that it allows decision makers to conduct "what if" and sensitivity analyses on various problem parameters and policy options. For example, Table 1 can be used interactively by the decision maker to "modify" the underlying "problem". The Input Matrix can be used to add constraints on various objective function values or to change the relative weights on the objectives to generate new non-dominated solutions.

#### Insert Figure 4 about here

The earlier analysis assumed that more than one facility could be opened. A single facility (i.e., uncapacitated) scenario was run to see how the Souselas location (site K) initially selected by the central government ranked vis-à-vis the other 12 potential locations. As Table 4 shows, site K is not optimal for any of the 5 objectives and is dominated by site D. These solutions and Table 2 can be generated readily by the decision maker via straightforward input to the IDSS.

#### Insert Table 4 about here

#### 5. Summary and conclusions

The motivation for this research was a central government decision to locate a hazardous industrial waste (HIW) incineration facility in central Portugal. Due to the risks involved with such a facility, the decision resulted in intense opposition from various organizations and individuals at the local, national, and international levels. In response to this opposition, this research was undertaken to develop a multiobjective, interactive decision support system (IDSS) to help decision makers understand, analyze, and explain the extremely complicated decisions involved. The IDSS integrates sophisticated techniques from the fields of atmospheric dispersion modeling, facility location modeling, geographical information systems (GIS), and multiobjective decision analysis.

Model input (e.g., data, user options and preferences) can be entered and edited by the users via four interlinked matrices. The web-based IDSS includes a sophisticated algorithm server that automatically constructs the linear programming model, calculates the solution, and returns the results to the user in a table. The IDSS incorporates numerous graphical tools to help planners generate and compare non-dominated solutions and to determine if additional solutions might be of interest. The user needs no specialized training or software to utilize these features.

Due to the strong opposition of the population and local governments, co-incineration in Souselas has not yet begun. Although it may be too late to ultimately influence the HAZMAT location decision that initiated this effort, it is expected that this research will provide the structure and tools to analyze future location decision that impose risk on various members of the overall population.

#### 6. Authors' Note

The motivation for the approach taken in this research was generated, in large part, by research conducted by Professor Charles (Chuck) ReVelle over the past 30 years. The underlying problem is one of facility location. Chuck was a pioneer in modeling these



problems [43], [46], [41], [53], [11] as well as a pioneer in the use of multiobjective analysis for public facility location problems [49] and for HAZMAT facility location [13]. The modeling of environmental issues was another major concern of his dating back to ReVelle et al [40] and including ReVelle and ReVelle [42], [44], [45], ReVelle and Ellis [39], and ReVelle [38] among others. The authors are particularly honored that this research will appear in a special issue dedicated to the memory of Professor ReVelle as we represent three "generations" of his PhD student family (in reverse order of authorship which would please him).

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# **APPENDIX – The Gaussian diffusion equation**

$$c_{(x^{*},y^{*},z^{*})} = \frac{Q}{2\pi\sigma_{y^{*}}\sigma_{z^{*}}U}e^{\left[-\frac{1}{2}\left(\frac{y^{*}}{\sigma_{y^{*}}}\right)^{2}\right]}\left\{e^{\left[-\frac{1}{2}\left(\frac{z^{*}-z^{*}_{s^{*}}}{\sigma_{z^{*}}}\right)^{2}\right]}+e^{\left[-\frac{1}{2}\left(\frac{z^{*}+z^{*}_{s^{*}}}{\sigma_{z^{*}}}\right)^{2}\right]}\right\}$$

$$\Delta h = \frac{2V_{s}r_{s}}{U}\left[1.5+2.68\times10^{-2}\times P\times\left(\frac{T_{s}-T_{a}}{T_{s}}\right)\times2r_{s}\right]$$

$$U = \sqrt{x_{w}^{2}+y_{w}^{2}} - \text{ wind speed (m/s)}$$

$$Q - \text{ emission flow rate (g/s)}$$

$$\sigma_{y^{*}}, \sigma_{z^{*}} - \frac{\text{standard deviation of plume concentration in crosswind horizontal (y^{*}) and crosswind vertical (z^{*}) directions at x^{*} (according to stability parameters)$$

$$X^{*} - \text{ downwind distance to source }(x_{s}, y_{s})$$

$$Z^{*} - \text{ receptor height above ground}$$

$$Z_{s}^{*} - \text{ effective height of emission (m) = physical height + plume rise (\Delta h)$$

$$V_{s} - \text{ emission speed (m/s)}$$

$$P - \text{ atmospheric pressure (kPa)}$$

$$T_{s} - \text{ chinney interior temperature (K)}$$

C – concentration at reception point (g/m<sup>3</sup>)

# Table 1: Example of "Incinerator Input Matrix" for the IDSS.

2	0					Matrix				
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				Edit Spec.	Default	Default	Default	Default	Default	ы.
				Att. Name	Name	Install	Daily capacity (Kg)	Install Cost	Cost Ton	
EI	ement Type		Order	Active		ý	ψw	ф-		$\Phi$
	Real	-	0		A	?	?	879 000	1.31	4
•	Real	-	1		В	?	?	596 000	1.44	$\Phi$
	Real	-	2		С	?	?	623 000	1.12	4
	Real	-	3		D	?	?	545 000	1.61	4
	Real	•	4		E	?	?	785 000	1.45	
	Real	-	5		F	?	?	972 000	1.09	4
	Real	•	6		G	?	?	865 000	1.26	4
	Real	-	7		н	?	?	761 000	1.03	$\Phi$
	Real	•	8		T	?	?	672 000	0.99	4
•	Real	•	9		J	?	?	918 000	1.52	
	Real	•	10		К	?	?	893 000	1.69	4
	Real	-	11		L	?	?	698 000	1.29	$\Phi$
	Real	•	12		м	?	?	847 000	1.18	4
Г										. 9
					4.2	4.5	4-5	4.2	4-	Y
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	Att. Cut	•	Max Indiv 👱				200 000			4
•	Att. Cut	•	Min Sum 💌				347 400			4
1					4-4	4-	4-	4-	4.00	4 9

Solutions	Investment Cost	Process. Cost	Average Impact	Max Parish Impact	Max Individual Impact	ΔL <sub>1</sub> (%)	ΔL <sub>∞</sub> (%)
(1) opt 1	1 141 000	525 314	41	545	1 467	992.7%	492.2%
(2) opt 2	1 433 000	349 822	256	812	2 306	2 616.3%	1 197.4%
(3) opt 3	1 726 000	429 094	20	551	1 405	890.4%	467.3%
(4) opt 4	6 082 000	492 599	86	123	762	1 016.0%	433.0%
(5) opt 5	8 243 000	432 260	92	333	248	1 182.5%	622.4%
(6) Equal Weights	3 107 000	465 615	24	288	597	501.5%	172.3%
(7) Weighted (10,10,20,30,30)	3 652 000	479 214	29	248	513	515.7%	220.1%
(8) Constr (Obj4<220, Obj5<420)	5 140 000	454 719	47	220	420	665.7%	350.5%
(9) Goal L <sub>1</sub> (Norm)	3 107 000	465 615	24	288	597	501.5%	172.3%
(10) Goal $L_{\infty}$ (Norm)	2 773 000	483 678	31	295	605	521.6%	144.2%
Ideal Solution	1 141 000	349 822	20	123	248	0.0%	0.0%

Table 2 – Summary of the first 10 non-dominated solutions generated by the IDSS

	# Incin. Opened	Candidate Facilities										Total	Incin.			
Solutions		A	В	с	D	E	F	G	н	I	J	к	L	м	HIW (kg/day)	Opened No capacity limit
(1) opt 1	2	0	200 000	0	147 400	0	0	0	0	0	0	0	0	0	347 400	D
(2) opt 2	2	0	0	0	0	0	0	0	147 400	200 000	0	0	0	0	347 400	I
(3) opt 3	2	147 400	0	0	0	0	0	0	0	0	0	0	0	200 000	347 400	м
(4) opt 4	8	32 789	44 866	0	69 534	33 996	0	21 368	0	35 939	0	64 274	0	44 634	347 400	D
(5) opt 5	11	25 833	43 259	37 334	24 860	27 118	54 603	26 905	23 727	21 428	0	0	21 302	41 032	347 400	F
(6) Equal Weights	4	62 368	105 582	0	0	74 531	0	0	0	0	0	0	0	104 918	347 400	м
(7) Weighted (10,10,20,30,30)	5	53 618	90 717	0	51 588	61 270	0	0	0	0	0	0	0	90 208	347 400	в
(8) Constr (Obj4<220, Obj5<420)	7	43 918	29 530	63 326	42 200	49 879	0	44 828	0	0	0	0	0	73 719	347 400	(Infeasible)
(9) Goal L <sub>1</sub> (Norm)	4	62 368	105 582	0	0	74 531	0	0	0	0	0	0	0	104 918	347 400	м
(10) Goal L <sub>o</sub> (Norm)	4	0	108 168	0	60 776	72 181	0	0	0	0	0	0	0	106 275	347 400	В
Max amount assigned =		147 400	200 000	63 326	147 400	74 531	54 603	44 828	147 400	200 000	0	64 274	21 302	200 000		

# Table 3 – Load assigned to each opened facility for each solution generated

22

Facility opened	Investment Cost	Processing Cost	Average Parish Impact	Max Parish Impact	Max Individual Impact
А	879 000	455 094	23	1 299	3 312
В	596 000	500 256	24	946	1 935
С	623 000	389 088	33	763	2 280
D	545 000	559 314	63	521	3 457
E	785 000	503 730	33	1 254	2 774
F	972 000	378 666	141	2 062	1 566
G	865 000	437 724	152	1 235	3 166
H	761 000	357 822	340	1 156	3 626
I	672 000	343 926	194	808	3 985
J	918 000	528 048	89	1 768	3 704
K	893 000	587 106	178	548	4 049
L	698 000	448 146	85	721	3 537
М	847 000	409 932	18	954	1 977

 Table 4 – Objective function values for each of the potential sites serving as the only facility opened







Figure 2: 13 candidate locations and individual pollutant dispersion plumes normalized for 1 kg of emission at each source showing maximum concentration and the decay



Figure 3: BAGAL showing the five solutions that optimize objectives 1-5 and define the inner and outer boundaries of the BAGAL



Figure 4: BAGAL showing solutions 5 and 8