A Sensitivity Analysis of a Heuristic Model used for the Placement Allocation of Utilities in Transportation Right-of-Way Corridors

by

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‘That is what we mean by science. That both question and answer are tied up with uncertainty, and that they are painful. But there is no way around them and that you hide nothing, instead everything is brought out into the open.’

-- Peter Høeg (1995)
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“Gratitude is the least of the virtues, but ingratitude is the worst of vices.”

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A SENSITIVITY ANALYSIS OF A HEURISTIC MODEL USED FOR THE
PLACEMENT ALLOCATION OF UTILITIES IN TRANSPORTATION RIGHT-
OF-WAY CORRIDORS

Steve Clarence Christian

ABSTRACT

The requirements for public utility systems in the United States of America have
grown enormously over the years triggering a tremendous shortage for space available to
public utilities on and within transportation right-of-ways (ROW). Overcrowding and
improper location of utilities has resulted in problems such as, damage to infrastructure,
traffic accidents and, interruption of service to customers. The project titled, “Optimal
Placement of Utilities within FDOT Right-of-Way”, sponsored by the Florida
Department of Transportation (FDOT), and currently being investigated at the University
of South Florida, presents a decision-making heuristic aimed at developing a better utility
placement allocation system (Kranc et. al) [6]. Working in accordance with the guidelines
of safety, relocation, and clearance for utility placement set by the American Association
of State Highway and Transportation Officials organization (AASHTO), the heuristic
finds suitable locations for the utilities in ROW corridors. However, a model being used
to advocate a practice having large social and economical impacts is more likely to play
the role of generic evidence in a trial, whose weight must ultimately be established by a ‘jury’. The question being addressed to the system must be scrutinized carefully, and the formal structure updated iteratively until it proves capable of providing an answer to the given question. A good sensitivity analysis can provide this generic quality assurance to the model and help demonstrate the worthiness of the model itself.

This thesis is a quantitative and qualitative sensitivity analysis of the abovementioned heuristic. The analysis is conducted in two parts,

1. The ‘Model Factor Sensitivity Analysis’, with the objective of assessing the uncertainties associated with the modeling of the heuristic. This analysis focuses primarily on providing an evaluation of the confidence in the heuristic and its predictions by analyzing the influences that variations in the input factors have on the outputs of the utility cost assessment models and the final output of the heuristic itself. Variance based sensitivity indices derived from Sobol’ sensitivity indices [42] are used here for this purpose.

2. The ‘Model Output Evaluation and Enhancement’ study, which initially focuses on understanding / evaluating the complexities of the discrete step, cost optimization procedure used in the heuristic and later, based on certain observed shortcomings and problems develops an enhancement, the Ideal Configuration Selector (ICS) to be implemented with the heuristic. The ICS addresses all the problems of the heuristic with the help of experimental speedup, positional sensitivity and refinement tools and employs a multi criterion evaluation technique for utility configuration assessment to provide substantiation to the outputs determined by the heuristic.
CHAPTER 1
INTRODUCTION

Roads and highways are the backbone of our transportation system. But apart from their obvious application, they also play the important role of accommodating utilities in their right-of-way (ROW). A utility is defined as “a privately, publicly or cooperatively owned line, facility or system, for producing, transmitting or distributing communications, cable television, power, electricity, light, heat, gas, oil, crude products, water, steam, waste and storm water, not connected with highway drainage or any other similar commodity including any fire or police signal system or street lighting system, which directly or indirectly serves the public” [2]. Utility lines can be subsurface lines (like water or sewer lines) or above the ground aerial structures (like telephone or electric lines).

Around 1916, the United States of America embraced the concept of utility – transportation corridors [1]. Since then, utilities have been located within the ROW of transportation roads and highways (Figure 1.1 is an illustration of a Highway with Utilities placed within the ROW). A right-of-way is defined as “any part or access to a public agency’s transportation facility above, at the surface or below the ground” [3]. State Departments of Transportation (DOT) are public agencies that have regulatory responsibility for the maintenance and operations of the roads and highways in a state. It is their duty to carry out these functions in an efficient manner, ensuring the safety, traffic
carrying ability, and physical integrity of the facilities within and along the ROW. A utility’s presence in the ROW affects these functions and hence the DOT is in part responsible for its location.

Figure 1.1: Diagram Of Utilities Placed In Transportation ROW
The previous systems used by the DOT’s for allocating placement locations to utilities within the ROW were based on a first come first served method with no governing rules or regulations. Such evolutionary systems were neither safe nor economic solutions to the problem. In 1956, when the national system of interstate highway program was created it became apparent that the control of access by utility firms to the ROW was essential to ensure the safe operations of the highway systems. The AASHTO prepared the “Policy on the Accommodation of Utilities on the National System of Interstate and Defense Highways” [4] in 1959, and in 1966 it was made mandatory for all DOT’s in-charge of their state’s roadways and highways to follow the regulations given by the AASHTO. The Federal Government required each State to develop and maintain a Utility Accommodation Manual (UAM) to summarize policies regarding location and relocation of facilities within transportation corridors [4].

Since then, there has been a rapid growth in vehicular volumes, speeds and weights resulting in a larger network of roads and highways. Recent years have also witnessed a tremendous growth in traffic and customers for companies like telecommunication, cable television and internet providers. This has created a demand for increased access to various utility lines and, a much bigger distribution of utility systems. Considering the present number of utilities and forecasting a probable requirement for new ones, in the future, a wide range of utilities will have to share the already crowded ROW’s. Many of the present roads have narrow ROW’s or are running through crowded urban areas. It has become increasingly difficult for the DOT’s to upgrade older roads to provide the necessary capacity for placement of new utilities, and also ensure the safety of motorists using them. Crowding and increase in the demand for space has resulted in
problems of damage to infrastructure, public safety, interruption of service to customers and traffic disruptions. Obviously, there exists a very urgent need for a better solution to the utility placement problem than that provided in the utility accommodation manuals alone.

The ongoing research project titled, “Optimal Placement of Utilities within FDOT right-of-way”, sponsored by the FDOT and currently being investigated at the University of South Florida (Kranck et. al.) [6], presents a decision-making heuristic, the goal of which is to build a better utility placement allocation system. The heuristic, described as a discrete step, cost optimization model, numerically simulates the shape and dimensions of the transportation corridor, and physical information of the utilities to be located within it. Working in accordance with the rules and regulations of safety, relocation, and clearance for utility placement set by AASHTO, and utilizing positional cost assessment models, the heuristic finds suitable (near optimal cost) locations for the utilities in the ROW corridors.

1.1 Thesis Focus : Sensitivity Analysis & Model Enhancement

When a model is used for making decisions that could have large social and economical impacts, verification analysis is naturally invoked for the corroboration, quality assurance, and defensibility of its output. Issues of relevance and transparency become critical in this context. This thesis is a quantitative and qualitative sensitivity study of the abovementioned heuristic. The study primarily aims at providing an evaluation of the confidence in the model by assessing the uncertainties associated with the modeling process and the outcome of the model itself.
The heuristic finds suitable placement locations for utilities within the ROW corridors by optimizing the total costs of entire utility systems. Positional costs of individual utilities of a configuration (a positional arrangement of utilities in the cross section view of the corridor) are determined from respective overall cost functions, estimated from various global model factors and smaller cost models integral to the main model. The first part of the model analysis, that is, the factor sensitivity study, addresses the issue of assessing the uncertainties associated with the modeling process by analyzing the influences that variations in the input factors (both global and intra modular) have on the outputs of the utility cost assessment models and the heuristic itself. The approach adopted for this purpose is a combination of the design of experiments (DOE) technique and sensitivity analysis performed in a specific manner to determine variance sensitivity indices (based on Sobol’ sensitivity indices) [42], a measure used commonly for quantifying the effect of input factors on the output of complex models. The factors considered in this study are categorized and analyzed separately based on their specific application and area of influence in the model. The different categories considered are,

1. Accident Model Factors
2. Damage Model Factors
3. and, Installation Surcharge Models Factors.

The second part of the model analysis is an enhancement study (an assessment of the quality) of the final output of the heuristic. This study initially focuses on better understanding the complexities of the discrete step, cost optimization procedure used in the heuristic, and later, based on certain observed shortcomings and problems in the
output determination technique, suggests an enhancement, that is, the Ideal Configuration Selector (ICS) to be implemented with the heuristic.

During conference presentations, it was noticed that besides the DOT, a diverse group of stakeholders such as, the public (consumers), utility owners (public and private,) and other corporate parties (contractors, services etc.) expressed interests in the development of a utility corridor organization scheme. A study was conducted to determine a set of criteria to be used for the assessment of utility configurations. Considering the requirements of each party (stakeholder), the following characteristics (qualities) of an ideal utility configuration was finally decided on.

1. Optimality in the total cost of the configurational solution.
2. Fairness in location for utilities of the configuration.
3. Flexibility in the positioning of utilities of the configuration.
4. Low usage of corridor space by the configuration.

The next steps involved defining and calculating quantifying measures for these ideal configurational characteristics. Experimental tools and techniques like, the Jiggle Sensitivity Tool (JST), for determining the positional sensitivities and positional flexibilities of utilities in a configuration, the Cost Dot Technique (CDT), and the Metric used in conjunction to identify and quantify differences between output configurations were developed and put to use in the proposed Ideal Configuration Selector (ICS). The ICS can be described as an experimental utility configuration assessment tool which uses a multi-criterion decision making procedure called the Weighted Product Model (WPM) to assess and rank configurations according to their conformity to the desired configurational characteristics. The utility configuration embodying most of the ideal
configurational characteristics is selected as the best solution. The configurational rankings obtained from the ICS depend heavily on the weights (importance measures) assigned by the decision maker to each quality characteristic. The sensitivity and criticality of the results (rankings) to the weights assigned is also determined to provide the decision maker with further insight into the configuration selection procedure.

1.2 Thesis Outline

This thesis underscores through a real-world application, the usefulness of sensitivity analysis and the scientific challenges faced in model development and model corroboration. This thesis is organized as follows:

1. Chapter 2 discusses the literature review of sensitivity analysis and describes the present techniques that are being employed for sensitivity studies. Examples are presented to illustrate the use of sensitivity analysis in a wide variety of application areas.

2. Chapter 3, titled ‘The Heuristic’, describes the formulation and the working structure of the heuristic. The cost factors, cost assessment models and, rules (constraints) of safety and clearance set by the AASHTO for placement of utilities are also explained here.

3. Chapter 4, ‘The Problem Statement’, describes the reason for this research and details the proposed studies and work to be performed in the chapters ahead.

4. Chapter 5 is the first part of the analysis titled, “Model Factor Sensitivity Analysis”. It is aimed at increasing the confidence in the heuristic and its predictions by assessing the uncertainties associated with the certain input factors (global and intra
modular) of the model. The chapter introduces variance based sensitivity indices (Sobol’ sensitivity indices) [42] for quantifying the effect of the input factors on the output of the heuristic.

5. Chapter 6 presents the results of the factor sensitivity studies conducted in chapter 5.

6. Chapter 7, the second part of the model analysis titled, ‘Model Output Evaluation & Enhancement’, is an evaluation (assessment) study of the final output of the heuristic. This chapter defines characteristics / criterion for an ‘ideal’ utility configuration, the quantifying measures for which are then used in an experimental utility configuration assessment tool, the Ideal Configuration Selector (ICS) designed to work in conjunction with the previously developed heuristic.

7. An example illustrating the working of the ICS is included in Chapter 8. Output substantiation advantages of using the ICS are highlighted here.

8. Chapter 9 provides recommendations for future work and interesting topics for further research / development of the heuristic.

9. The Appendices of the thesis is organized as follows
   a. The proof for the variance based sensitivity indices developed by Sobol’ (1990b) [42] is included in Appendix A.
   b. Appendix B describes the standard utility placement problem considered for most of the analysis conducted on the heuristic.
   c. Appendix C contains the analysis of variances (ANOVA) results for the design of experiment tests conducted on the cost models.
d. Appendix D describes the experimental Cost Dot Technique and the Metric used together in the Ideal Configuration Selector for differentiating between, and clustering common orientation utility configurations.

e. Another experimental tool called the Jiggle Sensitivity Tool used in the ICS to determine positional sensitivities and utility jiggle (positional flexibility) capabilities is described in Appendix E.
CHAPTER 2  
LITERATURE REVIEW

This thesis is a quantitative and qualitative sensitivity analysis of the heuristic being developed with the intension of building a good utility placement allocation system. Sensitivity analysis is being used here for the corroboration, quality assurance, and defensibility of this model. In this chapter, sensitivity analysis and present techniques that are being employed for sensitivity studies are introduced. Practical hints about the associated advantages and efforts needed to effectively select a technique and perform a functional sensitivity analysis of a numerical model are included. As a final point, the discussions are illustrated into concrete examples showing the power of sensitivity analysis in a wide variety of application areas.

2.1 Sensitivity Analysis

Sensitivity analysis is defined as the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation, and of how the given model depends upon the information fed into it [60]. Sensitivity analysis is, in the opinion of most scientists, an important element of modeling. Kolb, quoted in Rabitz [36], states that “theoretical methods are sufficiently advanced, and, it is intellectually dishonest to perform modeling without sensitivity analysis”, while Furbringer [24] argues in ‘Sensitivity analysis for modelers’,
“Would you go to an orthopedist that didn’t use X-rays?”. Rabitz [36] presented sensitivity analysis as a fundamental ingredient for model building and a key tool in the understanding of complex physical processes. According to him, sensitivity analysis helps analyze the contents of the model and interface it with observational data. It helps to identify, which factors are critically important, how they are interrelated, and especially how they at a given level of description of the system influence the behavior of the model.

2.1.1 Why Carry Out A Sensitivity Analysis?

Many processes are so complex that physical experimentation is too time consuming, too expensive, or even impossible. As a result, to explore systems and processes, investigators often turn to mathematical or computational models. When models are used for making decisions, having a large social and economical impact it is not surprising to meet cynic opinions about them. According to Hornberger and Spear [28], “….most heuristics will be complex, with many parameters, state-variables and non linear relations. Under the best circumstances, such models have many degrees of freedom, and with judicious fiddling, can be made to produce virtually any desired behavior, often with both plausible structure and parameter values.” This problem highlighted by Hornberger is acutely felt in the modeling community. The awareness of the danger implicit in selecting a model structure as true and working happily thereafter leads to the attempts to map rigorously alternative model structures into the space of the model predictions [60]. The natural extension of which is the analysis of how much each source of uncertainty weighs on the model prediction.
Thus, almost all models have use for sensitivity analysis. Applications worked by the Joint Research Centre group for Applied Statistics include: Atmospheric Chemistry [13], transport emission modeling, fish population dynamics [60], composite indicators [60], portfolios, oil basin models [60], capital adequacy modeling, macroeconomic modeling, radioactive waste management [60]. The EC handbook for extended impact assessment, a working document by the European Commission, 2002, states “A good sensitivity analysis should conduct analyses over the full range of plausible values of key factors and their interactions, to access how impact change in response to change in key factors”. Similar recommendations are found in the United States EPA’s White Paper on model acceptability, 1999.

In the context of numerical modeling, sensitivity analysis means very different things to different people. For a reliability engineer, sensitivity analysis could be the process of moving or changing components in the design. For a chemist, sensitivity analysis could be the analysis of the strength of the relation between kinetic or thermodynamic inputs and measurable outputs of a reaction system, and for a software engineer, sensitivity analysis could be related to the robustness and reliability of the software with respect to different assumptions. These different types of analyses have in common the aim to investigate how a given computational model responds to variations in its input. Modelers generally conduct sensitivity analysis to determine:

1. If a model resembles the system or process under study. This process is also known as the validation of the model.

2. Which factors contribute largely to the output variability and require additional research. This process is conducted primarily to strengthen the modeler’s knowledge
base and is known as the calibration process. Part of the calibration study would involve determining the optimum regions within the space of the influential model factors.

3. If certain model factors (or parts of the model) are significant, and if not can be eliminated from the final model. This process is known as the mechanism reduction which enables building a simpler model from a more complex (lumped) model.

4. If there is some region in the space of the input factors for which the model variation is maximum.

5. If and which group of model factors interact with each other enough to effect the output of the model.

2.1.2 Types Of Sensitivity Analysis

This section, gives an overview of the various methods that are currently used in sensitivity studies. The choice of which sensitivity analysis method is a difficult, since each technique has strengths and weaknesses and would depend on the problem the investigator is trying to address and the characteristics of the model under study.

Let us assume that we are studying a system of \( k \) input factors \( x = (x_1, x_2, \ldots, x_k) \) and an output variable \( y \). In practice, the input factors are affected by several kinds of heterogeneous uncertainties that reflect our imperfect knowledge of the system. Hence it is convenient for the purpose of sensitivity analysis to treat them as random variables with assumed probability distributions. The vector \( x \) can be seen as a realization of a random vector \( \mathbf{X} \), characterized by a joint probability density function \( P(\mathbf{X}) = P(X_1, \ldots, X_k) \).
\( X_2, \ldots, X_k \) assumed to be known. The output variable \( y \) can then also be seen as a realization of a random variable \( Y \), and the relationship between the input factors and the output under study can be represented by a mathematical construction \( f(.) \) such that,

\[
Y = f(X_1, X_2, \ldots, X_k) = f(X)
\]

Different sensitivity analysis strategies may be applied, depending on settings. The three main settings identified are,

1. **Factor Screening**: Where the task is to identify influential factors in a system with many factors. This method is used in dealing with models that are computationally expensive to evaluate and have a large number of input factors. As a drawback these economical methods tend to provide only qualitative sensitivity measures i.e. they rank the input factors in importance but do not quantify how much more important a given factor is than another.

2. **Local Sensitivity Analysis**: Where the emphasis is on the local impact of the factors on the model. Local sensitivity analysis involves computing partial derivatives of the output functions with respect to input factors.

3. **Global Sensitivity Analysis**: Where the emphasis is on apportioning the output uncertainty to the uncertainty in the input factors described typically by probability distribution functions or range of factor existence. Global sensitivity analysis typically takes a sampling approach, and the uncertainty range given in the input reflects the imperfect knowledge of the model factors and parameterization. A global method evaluates the effect of input factor \( x_i \) while all other \( x_j, j \neq i \), are varied as well. In contrast, the local perturbative approach is based on partial derivatives, the
effect of the variation of the input factor $x_i$, when all other $x_j, j \neq i$, are kept constant at their central value [32].

2.1.2.1 Screening Designs

Screening designs are preliminary numerical experiments whose purpose is to isolate the most important factors from amongst a large number that may affect the model response. Typical screening designs are One-At-a-Time (OAT) experiments in which, the impact of changing the values of each factor is evaluated in turns (Daniel, [19], [20]). The experiment which uses the standard values is defined as the control experiment. For each factor, two extreme values are selected and then the analyst decides the control value (normally, ‘midway’ between the two extremes). The magnitude of residuals, defined as the difference between the perturbed experimental results and the control, are compared in order to evaluate factors to which the model is significantly sensitive.

One major limitation of the OAT experiments is that they allow only the evaluation of the main effects (the effects of the input factors without including their mutual interactions). The use of factorial experimentation (Box et al., [12]) allows not only for the evaluation of the main effects, but also that of the interactions. In a factorial experiment approach, all factors are perturbed simultaneously to one of their possible values called ‘levels’ and all possible combinations of values are covered. When the number of factors is too large, or the model evaluation is very time consuming, a useful alternative is given by the fractional factorial experiment (Box et al., [12]). Andres developed the Iterated Fractional Factorial Design (IFFD) (Andres and Hajas, [10]),
which required fewer runs than there were factors. IFFD estimated the main effects, quadratic effects and two factor interactions of influential factors.

Many of the screening methods described rely on strict assumptions about the nature or absence of interactions between factors. One exception however, is that of Cotter [16]. Cotter’s method does not require prior assumptions about interactions, and its results are hence easier to interpret. This design is also called the systematic fractional factorial design.

2.1.2.2 Local Sensitivity Analysis

Local sensitivity analysis concentrates on the local impact of the factors on the model. Local sensitivity analysis is usually carried out by computing partial derivatives of the output function with respect to the input variables, that is, local sensitivities provide the slope of the calculated model output in the factor space at a given set of values.

A differential sensitivity analysis involves the following four steps. In the first step, base values and ranges are selected for each input factor. In the second step, a Taylor series approximation of the output is developed around the base values of the input. In the third step, variance propagation techniques are used to estimate the uncertainty in the output in terms of its expected value and its variances. In the final step, the Taylor series approximations are used to estimate the importance of individual input factors [32].
The greatest effort in a differential sensitivity analysis is the determination of the partial derivatives in the Taylor series approximation. A number of specialized techniques have been developed to facilitate the calculation of these derivatives, namely,

1. The **Brute force method**, which uses the finite difference approximations.
2. The method of Miller and Frenklach [34], based on *approximations by empirical models* of the solution of the system in a parameter region.
3. The **Green function method**, also called the variation method.
4. The **polynomial approximation method**, elaborated by Hwang [29], which transforms the sensitivity differential equations into a set of algebraic ones.

Usually only the first order partial derivatives called the first order local sensitivity coefficients are computed and studied. They constitute the sensitivity matrix $S$ which represents a linear approximation of the dependence of the solutions on factor changes. The order of importance that can be deduced from local sensitivities is called order of tuning importance (Turanyi [43]).

If the system under consideration is not spatially homogeneous constant factor system (factors are also a function of time and space), sensitivity analysis is based on their perturbation by another function using the principles of non linear functional analysis. Dickinson and Gelinas [22] were the first to tackle the problem of factor function, and introduced a sensitivity measure depending on the perturbing function (Turanyi [43]). The sensitivity measure was named sensitivity density (Demiralp and Rabitz [21]).

For all models of real systems, the values of the factors are subject to some uncertainty. In most cases, such uncertainties can be very high, and sometimes when the
factors are changed within the range of uncertainty, a qualitatively different model is obtained. Local sensitivities however, are totally incapable of providing information on the effect of significant factor changes. Local sensitivities are really local, and the information provided is related to a single point in the space of factors.

2.1.2.3 Global Sensitivity Analysis

Global sensitivity analysis techniques have been discussed by Cukier et al. [18], Iman and Helton [30], Sobol [42] and Saltelli and Homma [26]. Global sensitivity analysis apportions the output uncertainty to the uncertainty in the input factors, described typically by probability distributive functions that cover the factors’ ranges of existence. The ranges are valuable since they represent our knowledge or lack of it with respect to the model and its parameterization. Global sensitivity analysis methods can be characterized by the following two properties:

1. *The inclusion of influence of scale and shape*: The sensitivity estimates of individual factors incorporate the effect of the range and the shape of their probability density functions.

2. *Multidimensional averaging*: The sensitivity estimates of individual factors are evaluated varying all other factors as well.

Global sensitivity analysis techniques are known as variance based methods. Variance based techniques such as the standardized regression coefficients (SRC), correlation coefficients (Pearson) and partial correlation coefficients (PCC) rely on the assumption that the output and the input factors are near linearly related, and their rank equivalents such as the standardized rank regression coefficients (SRRC), Spearman
correlation and partial rank correlation coefficients (PRCC) rely on the assumption that the output and input are near monotonically related.

Correlation ratios and importance measures (Hora and Iman [27]) are derived from a simple description of uncertainty using probability distributions and are based on the conditional variance of the model output.

The Fourier amplitude sensitivity test (FAST), created in the 1970’s by Cukier, Schaibly [17] and others and further developed by Koda and McRae [32], offers a sensitivity analysis method that is independent of any assumptions about the model structure, and works for monotonic and non-monotonic models. The core feature of the FAST is that it explores the multidimensional space of the input factors by a search curve that scans the entire input space. Some variations of the basic scheme of the FAST are also known an example is given by the Walsh amplitude sensitivity procedure (WASP) (Pierce and Cukier [35]). Saltelli et al.[38] proposed a new FAST technique which uses a new Fourier transform function and a re-sampling plan.

The Sobol’ sensitivity indices [42], an original extension of design of experiments (DOE) to the world of numerical experiments first published in 1990, are similar to FAST in the sense that the total variance of the model output is assumed to be made up of terms of increasing dimensionality. Sobol’ indices are superior to the original FAST in that the computation of the higher interaction terms is very natural and is similar to the computation of the main effects. In recent years, global quantitative sensitivity analysis techniques have received considerable attention in the literature (RESS 1997; JSCS 1997; CPC 1999; JMCDA 1999).
2.1.3 Application Examples Of Sensitivity Analysis

The following illustrations are examples of the applicability of sensitivity analysis in a wide variety of functional areas.

1. **Scenario and Parametric Sensitivity and Uncertainty Analysis in Nuclear Waste Disposal Risk Management**: The case of GESAMAC. Sensitivity analysis was used here in the process of model audit, studying the scenario and parametric uncertainty in nuclear waste disposal risk assessment [23].

2. **Sensitivity Analysis for Signal Extraction in Economic Time Series**: Sensitivity analysis was used here to answer the question of how sensitive the unobserved components in a time series are to a model and the parameter choice within the chosen model. Bayesian techniques and importance measures were used to explore the effect of different model assumptions and to direct the model choice [60].

3. **Analysis and Interpretation of Sensitivity Measures related to Ground water Pressure Decrease and Resulting Ground Subsidence**: Application of First order FORM and second order (SORM) reliability methods were used to determine reliability measures to study sensitivity measures for ground subsidence in an engineering context [60].

4. **One-at-a-Time and Mini Global Analysis for Characterizing Model Sensitivity in the Nonlinear Ozone Predictions from the US EPA Regional Acid Deposition Model (RADM)**: This analysis involved applying sensitivity analysis to a large, complex Eulerian air quality model. Both One-at-a Time and global techniques for a restricted set of model inputs under two scenarios of emission [60].
5. *An Application of Sensitivity Analysis to Fish Population Dynamics*: Sensitivity Analysis was applied to an ecological model used to explore the dynamics of fish ecosystems, particularly the collapse and regeneration of fish species. Morris screening techniques were applied to identify factors that required further investigation [60].

6. *Global Sensitivity Analysis: A Quality Assurance Tool in Environmental Policy Modeling*. This study was a policy problem, ‘how to dispose of solid waste’ and explore an incineration versus landfill option for solid waste using different sets of indicators. The FAST method was used here to quantitatively rank the group of factors according to their influence on the output uncertainty [60].
CHAPTER 3
THE HEURISTIC

The network of roads and highways in the United States of America has grown enormously over the years, and with it, the need for public utilities. Crowding and improper location of utilities in public transportation right-of-ways (ROW) has resulted in problems such as, damage to infrastructure, traffic accidents and, interruption of service to customers. The present system adopted by the State Department’s of Transportation (DOT) for allocating placement locations to utilities within ROW corridors is based on a first come first served method with certain governing rules set by the AASHTO way back in 1959. This regulatory system however is neither a safe nor an efficient (economically or space utilization wise) solution to the utility placement allocation problem.

The research project titled, “Optimum Placement of Utilities within FDOT Right-of-Way,” (Kranc et. al.) [6], sponsored by the Florida Department of Transportation (FDOT) and currently being investigated at the University of South Florida, aims at building a better utility placement allocation system. The formulation and working of the heuristic being developed as part of this investigation to provide a basis for making rational decisions regarding the organization of utilities within transportation ROW corridors is described in the following sections.
3.1 Mathematical Representation Of The Heuristic

A mathematical model is defined as a series of equations, input factors, parameters, and variables aimed at characterizing the process being investigated or simulated. The utility placement allocation heuristic related to this research is characterized as a discrete step, cost optimization mathematical model. It numerically simulates the shape and dimensions of the transportation ROW corridor, and the physical information of the utilities to be located within the corridor. Guided by the constraining rules and regulations of safety, relocation, and clearance for utility placement set by the AASHTO, and with the help of four positional utility cost assessment models the heuristic finds optimal cost locations for the utilities in the ROW corridors. The models objective function, the formulation of its constituent cost models and the AASHTO utility placement guidelines (constraints) under which it operates are explained in the following sections.

3.1.1 Model Objective Function

The objective of the heuristic is to determine the most economically advantageous configuration of the utilities selected for installation in a transportation ROW corridor. The total cost of a configuration is the sum of the individual position sensitive cost of each of its constituent utilities. The best utility configuration is determined by optimizing the total cost of all feasible configurations determined for that ROW corridor.

Mathematically this objective function is represented as,

$$\text{Min } \sum_{j=1}^{N} C_{1}(x, y) + C_{2}(x, y) + \ldots + C_{N}(x, y)$$
Where,

\[ TC_i = \text{Total cost of the utility configuration } \text{“}i\text{”} \text{ and,} \]

\[ C_j(x,y) = \text{Positional cost of utility “}j\text{”}. \quad (j = 1 \text{ to } N) \]

The individual positional cost of a utility “\(j\)” located at \((x, y)\) is the sum of the four position sensitive cost components. That is,

\[
C_j(x, y) = \sum \left( c_{j\text{INSTALLATION}}(x, y) + c_{j\text{ACCESS}}(x, y) + c_{j\text{DAMAGE}}(x, y) + c_{j\text{ACCIDENT}}(x, y) \right)
\]

where,

\[ c_{j\text{INSTALLATION}}(x, y) = \text{Positional Installation cost of utility “}j\text{”}. \]

\[ c_{j\text{ACCESS}}(x, y) = \text{Positional Access cost of utility “}j\text{”}. \quad (j = 1 \text{ to } N) \]

\[ c_{j\text{DAMAGE}}(x, y) = \text{Positional Damage cost of utility “}j\text{”}. \]

\[ c_{j\text{ACCIDENT}}(x, y) = \text{Positional Accident cost of utility “}j\text{”}. \]

### 3.1.2 Cost Models

A principal requirement for corridor optimization is the understanding and quantification of the position sensitive costs (initial and recurring) associated with individual utilities installed in the ROW corridor. The cost of the \(j^{th}\) utility of a configuration located at position \((x, y)\) in the ROW corridor is given as, the sum of four
position sensitive components $c_j$, namely, installation, access, damage and accident costs.

These costs are determined from respective cost models described below.

### 3.1.2.1 Installation Cost Model

The installation cost of a utility is defined as, the initial (non-recurring) cost of placing the utility within a ROW corridor. This includes the costs of excavation, maintenance of traffic, conflict accommodation, and shoring but excludes the material costs of the utility conduit itself. The installation cost model assumes that all utilities have approximately the same position sensitive installation costs which are determined by the following.

1. **Depth of Installation**: Installation costs of a utility increases with increase in the installation depth because of added digging, burying, reinforcing (shoring), and soil treatment costs at deeper locations.

2. **Horizontal Positioning**: Installation costs of a utility vary horizontally based on the placement region in the ROW. The two basic regions defined are,
   a. **Paved Region**: The part of the ROW that is below the pavement (road).
   b. **Unpaved area**: The part of the ROW that is not presently paved over.

   Installation costs for utilities placed below the pavement are generally greater than for those placed in the unpaved region for obvious reasons.

   Figure 3.1 shows a typical installation cost function plot obtained from information collected by a survey of utility companies. The plot shows the cost of installation of a utility in K$/Mile with respect to the depth of installation in inches. For
this plot, the paved region installation costs were considered to be twice that of the unpaved region, shown as two different installation cost function curves.

Figure 3.1: Installation Cost Function Of A Utility

Besides the default costs, a utility might also have additional installation surcharges applied, conditional to it being located in certain ‘undesirable’ regions within the ROW corridor. These surcharges are used primarily as deterrents in the heuristic. The surcharges are summarized as,

1. *Inconvenience Surcharge*: This is an additional installation charge applied to a utility when it has to be placed within the ROW in close proximity to the pavement. Since installation and access events to this utility will cause disruption of traffic plying the road, the inconvenience caused is factored in as a surcharge to the utility for installation at that particular location. The inconvenience surcharge model adds a surcharge that is maximum starting from the edge of the pavement and reduces linearly to zero at the end of the surcharge region. Figure 3.2 shows the surcharge region and the associated inconvenience surcharge model.
2. *Shoring Surcharge:* This additional installation charge is applied to a utility that has to be placed close to the extreme most position (easement) of the ROW corridor. Shoring costs are used to factor in, the difficulties involved, additional labor and extra materials required for locating utilities at this ‘undesirable’ location. The shoring surcharge model assumes the region starting from the edge of the ROW extending 3 feet inward as the shoring region. A flat cost is applied to all utilities to be placed in this region. Figure 3.3 depicts the shoring region and the associated shoring surcharge model.
Mathematically, as shown by equation (1), the installation costs of a utility is typically modeled as a vertical function $g(y)$, modified by a multiplicative factor, represented as $a(x)$ (a function of horizontal position), to account for under pavement installation and, an additive cost $b(x, y)$ to account for additional charges like shoring surcharge, inconvenience surcharge, or material costs associated with deep installations. $P_j$ is the probability of installation of utility “$j$” in year $Y_{inst}$, and to cover cases involving damage incidents during deferred installation or relocation, an additional additive damage factor $c_{j\text{dam}}$, is included in the installation cost model.

$$c_{j\text{INSTALLATION}}(x, y) = P_j[a(x)g_{inst}(y) + b_j(x, y) + c_{j\text{dam}}(y)]$$ (1)
3.1.2.2 Access Cost Model

For any facility placed within the ROW corridor there exist needs to access the subsurface utility installation, perhaps for a new connection or for routine maintenance. The costs incurred per year over the entire project life for providing this kind of access to a utility is known as the access cost of the utility. This cost is determined by the following.

1. Depth of Installation: Access costs of a utility increases with increase in the installation depth because of added digging, burying, reinforcing (shoring), and soil treatment costs at deeper locations.

2. Horizontal Positioning: Access costs of a utility vary horizontally based on the placement region in the ROW. The two basic regions defined are,
   a. Paved Region: The part of the ROW that is below the pavement (road).
   b. Unpaved area: The part of the ROW that is presently not paved over.

   Access costs of utilities placed below the pavement are generally greater than for those placed in the unpaved region.

3. Frequency of access: Is the number of times a year the utility will be accessed for maintenance.

4. Length of excavation: Access to a subsurface utility requires only certain parts of the entire line to be exposed. The ratio of the trench length excavated to the length of the entire utility line is known as the equivalent length of excavation.

   Figure 3.4 shows a typical utility access cost function plot with the access costs of a utility in K$/Mile with respect to the depth of installation in inches. For this plot, the
paved region access costs were considered to be twice that of the unpaved region, shown as two different access cost function curves.

\[ c_{j,\text{ACCESS}}(x, y) = P_j[a(x)g_{\text{inst}}(y) + b_j(x, y) + c_{j,\text{dam}}(y)]L_{eq}(Y_{sl} - Y_{\text{inst}})f_{\text{acc}} \]  

(2)

3.1.2.3 Damage Cost Model

During routine excavations (new installations or access events) in the corridor there exists some probability of accidental damage to the utility itself or to facilities already located in the corridor.
The data on damage events is not very accurate and hence a simple linear damage model is used to determine damage costs. The model assumes that the number of accidental damage incidents is proportional to the expected number of access events and that excavating to conduits buried deep within a corridor will more likely result in damage to the utility itself and other utilities in the corridor (Depicted in Figure 3.5).

![Figure 3.5: Damage Cost Model](image)

Mathematically, as assumed in the damage model, the cost per damage incident is primarily a function of depth $g_{\text{dam}}$, modified by multiplicative factors such as, the rate of access $f_{\text{acc}}$, the fraction of events resulting in damage incidents $f_{\text{dam}}$ (taken arbitrarily as 1%) and a maximum cost per incident $c_{\text{j max}}$ at the maximum depth that reduces linearly to the highest possible location for the utility.
\[ c_{jDAMAGE} (x, y) = P_j [c_{jmax} g_{dam} (y)] (Y_{sl} - Y_{inst}) f_{acc} f_{dam} \] (3)

The plot in Figure 3.6 shows the access damage costs in K$/Mile versus installation depth in inches.

![Figure 3.6: Damage Cost Function Of A Utility](image)

### 3.1.2.4 Accident Cost Model

The cost of traffic accidents with the above ground component of a utility is an important part of a utility’s cost function. This cost is primarily dependent on the horizontal positioning of the utility in the ROW corridor. A procedure to estimate the economic values for traffic accidents with stationary objects at the side of the roadway was developed by the Federal Highway Administration and is used for developing the accident model. The construction of the accident function and model is based on Figure 3.7. Consider the traffic traveling in one direction along the roadway in adjacent lanes (i.e. the lanes closest to an above ground object). A certain fraction of these vehicles will leave the pavement and travel for some distance beyond the pavement edge. The
approach used in the accident model is to calculate the probability that a vehicle leaving the roadway within an interval along the pavement, travels sufficiently far to collide with some portion of the object. For an approximate mix of vehicular traffic, a single encroachment angle $\Phi_e$ is defined, characterized as a function of the roadway design speed. $P(x)$, the probability of an encroaching vehicle traveling a perpendicular distance $x_{eq}$ from the pavement (encroachment distance) for a set of typical design speed is also tabulated. The above ground object is partitioned into several zones, each with different likelihood for impact. For a rectangular object, collisions with the face perpendicular (Zone 1) and the face parallel (Zone 3) to the roadway are possible, as is a collision with the corner of an object facing the traffic (Zone 2). Round objects are treated in a slightly different manner and are represented in terms of reduced diameter. To account for the possibility of skid with rotation, the vehicle path width is taken to be a swath of 3.6 meters.

The encroachment factor $EF$, which is the dimensionless ratio between the distance along the pavement, and the distance along the line perpendicular to the pavement, defines the impact zone of interest. The number of impacts with a particular zone occurring as a result of vehicles leaving the pavement within the boundaries of the path leading to the zone is defined as the impact factor $IF$, and is given by the product of the encroachment factor and the integrated probability that a vehicle will travel to the offset distance of the zone. This distance corresponds to the distance along the pavement equivalent to a particular component of the object times the ratio of impacts per encroachment.
For Zone 1, EF₁ is the distance along the traveled way corresponding to a unit length along the perpendicular face of the object equal to 1/tan Φₑ. To obtain the number...
of impacts with this face resulting from encroachments from the corresponding interval along the pavement AB requires an integration of the probability of impact over the offset of the face (from XA’ to XB’) then multiplication by the encroachment factor to give,

$$\int \int - = \int_0^{X_e} P(x)dx \int_0^{X_e} P(x)dx (4)$$

To obtain the encroachment factor for Zone 2, an integrated probability is again required between the offsets for C’ and D’ to account for the variable offset across the swath path. Calculation of the encroachment factor for this zone requires the length along the normal distance across the swath that project to give a unit length along the perpendicular \((1/\cos \Phi_e)\). This dimension corresponds to a length along the traveled way so that \(EF_2 = (1/\sin \Phi_e)/\cos \Phi_e\). Thus the impact factor for Zone 2 is,

$$\int \int - = \int_0^{X_e} P(x)dx \int_0^{X_e} P(x)dx (5)$$

For Zone 3 the encroachment factor \(EF_3 = 1\), unit length along the traveled way/unit length along the face (since the parallel face has a constant offset) so that the number of impacts with this face along the pavement is,

$$IF_3 = P(x_{os}) (6)$$

A severity index is utilized to describe the nature of possible accidents by the type of object involved and the design speed of the roadway. To establish a cost per impact a relationship between accident costs and the severity index is established. Consistent with the partitioning of the object into separate accident zones different severity indices \(c_{coll}(SI)\) are employed for each impact factor defined above. The product of \(ER\), \(IF\) and
the cost of a single accident is the total cost of accidents expected annually per traffic volume due to a single object at nominal offset \( x_{os} \). The cost of an impact with a specific object at \( x_{os} \) is then given in units of cost / annual traffic volume,

\[
e_{imp} = ER \sum_{i=1}^{3} IF_i c_{coll}(SI_i) \tag{7}
\]

Where, the summation is over all impact zones considered. For traffic on one side of roadway, going in one direction the annual encroachment rate (annual encroachments per unit distance along pavement per vehicular volume) is taken as constant \( ER=0.0003 \) enc/km/y/vehicles/day. The average daily traffic (total traffic count, independent of direction or number of lanes) for the roadway in year \( i \), \( ADT_i \) can be expressed as,

\[
ADT_i = \frac{ADT_{dy}}{(1 + TGR)^{T_i}} \tag{8}
\]

Where, \( ADT_{dy} \) is the design value for average daily traffic. \( T_i \) is the number of years from \( i \) to the design year and \( TGR \) is the traffic growth rate expressed as a decimal fraction. If traffic is two way, the total volume in one direction is one half the \( ADT \). The model assumes that the traffic volume is the same in both directions. Since costs vary with the changing traffic volume a summation over years is conducted.

\[
c_{pl}(x_{os}) = \left[ c_{imp}(x_{os}) \sum_{i=0}^{Y_{pl}} ADT_i / 2 \right] \tag{9}
\]

Thus for utility “j” (having an above ground facility), the accident cost component is the sum of the terms accounting for traffic flow in the adjacent lanes, and those accounting for encroachments from the opposite direction, striking the above ground object. This
latter component is also calculated in the same manner as previously described, except that the adjacent lane width is added to increase the effective offset difference which changes the encroachment probabilities.

\[ c_{j\text{ACCIDENT}}(x, y) = N_j P_{ja}[c_{pl}(x_{os})] + N_j P_{jo}[c_{pl}(x_{os})] \] (10)

\( N_j \) represents the number of objects per unit distance along the roadway, \( P_{ja} \) and \( P_{jo} \) represent the encroachment probabilities for adjacent and opposite lanes of traffic respectively.

Accident costs generated by the accident model is a function for the cost per impact in K$/Mile as a function of offset (Ft) as seen in the Figure 3.8.

![ACCIDENT COST FUNCTION](image)

Figure 3.8: Accident Cost Function Of A Utility

The cumulative individual cost function \( C_j(x, y) \) shown in equation (11) of a utility “j” is, the sum of all position sensitive cost functions “\( c_j \)” (installation, access, damage and accident) for that utility. That is a sum of equations (1), (2), (3) and (10).
\[ C_j(x, y) = \sum \left( c_{j\text{INSTALLATION}}(x, y) + c_{j\text{ACCESS}}(x, y) 
+ c_{j\text{DAMAGE}}(x, y) + c_{j\text{ACCIDENT}}(x, y) \right) \]  

(11)

The plot in Figure 3.9 shows the overall cost function gradient for a typical utility over the cross section of a standard ROW corridor.

Figure 3.9: Cumulative Cost Function Of A Utility

3.1.3 AASHTO Utility Placement Constraints

The term ‘ROW corridor’ refers to a profile view of the cross section of the subterranean area adjacent to and underneath the pavement available for the placement of
utilities. The horizontal extent is the joint use ROW from the center of the pavement to the outer edge of the easement. The vertical extent of the corridor is governed by practical considerations (water table, shoring requirements).

Constraints are rules and regulations set by the AASHTO to ensure overall safety of the utilities placed within the ROW corridor. These constraints are summarized as follows.

1. **Clearance Constraints** also understood as proximity constraints are imposed on utilities to prevent interference leading to accidental damage. ‘Clearance’ is defined as the space around a utility, which should not be occupied by another utility. A utility’s clearance requirements are relative, that is, it depends on the type of the other utility being considered for proximal placement. The heuristic considers 10 different types of utilities and clearance requirements as specified by AASHTO are tabulated and utilized. The model demarcates utility clearance boundaries by two techniques (Bounding box and Radial boundaries) as shown in Figure 3.10.

Mathematically, the clearance required between two utilities “i” and “j” is as,

**Bounding box:**

\[
\begin{align*}
X_{ij} & \geq (x_j + r_j) - (x_i + r_i) \\
y_{ij} & \geq (y_j + r_j) - (y_i + r_i)
\end{align*}
\]

where, \(X_{ij}\) = Horizontal clearance, \(Y_{ij}\) = Vertical clearance

**Radial:**

\[
R_{ij} = \left| \left\{ (x,y)_j + r_j \right\} - \left\{ (x,y)_i + r_i \right\} \right| \geq R_{ij}
\]

Where, \((x_i, y_i)\) and \((x_j, y_j)\) are the placement positions of, and \(r_i\) and \(r_j\) are the radii of utilities “i” and “j” respectively.
2. **Safety Constraints** are placement constraints (depicted in Figure 3.11) that are imposed on utilities in the interest of overall safety. These constraints are,

a. **Minimum Cover** is the minimum depth below the surface of the ground, above which a utility should not be placed. This constraint is imposed on the placement of utilities to prevent damage caused due to superficial location. In the heuristic, the cover requirements are unique (specified by the user) for every utility type and the required cover adapts to the ground profile of the ROW to maintain a constant minimum earth cover over the utility. Mathematically, the cover constraint for a utility “j” with a radius of \( r_j \) is specified as,
b. Maximum Depth is the maximum allowed depth for placement a utility within the ROW corridor. This constraint governed by practical considerations of safety (presence of water tables, application of high pressures) prevents very deep placement of utilities. The heuristic considers a unique maximum depth constraint (specified by the user) for every utility type. Mathematically for a utility “j” with radius \( r_j \) the maximum depth constraint is specified as,

\[
\left| (y_{\text{max depth}}) - (y_j + r_j) \right| \geq 0
\]

Where, \( y_{\text{max depth}} \) is the maximum allowed positional depth for that utility.

c. Under Pavement: Utilities with above ground components for obvious reasons can not be placed below the pavement but besides these, certain other utilities for technical reasons and reasons of safety are not allowed placement below the pavement. The heuristic, uses the under pavement placement constraint to prevent restricted utilities from being placed below the pavement. Mathematically, this constraint for a utility “j” with radius \( r_j \) is specified as,

\[
\left| (x_j) - (x_{\text{pavement width}} + r_j) \right| \geq 0
\]

Where, \( x_{\text{pavement width}} = \text{Horizontal width of the pavement} \)
d. *Clear Zone* is the recovery area; the region starting from the edge of the pavement that should be free of utilities. This placement constraint can be imposed instead of the inconvenience surcharge (additional installation costs) to prevent traffic disruptions and accidents.

![Diagram of utility placements](image)

**Figure 3.11: Safety Constraints**

3. *Stacking Constraints*: Stacking in terms of utility placements is defined as the positioning of one utility above or below another in the ROW corridor. Inconvenience for accessing, interference, increased probability of accidental damage and overall safety, are some of the reasons why certain utilities are not allowed stack positioning. In the heuristic, utilities with above ground components
have an automatic no stack constraint applied to them (shown in Figure 3.12). Mathematically, the stacking constraint applied to utilities is specified as,

\[ |(x_j + r_j) - (x_i + r_i)| \geq X_{ij} \]

where, \( X_{ij} \) = Horizontal safety clearance

3.2 Model Structure And Working

The heuristic is characterized as a discrete step, cost optimization model, which determines economically advantageous utility configurations for transportation ROW corridors by optimizing the estimated total costs of entire utility systems (configurations).
The step by step working procedure of the model (shown in Figure 3.13) is explained as follows.

1. **Project analysis setup**: An analysis is initiated with problem defining inputs to the model such as,
   a. *Information on the utilities to be placed:*
      - Number, and type of utilities to be placed (with or without above ground component) and,
      - Utility parameters (probability of placement, diameter, minimum safety cover required etc.),
   b. *Project duration and evaluation parameters:*
      - Project life and,
      - Project design year,
   c. *Traffic details:*
      - Design year traffic and
      - Traffic growth rate,
      - Number of lanes of traffic
      - Lane width
      - Pavement Design Speed etc
   d. *Right-of-way corridor specifications:*
      - Max depth,
      - ROW width and,
      - Ground profile.
2. **Configurations Search**: Next, a search for all possible positional configurations for the utilities within the corridor is conducted using the mover program. The number of configurations obtained is a function of the user defined search step size used.
3. **Application of Filters**: Filters are basically rules and regulations of clearance, safety and, stacking, set by the AASHTO for placement of utilities in ROW corridors. Utility configurations obtained from the previous step are tested for acceptability (feasibility) by the application of filters. Configurations that violate filtering rules are eliminated at this stage.

4. **Configuration Costing**: The next step, that is, the valuation / costing of acceptable configurations is very important to the working of the model. The model is based on the premise, that every utility to be placed in the ROW corridor has certain position sensitive costs (both initial and recurring) associated with it. Individual costs of utilities are estimated from relevant cost functions, generated by four integral cost models (installation, access, damage and accident cost models). The summation of the individual costs of each of the constituent utilities of a configuration yields the total societal cost of that configuration.

5. **Optimize Total Costs**: The final operation in the working of the model is the optimization of the total costs of the utility configurations. The configuration associated with the least total societal cost is selected as the “optimal”.
CHAPTER 4

PROBLEM STATEMENT

The present system being used by the State Department’s of Transportation (DOT) for allocating placement locations to utilities within transportation right-of-ways (ROW) is based on a first come first served method with certain governing rules provided by the AASHTO in 1959. Unplanned installations and excessive crowding of utilities in ROW corridors has resulted in problems of damage to infrastructure, interruption of service to customers and traffic disruptions / accidents. It has become increasingly difficult for the DOT’s to upgrade older roads for placement of new utilities, and also ensure the safety of motorists using them. Obviously, there exists a very urgent need for a solution to the utility placement problem.

The project “Optimal Placement of Utilities within FDOT Right-of-Way,” sponsored by the Florida Department of Transportation (FDOT) and currently being investigated at the University of South Florida (Kranc et. at.)[6] is aimed at addressing this need. It presents a decision-making heuristic designed to be a safe and economically efficient utility placement allocation system. The model numerically simulates the shape and dimensions of the ROW corridor, and physical information of the utilities to be located within it. Working in accordance with the rules of safety, relocation, and clearance for utility placement set by AASHTO, and utilizing positional cost assessment
models, the heuristic finds suitable (optimal cost) locations for the utilities in the ROW corridors.

4.1 The General Problem

Heuristics are models / tools designed for a scientific task and must be proven capable of dealing with uncertainty. A model such as this heuristic, being used to advocate a practice having large social and economical impacts is more likely to play the role of generic evidence in a trial, whose weight must ultimately be established by a ‘jury’. Not only must the model be shown not to contradict the evidence, but it must do so when all driving forces relevant to the problem have been incorporated in a way that is plausible to the ‘jury’. During the formulation of a model, the questions being addressed to the system must be scrutinized carefully, and the formal structure possibly updated iteratively until it proves capable of providing an answer given the question.

A good sensitivity analysis can provide the generic quality assurance desired to the model and help demonstrate the worthiness of the model itself. According to Rabitz [36] a sensitivity analysis will help:

1. Analyze the contents of the model and interface it with the observational data.
2. Identify which factors are critically important, how they are interrelated, and especially how they influence the behavior of the model.
3. Serve as a guide to any further use of the model by effectively communicating the modeler’s confidence in the model, its properties and his understanding of the sources of uncertainties to the decision maker.
4.2 The Thesis Problem

This thesis is a quantitative and qualitative sensitivity analysis of the abovementioned heuristic conducted in two parts namely,

1. Model Factor Sensitivity Analysis
2. Model Output Evaluation & Enhancement

Part 1: Model Factor Sensitivity Analysis

Objective: is to assess (quantify) the uncertainties associated with the modeling of this heuristic.

Reason: As explained in chapter 3, the heuristic finds economically advantageous placement locations for utilities within transportation ROW corridors in accordance to the utility placement rules (constraints) set by the AASHTO, by optimizing the total costs of entire utility systems (configurations). The total cost of a configuration is the sum of the individual positional costs of each of its constituent utilities, determined from respective cumulative cost functions generated by utility cost assessment models (accident, installation access and damage) integral to the main heuristic. Each cost model is influenced by input factors (global and model specific) which determine the shape and value of the cost function generated by them. Since the output of the heuristic relies heavily on the cost models and their functions, it becomes imperative to fully understand the uncertainties associated with their input factor influences (direct and interaction). Preliminary analysis of the cost models revealed the following requirements for factor sensitivity analysis (i.e. for factor influence determination, factor calibration and further model development):
1. **Damage Model**: Accurate data on damage costs and events is not available, hence a make do linear damage model is utilized in the heuristic to estimate the damage costs associated with a utility.

2. **Accident Model**: The accident model is derived from the procedure developed by the Federal Highway Administration to estimate the economic value of traffic accidents with stationary objects at the side of the roadway.

3. **Installation Surcharge Models**: The installation cost model has experimental surcharge models (i.e. the inconvenience surcharge and the shoring surcharge model) which add to the installation cost functions only in certain regions of the ROW.

*Analysis*: The analysis focuses on providing an evaluation of the confidence in the heuristic and its predictions by analyzing the influences that variations in the input factors have on the cost models and, the final output of the heuristic itself. The following sensitivity studies are conducted:

1. A study of the local influence of the accident and damage cost model factors on their respective individual cost functions and,

2. A study to determine the global influence of untested installation surcharge models on the final output of the heuristic.

The sensitivity studies address the following questions:

1. Which factors contribute most to the output variability and require additional research?

2. Which model factors aren’t significant, and can be eliminated from the model?
3. Is there some region in the space of the input factors for which the model output variation is maximum?

4. And finally, which group of factors if any, interact with each other?

Part 2: Model Output Evaluation & Enhancement

Objective: An evaluation and enhancement study of the final output of the heuristic.

Reason: The working structure of the heuristic, though well defined has certain inherent problems that are highlighted when implemented as a program code, such as:

1. The model employs a mover program which moves each utility to be placed, one at a time, with a user specified search step size within the ROW corridor boundaries to find possible placement locations (configurations) for them. However, this discretized search is conducted over continuous cumulative individual cost functions generated for the utilities selected. Variability in the step size chosen causes unpredictable variability in the outputs determined (configurational and total costs).

2. Executing the program at the lowest possible step size (for the mover, 0.1 of a foot) to obtain the best possible refinement on the output solves the problem of variability but is computationally very expensive (time consuming).

3. The heuristic compares the estimated total costs of all feasible utility configurations determined for a ROW corridor to select the configuration associated with the least total cost as the optimal. Very often the analysis determines many configurations (somewhat similar or totally different) with the same least total cost. The program code in such a case selects either the first (if “<” is used) or the last configuration (if
“≤” is used) from the set of optimal configurations which does not always present the best solution.

During conference presentations it was noticed that besides departments of transportation (DOT), a diverse group of stakeholders such as, the public (consumers), utility owners (public and private,) and other corporate parties (contractors, services etc.) expressed interests in the development of this utility corridor organization scheme. Each stakeholder expressed requirements that the present single objective heuristic does not address, like,

1. The issue of locational fairness for all utility’s in the corridor.
2. Flexibility in the positioning accuracy required for installation of the utilities in the corridor and,
3. Renovation capabilities of the configuration (i.e. the scope for addition of more utilities, and pavement extensions).

**Analysis:** This analysis focuses initially on understanding (evaluating) the complexities of the discrete step, cost optimization procedure used in the heuristic. Based on the observed shortcomings and problems (implementation, speed, output identification and verification), develop an enhancement to be implemented with the heuristic. The enhancement will address all the problems of the heuristic by employing experimental speedup tools for refining the solutions (configurations) obtained from coarse step configuration searches with the mover program and also by implementing a multi objective / criterion evaluation technique for utility configuration selection to provide substantiation to the outputs determined by the heuristic.
CHAPTER 5
MODEL FACTOR SENSITIVITY ANALYSIS

This chapter constitutes the first part of the analysis of the heuristic. Its objective is to serve as a guide for any future use and development of the model. The main focus of this study will be on providing an evaluation of the confidence in the heuristic and its predictions by analyzing the influences that variations in the input factors (global and intra modular) have on the utility cost assessment models (i.e. the cost functions generated by them) and the final output of the heuristic itself. Variance based sensitivity indices derived from Sobol’ [42] sensitivity indices are used here for this purpose.

5.1 Sensitivity Analysis Of The Heuristic

Model development consists of several logical steps, one of which is the determination and analysis of the input factors which influence the model output. An input factor is defined as “any quantity that can be changed in the model prior to its running”. This quantity can be a parameter (to be estimated), an input variable (directly observable in the real system), or a module of the model. The heuristic has four integral utility cost assessment models (i.e. the installation, access, damage and accident cost model, explained in chapter 3), each having input factors (global and model specific) that determine the shape and value of the cost functions generated by them. Preliminary
examinations / observations made on the cost models and their input factor influences revealed the following.

1. The installation and access cost functions derived from the data collected by a survey of utility companies, show a vertical tendency (i.e. they vary with depth). The factors influencing these models have a uniform multiplicative or additive effect all through their cost functions. The installation cost model however, has additional surcharge models (i.e. the inconvenience surcharge and the shoring surcharge model) which add to the installation cost functions only in certain regions of the ROW. Both surcharge models are experimental and further investigation into their effect on the output of the heuristic is required for calibration and future model developments.

2. The data available on damage events is not very accurate and hence, a simple linear make shift damage model is used in the heuristic to determine damage costs associated with a utility. Since most of the factors in the damage model are assumed, their influences need to be assessed for calibration and further model development purposes.

3. The accident model employs the procedure developed by the Federal Highway Administration to estimate the economic value of traffic accidents with stationary objects at the side of the roadway. The accident model has several factors (model and problem specific) whose influences on the accident function have yet to be determined (quantified).

Based on these observations, the following factor sensitivity studies are conducted on the heuristic:
1. A study of the local influence of the accident and damage cost model factors on their respective individual cost functions and,

2. A study determining the global influence of untested installation surcharge models on the final output of the heuristic.

The sensitivity studies are guided by and answer the following questions in regards to model factors and their influences.

1. Which are the factors that mostly contribute to the output variability and require additional research?

2. The model factors that aren’t significant, and can be eliminated from the model.

3. Is there some region in the space of the input factors for which the model variation is maximum?

4. And finally, If and which group of factors interact with each other?

5.1.1 Sensitivity Indices

The method adopted here for determining factor sensitivity indices is a variance based technique, also called ANOVA (analysis of variances) like sensitivity method, used generally for estimating the influences of individual factors or a group of factors on the output of complex models. The technique is based on the fact that, the sensitivity index for a given input factor $X_i$ represents the fractional contribution to the total variance observed in the model output. In order to calculate the sensitivity indices, the total variance $V$ of the model output $Y$ is apportioned to all the input factors $X_i$ as,

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<m} V_{ijm} \ldots \ldots + V_{1,2,\ldots,k}$$ (1)
where,
\[ V_i = V[E(Y|X_i = x_i^*)] \quad \text{and,} \]
\[ V_{ij} = V[E(Y|X_i = x_i^*, X_j = x_j^*) - V[E(Y|X_i = x_i^*)] - V[E(Y|X_j = x_j^*)] \]
and so on.

\[ [E(Y|X_i = x_i^*)] \] denotes the expectation of \( Y \) conditional on \( X_i \) having a fixed value \( x_i \), and the operator \( V[. \] \) denotes conditional variance.

The first order sensitivity index \( S_i \) for the factor \( X_i \) is defined as,
\[ S_i = \frac{V_i}{V} \]  (3)

Higher order sensitivity indices responsible for interaction effects among input factors can also be determined. The sensitivity indices are non-negative and their cumulative sum is 1.

\[ \sum_{i=1}^{n} S_i + \sum_{1 \leq i < j \leq n} S_{ij} + \ldots + S_{1,2,\ldots,n} = 1 \]

The entire proof for Sobol’ sensitivity indices [42] is included in the appendix A.

5.1.2 Factor Sensitivity Studies

The approach adopted for factor sensitivity studies is a combination of the design of experiments (DOE) technique and sensitivity analysis performed in a specific manner to determine variance based sensitivity indices. DOE is a statistical technique that involves running a series of experiments in which purposeful changes are made to the
input variables of a process or system to provide an objective measure of how a given change in the output might be dependent upon the change in values of its input variables.

5.1.2.1 Sensitivity Analysis Of Accident Model Factors

The accident cost per impact with a utility’s above ground facility in the heuristic is estimated from the accident cost function generated by the accident model. The intention of this sensitivity analysis is to determine the influence that certain factors (accident model related factors and problem, corridor specific parameters) have on the accident cost function generated by the accident model. The factors considered for this analysis are,

1. Design Year: Since the present values for factors are not always known, the accident model allows for the use of predicted data for a future period (i.e. the design year).
2. Design Speed of the road: The vehicular speed for which the road is designed.
3. Design Year Average Daily Traffic (ADT<sub>dy</sub>): The average daily traffic predicted for the design year. It is also the capacity traffic for which the road is designed.
4. Traffic Growth Rate (TGR): The rate at which the average daily traffic (ADT) increases every year over the project life. Traffic volume is calculated backwards from the design year traffic to the present value, decreasing with the TGR explained by equation 8, in chapter 3. Traffic volume beyond the design year remains constant at the design year traffic for the rest of the project life as shown in Figure 5.1 (Design year = 10 and ADT<sub>dy</sub> = 10 K Cars /day).
5. **Number of Above Ground Facilities (AGF):** The measure of the number of above ground components that a utility has per mile of ROW.

6. **Number of Lanes:** The measure of the lanes of traffic in either direction.

7. **Lane Width:** The width of a traffic lane on the pavement.

8. **Project Life:** is the time interval from the original installation of the utility within the ROW until some time in the future when the roadway would be replaced or abandoned.

9. **Size of the AGF:** Is the size of the facility originating from the utility line below. The size of the component affects the possibility of impact and most importantly the severity of the impact in an accident. The size (diameter / dimensions) of the AGF is not considered for study in this analysis since the minimum diameter for severity index in the accident model is 0.5 meters or 19.685 inches and the utilities in this analysis are assumed not to have diameters greater than that.
10. **ROW Width**: The horizontal space available for the location of the utility in the ROW corridor. The right-of-way width for this analysis is fixed at the maximum possible value (40 Ft) to ensure accommodation space for lane addition and increase in the lane widths.

The accident model generates a function for the accident cost associated with a utility varying horizontally over the ROW width. Theoretically, unless forced by certain placement constraints, the heuristic would select an optimal configuration having the utility with an above ground facility at a position in the ROW where its accident cost contribution to the total cost of the configuration is minimal. For this analysis however, to study the effect of the abovementioned factors on the accident costs of a utility, the average of the accident function generated by the accident model is used as the response variable. A total of 90720 experimental runs of the accident model are made varying the accident factors mentioned above at various levels within their possible ranges, shown in Table 5.1.

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>UNITS</th>
<th>RANGE</th>
<th>FACTOR LEVELS</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Year</td>
<td>Yrs</td>
<td>5 - 20</td>
<td>5, 10, 15, 20</td>
<td>4</td>
</tr>
<tr>
<td>Design Speed</td>
<td>MPH</td>
<td>35 - 70</td>
<td>35, 40, 45, 50, 55, 60, 65, 70</td>
<td>8</td>
</tr>
<tr>
<td>Average Daily Traffic(DY)</td>
<td>K Cars/Day</td>
<td>5 - 40</td>
<td>10, 20, 30, 40</td>
<td>4</td>
</tr>
<tr>
<td>Traffic Growth Rate</td>
<td>%</td>
<td>0 – 20</td>
<td>5, 10, 15, 20</td>
<td>4</td>
</tr>
<tr>
<td>Number of Lanes</td>
<td>#</td>
<td>2 - 6</td>
<td>2, 3, 4</td>
<td>3</td>
</tr>
<tr>
<td>Lane Width</td>
<td>Ft.</td>
<td>12 - 15</td>
<td>11, 12, 13</td>
<td>3</td>
</tr>
</tbody>
</table>
5.1.2.2 Sensitivity Analysis Of Damage Model Factors

The data on damage events is not very accurate and hence a simple linear damage model is used in the heuristic to determine damage costs associated with a utility. Mathematically, as assumed in the damage model, the cost per damage incident is primarily a function of depth, modified by factors such as, the frequency of access, the fraction of events resulting in damage incidents (taken arbitrarily in the model as 1%) and a maximum cost per incident (specified by the user) at the maximum depth that reduces linearly to the highest possible location for the utility (default cover). The following factors are considered for sensitivity studies on the damage cost model.

1. Maximum Damage and,
2. Damage Fraction for factor calibration purposes.
3. Default Cover and,
4. Maximum Depth for function shape and value influence analysis.

The damage model generates a linear function for the damage costs of a utility varying vertically through the depth of the ROW. For this analysis, that is to study the effect of the abovementioned factors on the damage function generated by the damage model, the average value of the damage function is used as the response variable. A total
of 8470 experimental runs of the damage model are made varying the abovementioned factors at various levels within their possible ranges, shown in Table 5.2.

Table 5.2: Levels Of Factors Varied For The Damage Model Factor Analysis

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>UNITS</th>
<th>RANGE</th>
<th>FACTOR LEVELS</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Damage</td>
<td>K$ / Mile</td>
<td>0 - 1000</td>
<td>0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000</td>
<td>11</td>
</tr>
<tr>
<td>Default Cover</td>
<td>Inches</td>
<td>0 - 36</td>
<td>0, 6, 12, 18, 24, 30, 36</td>
<td>7</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>Inches</td>
<td>60 - 120</td>
<td>60, 66, 72, 78, 84, 90, 96, 102, 108, 114, 120</td>
<td>11</td>
</tr>
<tr>
<td>Damage Fraction</td>
<td>%</td>
<td>0.5 - 5</td>
<td>0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5</td>
<td>10</td>
</tr>
</tbody>
</table>

Total Number of Runs 8470

5.1.2.3 Sensitivity Analysis Of Installation Surcharge Models

The heuristic has additional surcharge models included in its utility installation cost assessment model, used primarily as deterrents for utility placements in ‘undesirable’ regions of the ROW. The inconvenience surcharge model adds a surcharge to the installation costs of a utility in the region in close proximity to the pavement. The surcharge is maximum starting from the edge of the pavement and reduces linearly to zero at the end of the specified region. The shoring surcharge model adds a surcharge to the installation costs of a utility in the region close to the extreme most position (easement) of the ROW corridor. A flat cost is applied to all utilities to be placed in the shoring region (3 ft inwards from the easement).

The experimental surcharge models while rather simple, in crowded right-of-way situations are capable of influencing the model output significantly. This sensitivity
analysis aims at exploring the influences that these surcharge models have on the output of the model with the intension of calibrating the models and providing guidelines for the correct use of their model factors. The analysis involves making a total of 1452 runs (3 replicates of 484 runs each) of the standard experiment 1 while varying the abovementioned factors at various levels within their possible ranges, shown in Table 5.3. The initial setup factors and the information of the utilities of the standard experiment 1 are shown in Tables AB.1, AB.2 in appendix B at the end of the thesis. The total cost of the optimal solution arrived at in the analysis is used as the output variable.

Table 5.3: Levels Of Factors Varied For The Installation Surcharge Model Factor Analysis

<table>
<thead>
<tr>
<th>FACTORS</th>
<th>UNITS</th>
<th>RANGE</th>
<th>FACTOR LEVELS</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconvenience Surcharge</td>
<td>K$ / Mile</td>
<td>0 - 1000</td>
<td>0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000</td>
<td>11</td>
</tr>
<tr>
<td>Surcharge Region</td>
<td>Ft.</td>
<td>0 - 3</td>
<td>0, 1, 2, 3</td>
<td>4</td>
</tr>
<tr>
<td>Shoring Surcharge</td>
<td>K$ / Mile</td>
<td>0 - 100</td>
<td>0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100</td>
<td>11</td>
</tr>
<tr>
<td>Replicates</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Total Number of Runs</td>
<td></td>
<td></td>
<td></td>
<td>1452</td>
</tr>
</tbody>
</table>
CHAPTER 6
RESULTS AND CONCLUSIONS OF MODEL FACTOR ANALYSIS

The results of the sensitivity studies conducted on the heuristic are,

6.1 Results Of The Sensitivity Analysis Of The Accident Model Factors

The sensitivity analysis of the accident model factors involved making a total of 90720 experimental runs of the accident model, varying 8 selected factors at various levels within their suggested ranges to determine their influences on the accident cost function generated for a utility (with above ground facilities). The average value of the accident function was used as the response variable for this analysis. The analysis of variances (ANOVA) output determined using Minitab Release 14 (Statistical Software) is shown in Table C.1 in appendix C. The test was conducted at a 5% level of significance (\(\alpha = 0.05\)). First order and second order sensitivity indices derived from the output variances from the ANOVA results are shown in Table 6.1 and Table 6.2 respectively,

Table 6.1: First Order Sensitivity Indices for Accident Model Factors

<table>
<thead>
<tr>
<th>ACCIDENT MODEL FACTORS</th>
<th>FIRST ORDER S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Year</td>
<td>0.00827</td>
<td>0.89%</td>
</tr>
<tr>
<td>Design Speed</td>
<td>0.31723</td>
<td>33.95%</td>
</tr>
<tr>
<td>Average Daily Traffic (DY)</td>
<td>0.07188</td>
<td>7.69%</td>
</tr>
</tbody>
</table>
Table 6.1 (Continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Growth Rate</td>
<td>0.00202</td>
<td>0.22%</td>
</tr>
<tr>
<td>Number of Lanes</td>
<td>0.00042</td>
<td>0.05%</td>
</tr>
<tr>
<td>Lane Width</td>
<td>0.00004</td>
<td>0.00%</td>
</tr>
<tr>
<td>Number of ABGF</td>
<td>0.18188</td>
<td>19.47%</td>
</tr>
<tr>
<td>Project Life</td>
<td>0.02882</td>
<td>3.08%</td>
</tr>
<tr>
<td>Total</td>
<td>0.6106</td>
<td>65.35%</td>
</tr>
</tbody>
</table>

Table 6.2: Second Order Sensitivity Indices For Accident Model Factors

<table>
<thead>
<tr>
<th>ACCIDENT MODEL FACTORS</th>
<th>SECOND OREDR S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Year &amp; Design Speed</td>
<td>0.00730</td>
<td>0.78%</td>
</tr>
<tr>
<td>Design Year &amp; Design Year Average Daily Traffic</td>
<td>0.00165</td>
<td>0.18%</td>
</tr>
<tr>
<td>Design Year &amp; Traffic Growth Rate</td>
<td>0.00059</td>
<td>0.06%</td>
</tr>
<tr>
<td>Design Year &amp; Number of Lanes</td>
<td>0.00001</td>
<td>0.00%</td>
</tr>
<tr>
<td>Design Year &amp; Lane Width</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Design Year &amp; Number of ABGF</td>
<td>0.00419</td>
<td>0.45%</td>
</tr>
<tr>
<td>Design Year &amp; Project Life</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Design Speed &amp; Design Year Average Daily Traffic</td>
<td>0.06345</td>
<td>6.79%</td>
</tr>
<tr>
<td>Design Speed &amp; Traffic Growth Rate</td>
<td>0.00179</td>
<td>0.19%</td>
</tr>
<tr>
<td>Design Speed &amp; Number of Lanes</td>
<td>0.00021</td>
<td>0.02%</td>
</tr>
<tr>
<td>Design Speed &amp; Lane Width</td>
<td>0.00002</td>
<td>0.00%</td>
</tr>
<tr>
<td>Design Speed &amp; Number of ABGF</td>
<td>0.16054</td>
<td>17.18%</td>
</tr>
<tr>
<td>Design Speed &amp; Project Life</td>
<td>0.02544</td>
<td>2.72%</td>
</tr>
</tbody>
</table>
The main factor (first order) influences account for 65.35%, and the factor interaction (second order) influences account for 34.65% of the total variations in the accident model output (i.e. the average accident cost). The following inferences are made about the accident factor influences on the accident cost of a utility based on the sensitivity indices calculated.

<table>
<thead>
<tr>
<th>Term Description</th>
<th>Sensitivity Index</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Daily Traffic Design Year &amp; Traffic Growth Rate</td>
<td>0.00040</td>
<td>0.04%</td>
</tr>
<tr>
<td>Average Daily Traffic Design Year &amp; Number of Lanes</td>
<td>0.00008</td>
<td>0.01%</td>
</tr>
<tr>
<td>Average Daily Traffic Design Year &amp; Lane Width</td>
<td>0.00001</td>
<td>0.00%</td>
</tr>
<tr>
<td>Average Daily Traffic Design Year &amp; Number of ABGF</td>
<td>0.03638</td>
<td>3.89%</td>
</tr>
<tr>
<td>Average Daily Traffic Design Year &amp; Project Life</td>
<td>0.00576</td>
<td>0.62%</td>
</tr>
<tr>
<td>Traffic Growth Rate &amp; Number of Lanes</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Traffic Growth Rate &amp; Lane Width</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Traffic Growth Rate &amp; Number of ABGF</td>
<td>0.00102</td>
<td>0.11%</td>
</tr>
<tr>
<td>Traffic Growth Rate &amp; Project Life</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Number of Lanes &amp; Lane Width</td>
<td>0.00002</td>
<td>0.00%</td>
</tr>
<tr>
<td>Number of Lanes &amp; Number of ABGF</td>
<td>0.00021</td>
<td>0.02%</td>
</tr>
<tr>
<td>Number of Lanes &amp; Project Life</td>
<td>0.00003</td>
<td>0.00%</td>
</tr>
<tr>
<td>Lane Width &amp; Number of ABGF</td>
<td>0.00002</td>
<td>0.00%</td>
</tr>
<tr>
<td>Lane Width &amp; Project Life</td>
<td>0.00000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Number of ABGF &amp; Project Life</td>
<td>0.01458</td>
<td>1.56%</td>
</tr>
<tr>
<td>Total</td>
<td>0.32371</td>
<td>34.65%</td>
</tr>
</tbody>
</table>
6.1.1 Main Effects Of Accident Model Factors

1. *Design Year:* The present values for factors such as the average daily traffic (ADT) are not always known, hence the accident model allows for the use of predicted data for a future period (i.e. the design year). The traffic volume for every year of the project life is then calculated using a compounding formula (shown as cost equation 8, in chapter 3). Since the traffic volume plying the road directly affects the accident probabilities, the design year is influential in determining the accident costs of a utility, as seen in Figure 6.1.

![Main Effects Plot for Design Year](image)

**Figure 6.1: Main Effect Of Design Year On The Accident Costs**

*Change in Design Year:* From 5 to 20 (yrs)

*Change in Average Accident Costs:* Decrease from 2311.8 to 1526 (K$/Mile)

The reason for this decrease is a direct effect of the method used for calculating the average daily traffic for every year of the project life using the traffic growth rate.
The F-test value (3852.0) and the P-value (0.00) from the ANOVA results verifies this factors mild influence on the accident cost of a utility.

*Sensitivity Index* is 0.00827, which accounts for about 0.89% of the variation in the average accident costs.

2. *Design Speed* of the road is the vehicular speed for which the road is designed. It has a strong influence on the value and shape of the accident cost function (as depicted in Figure 6.2), because it influences the following:
   a. the lateral encroachment probabilities which is used to determine the number of accidents per year,
   b. the finite lateral extent of encroachment into the right-of-way for a vehicle,
   c. the length of the road which contributes towards impacts with the facility and,
   d. the severity of accidental impacts.

![Main Effects Plot for Design Speed](image)

Figure 6.2: Main Effect Of Design Speed Of The Road On The Accident Costs
Change in Design Speed of Road: From 35 to 70 (M / hr)

Change in Average Accident Costs: Increases exponentially from 192.2 to 5673.2 (K$/ Mile)

The F-test value (63324.9) and the P- value (0.00) from the ANOVA results table verifies this factors very strong influence on the accident cost of a utility.

Sensitivity Index: is 0.31723, which accounts for about 33.95% of the variation in the average accident costs.

3. Design Year Average Daily Traffic (ADT\textsubscript{dy}) is the average daily traffic predicted for the design year. It is also the capacity traffic for which the road is designed. The accident model estimates a present day value for future accident costs associated with a utility by summing the ADT calculated over all the years of the project life. Thus the predicted ADT\textsubscript{dy} value is influential to the accident costs of a utility, shown in Figure 6.3.

![Main Effects Plot for Design Year Average Daily Traffic](image_url)

Figure 6.3: Main Effect Of Average Daily Traffic On The Accident Costs
Change in the Design Year Average Daily Traffic: From 10 to 40 (KCars / day)

Change in Average Accident Costs: Increases from 777.3 to 3109.2 (K$ / Mile)

The F-test value (33481.7) and the P-value (0.00) from the ANOVA results table verifies this factor's moderately strong influence on the accident cost of a utility.

Sensitivity Index: is 0.07188, which accounts for about 7.69% of the variation in the average accident costs.

4. Traffic Growth Rate (TGR) is the rate at which the average daily traffic (ADT) increases every year over the project life. Thus the TGR is important to determining the accident cost of a utility, illustrated by Figure 6.4.

![Main Effects Plot for Traffic Growth Rate](image)

Figure 6.4: Main Effect Of Traffic Growth Rate On The Accident Costs

Change in the Traffic Growth Rate: From 5 to 20 (% / yr)

Change in Average Accident Costs: Decreases from 2164.7 to 1777.6 (K$ / Mile)
The reason for this decrease is explained by the fact that a higher rate of growth in traffic means a smaller number of vehicles plying the roads initially, building up to the design year traffic.

The F-test value (942.4) and the P-value (0.00) from the ANOVA results table verifies this factor’s weak influence on the accident cost of a utility.

*Sensitivity Index*: 0.00202, which accounts for about 0.22% of the variation in the average accident costs.

5. **Number of Lanes** is the measure of the lanes of traffic in either direction. Vehicular traffic from both the directions have lateral encroachment possibilities. Encroachment probabilities for the adjacent lanes are smaller because of the additional offset (i.e. the pavement width), shown in Figure 6.5.

![Figure 6.5: Highway Diagram Explaining Accident Factors](image-url)
As seen in Figure 6.6,

*Change in the Number of Lanes*: From 2 to 4

*Change in Average Accident Costs*: Increases from 1874.5 to 2033.7 (K$/Mile)

Increase in the number of lanes reduces the offset distance of the utility from the traffic thus increasing the possibilities of accidents and the associated accident costs. The F-test value (296.6) and the P-value (0.00) from the ANOVA results table verifies this factors weak influence on the accident cost of a utility.

*Sensitivity Index*: 0.00042, which accounts for about 0.05% of the variation in the average accident costs.

6. *Lane Width* is the width of a traffic lane on the pavement. Lane width affects the lateral encroachment probability values in the accident model. The main effect of variation in lane width on the accident cost of a utility is illustrated in Figure 6.7.
Change in the Lane Width: From 11 to 13 (Ft.)

Change in Average Accident Costs: Increases from 1920.7 to 1967.7 (K$ / Mile)

The F-test value (24.6) and the P-value (0.00) from the ANOVA results table verifies this factors very weak influence on the accident cost of a utility.

Sensitivity Index: 0.00004, which accounts for about 0.004% of the variation in the average accident costs.

7. Number of Aboveground Facilities (AGF) The measure of the number of above ground components that a utility has per mile of ROW. The number of above ground facilities per mile affects the probability of accidents and thus the accident costs, shown in Figure 6.8.
Figure 6.8: Main Effect Of Number Of Aboveground Facilities On The Accident Costs

*Change in the Number of AGF:* From 1 to 30

*Change in Average Accident Costs:* Increases from 127.4 to 2033.7 (K$/Mile)

The F-test value (84716.2) and the P-value (0.00) from the ANOVA results table verifies this factor’s strong influence on the accident costs of a utility.

Sensitivity Index: 0.18188, which accounts for about 19.47% of the variation in the average accident costs.

8. *Project Life* is the time interval from the original installation of the utility within the ROW until some time in the future when the roadway would be replaced or abandoned. The project life is used to calculate the total traffic plying the road over all the years under consideration, thus determining the total number of possible accidents over the entire life of the utility. The Main effect plot for project life on the accident cost of a utility is shown in Figure 6.9.
Change in the Project Life: From 20 to 40

Change in Average Accident Costs: Increases from 1165.1 to 2721.4 (K$/Mile)

The F-test value (10066.8) and the P-value (0.00) from the ANOVA results table verifies this factor's strong influence on the accident costs of a utility.

Sensitivity Index: 0.02882, which accounts for about 3.08% of the variation in the average accident costs.

### 6.1.2 Accident Model Factors Interactions

Certain accident model factors interact with each other to produce variation in the cost function generated by the accident model. Table 6.3 and Figure 6.10 detail the major factor interactions contributing towards the variations in the accident cost of a utility.
Table 6.3: Major Factor Interactions Influencing The Accident Costs

<table>
<thead>
<tr>
<th>FACTOR INTERACTIONS</th>
<th>CHANGE IN ACCIDENT COST (K$/Mile)</th>
<th>SENSITIVITY INDEX</th>
<th>CONTRIBUTION TO VARIATION IN OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Speed &amp; Design Year Average Daily Traffic</td>
<td>924.7 to 2441.6</td>
<td>0.06345</td>
<td>6.79%</td>
</tr>
<tr>
<td>Design Speed &amp; Number of ABGF</td>
<td>151.6 to 3002</td>
<td>0.16054</td>
<td>17.18%</td>
</tr>
<tr>
<td>Design Speed &amp; Project Life</td>
<td>1533.6 to 2304.2</td>
<td>0.02544</td>
<td>2.72%</td>
</tr>
<tr>
<td>Design Year Average Daily Traffic &amp; Number of ABGF</td>
<td>51.0 to 6116.4</td>
<td>0.03638</td>
<td>3.89%</td>
</tr>
<tr>
<td>Number of ABGF &amp; Project Life</td>
<td>76.4 to 5353.57</td>
<td>0.01458</td>
<td>1.56%</td>
</tr>
</tbody>
</table>

Figure 6.10: Interaction Effects Of Accident Factors
6.2 Results Of The Sensitivity Analysis Of The Damage Model Factors

The sensitivity analysis of the damage model factors involved making a total of 8470 experimental runs of the damage model, varying 4 selected factors at various levels within their suggested ranges to determine their influences on the damage cost function generated for a utility. The average value of the damage function generated was used as the response variable. The analysis of variances output (ANOVA) that were determined using Minitab Release 14 (Statistical Software) is shown in Table C.2 in appendix C. The test was conducted at a 5% level of significance ($\alpha = 0.05$). First and second order sensitivity indices derived from the output variances from the ANOVA results are shown in Table 6.4 and Table 6.5 respectively,

Table 6.4: First Order Sensitivity Indices For Damage Model Factors

<table>
<thead>
<tr>
<th>DAMAGE MODEL FACTORS</th>
<th>FIRST ORDER S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Damage</td>
<td>0.42087</td>
<td>42.66%</td>
</tr>
<tr>
<td>Default Cover</td>
<td>0.00070</td>
<td>0.07%</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>0.09496</td>
<td>9.63%</td>
</tr>
<tr>
<td>Damage Fraction</td>
<td>0.28696</td>
<td>29.09%</td>
</tr>
<tr>
<td>Total</td>
<td>0.8035</td>
<td>81.45%</td>
</tr>
</tbody>
</table>

Table 6.5: Second Order Sensitivity Indices For Damage Model Factors

<table>
<thead>
<tr>
<th>DAMAGE MODEL FACTORS</th>
<th>SECOND ORDER S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Damage &amp; Default Cover</td>
<td>0.00028</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
Table 6.5 (Continued)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Damage &amp; Maximum Depth</td>
<td>0.03798</td>
<td>3.85%</td>
</tr>
<tr>
<td>Maximum Damage &amp; Damage Fraction</td>
<td>0.11478</td>
<td>11.64%</td>
</tr>
<tr>
<td>Default Cover &amp; Maximum Depth</td>
<td>0.00389</td>
<td>0.39%</td>
</tr>
<tr>
<td>Default Cover &amp; Damage Fraction</td>
<td>0.00019</td>
<td>0.02%</td>
</tr>
<tr>
<td>Maximum Depth &amp; Damage Fraction</td>
<td>0.02590</td>
<td>2.63%</td>
</tr>
<tr>
<td>Total</td>
<td>0.18303</td>
<td>18.55%</td>
</tr>
</tbody>
</table>

The main factor (first order) influences account for 81.45% and the factor interaction (second order) influences account for 18.55% of the total variations in the damage model output (i.e. the average damage cost). The following inferences are made about the damage factor influences on the damage costs of a utility, based on the sensitivity indices calculated.

6.2.1 Main Effects Of Damage Model Factors

The data on damage events is not very accurate and hence a simple linear damage model is used in the heuristic to determine damage costs associated with a utility. The damage model is based on the assumption that the cost per damage incident is primarily a function of depth, modified by factors such as,

1. Maximum Damage: a maximum cost per incident, specified by the user at the maximum depth. The damage cost of the utility reduces linearly from this maximum value at the deepest possible position to the highest possible location for the utility (i.e. the default cover). Main effect of variation in maximum damage specified by the user is depicted in Figure 6.11.
Figure 6.11: Main Effect Of Maximum Damage On The Damage Costs

*Change in the Maximum Damage:* From 0 to 1000 (K$/ event)

*Change in Average Damage Costs:* Increases from 0 to 97.67 (K$ / Mile)

The F-test value (24918.3) and the P-value (0.00) from the ANOVA results table verifies this factor's strong influence on the damage cost associated with a utility.

*Sensitivity Index:* 0.42087, which accounts for about 42.67% of the variation in the average damage costs.

2. *Default Cover:* the minimum depth below the surface of the ground, above which the utility should not be placed. This constraint is imposed on the placement of utilities to prevent damage caused due to superficial location. Main effect of variation in default cover required for a utility on the associated damage costs is shown in Figure 6.12.
Change in the Default Cover: From 0 to 30 (inches)

Change in Average Damage Costs: Decreases from 51.17 to 47.53 (K$/Mile)

After which any increase in a mandatory cover imposed causes the damage cost associated with a utility to increase. This is explained by the fact that the linear damage function tends to flattens out as the corridor height is reduced.

The F-test value (69.1) and the P-value (0.00) from the ANOVA results table verifies this factors extremely weak influence on the damage cost of a utility.

Sensitivity Index: 0.00070, which accounts for about 0.07% of the variation in the average damage costs.

3. Maximum Depth is the maximum allowed depth for placement a utility within the ROW corridor. This constraint governed by practical considerations of safety (presence of water tables, application of high pressures) prevents very deep
placement of utilities. Main effect of variation in maximum depth for positioning of the utility on the damage costs is illustrated in Figure 6.11.

Figure 6.13: Main Effect Of Maximum Depth On The Damage Costs

*Change in the Maximum Depth:* From 60 to 120 (Inches)

*Change in Average Damage Costs:* Decreases from 79.40 to 31.58 (K$/Mile)

The F-test value (5622.2) and the P-value (0.00) from the ANOVA results table verifies this factor's mild influence on the damage costs of a utility.

*Sensitivity Index:* 0.09496, which accounts for about 9.63% of the variation in the average damage costs.

4. *Damage Fraction* is the fraction of events (access or installation) assumed to result in damage incidents. The heuristic arbitrarily takes the value 1%. This analysis experiments with different values for this fraction starting from 0.05% until 5%. As seen from Figure 6.14,
Change in the Damage Fraction: From 0.5 to 5 (%)

Change in Average Damage Costs: Increases from 8.88 to 88.78 (K$/Mile)

The F-test value (18877.5) and the P-value (0.00) from the ANOVA results table verifies this factor’s strong influence on the accident costs of a utility.

Sensitivity Index: 0.28696, which accounts for about 29.09% of the variation in the average damage costs.

6.2.2 Damage Model Factor Interactions

Certain damage model factors interact with each other to produce variation in the output of the damage model. Table 6.6 and Figure 6.10 detail the major factor interactions contributing towards the variations in the damage cost of a utility.
Table 6.6: Major Factor Interactions Influencing The Damage Costs

<table>
<thead>
<tr>
<th>FACTOR INTERACTIONS</th>
<th>CHANGE IN AVERAGE DAMAGE COSTS (K$/ Mile)</th>
<th>SENSITIVITY INDEX</th>
<th>CONTRIBUTION TO VARIATION IN OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Damage &amp; Maximum Depth</td>
<td>0 to 63.16</td>
<td>0.03798</td>
<td>3.85%</td>
</tr>
<tr>
<td>Maximum Damage &amp; Damage Fraction</td>
<td>0 to 177.57</td>
<td>0.11478</td>
<td>11.64%</td>
</tr>
<tr>
<td>Maximum Depth &amp; Damage Fraction</td>
<td>14.44 to 57.42</td>
<td>0.02590</td>
<td>2.63%</td>
</tr>
</tbody>
</table>

Interaction Plot for Damage Model Factors

Figure 6.15: Interaction Effects Of Damage Model Factors
6.3 Results Of The Sensitivity Analysis Of The Installation Surcharge Models Factors

The heuristic has additional surcharge models (inconvenience and shoring) included in its utility installation cost assessment model, used primarily as deterrents for utility placements in ‘undesirable’ regions of the ROW. The sensitivity analysis of the installation surcharge models involved making a total of 1452 experimental runs of the heuristic (experiment 1, appendix B), varying 3 factors at various levels within their suggested ranges to determine their influences on the total costs of the optimal configuration and the positioning of the utilities of the optimal solution. 3 replicates of the experiment were made, varying the ROW width on each occasion to eliminate (block) the effect of the corridor and problem setup. The analysis of variances output (ANOVA) generated using Minitab Release 14 (Statistical Software) is shown in Table C.3 in appendix C. The test was conducted at a 5% level of significance ($\alpha = 0.05$). First and second order sensitivity indices derived from the output variances from the ANOVA results are shown in Table 6.7 and Table 6.8 respectively,

Table 6.7: First Order Sensitivity Indices For Installation Surcharge Model Factors

<table>
<thead>
<tr>
<th>INSTALLATION SURCHARGE FACTORS</th>
<th>FIRST ORDER S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoring Surcharge</td>
<td>0.03329</td>
<td>4.05%</td>
</tr>
<tr>
<td>Inconvenience Surcharge Region</td>
<td>0.23320</td>
<td>28.37%</td>
</tr>
<tr>
<td>Inconvenience Surcharge</td>
<td>0.24862</td>
<td>30.25%</td>
</tr>
<tr>
<td>Total</td>
<td>0.5151</td>
<td>62.67%</td>
</tr>
</tbody>
</table>
Table 6.8: Second Order Sensitivity Indices For Installation Surcharge Model Factors

<table>
<thead>
<tr>
<th>DAMAGE COST FACTORS</th>
<th>SECOND ORDER S.I.</th>
<th>PERCENTAGE VARIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoring Surcharge &amp; Inconvenience Surcharge Region</td>
<td>0.03648</td>
<td>4.44%</td>
</tr>
<tr>
<td>Shoring Surcharge &amp; Inconvenience Surcharge</td>
<td>0.00550</td>
<td>0.67%</td>
</tr>
<tr>
<td>Inconvenience Surcharge Region &amp; Inconvenience Surcharge</td>
<td>0.02960</td>
<td>3.60%</td>
</tr>
<tr>
<td>Total</td>
<td>0.07158</td>
<td>8.71%</td>
</tr>
</tbody>
</table>

The ANOVA results determined a 28.62% effect of the blocks and 71.38 % effect of the factors. The main factor (first order) influences account for 81.45% and, the factor interaction (second order) influences account for 18.55% of the total variations in optimal total costs due to factor effects. Based on the sensitivity indices calculated, the following inferences are made about the installation surcharge factor influences.

6.3.1 Main Effects Of Installation Surcharge Model Factors

1. *Shoring Surcharge* is applied to a utility that has to be placed close to the extreme most position (easement) of the ROW corridor. Shoring costs are used to factor in, the difficulties involved, additional labor and extra materials required for locating utilities at this ‘undesirable’ location. The shoring surcharge model assumes the region starting from the edge of the ROW extending 3 feet inward as the shoring region and applies a flat cost to all utilities placed there. The effect of varying the maximum shoring charge associated with a utility is shown in Figure 6.16.
Figure 6.16: Main Effect Of Shoring Surcharge On The Total Optimal Costs

*Change in the Shoring Surcharge:* From 0 to 1000 (K$ / Mile)

*Change in Optimal Total Costs:* Increases from 1134 to 1179 (K$ / Mile)

The following observations were made in regards to the positional changes of the utilities of the optimal configurations determined with changes in the shoring surcharge applied (Figures 6.17 and 6.18)

a. Initial application and increase in shoring surcharge moves the utilities of the optimal configuration to the left (if there is space available to do so).

b. Further increase in the shoring surcharge just increases the optimal cost determined.

c. The maximum shoring surcharge (range is 0 to 100 K$ / Mile) never gets large enough to move a utility to a deeper position in the corridor.
The F-test value (23.7) and the P-value (0.00) from the ANOVA results table verifies this factor's weak influence on the output of the heuristic.

*Sensitivity Index*: 0.03329, which accounts for about 4.05% of the variation in the optimal total costs.

2. *Inconvenience Surcharge* is an additional installation charge applied to a utility when it has to be placed within the ROW in close proximity to the pavement. Since installation and access events to this utility will cause disruption of traffic plying the
road, the inconvenience caused is factored in as a surcharge to the utility for installation at that particular location. The effect of varying the maximum inconvenience charge associated with undesirable positioning of a utility is illustrated in Figure 6.17.

![Main Effects Plot for Shoring Surcharge](image)

Figure 6.19: Main Effect Of Inconvenience Surcharge On The Total Optimal Costs

*Change in the Inconvenience Surcharge:* From 0 to 40

*Change in Optimal Total Cost:* Increases from 1134 to 1224 (K$ / Mile)

The optimal cost increases rapidly with initial increase in the inconvenience surcharge but flattens out with further increase. The following observations were made in regards to the positional changes of the utilities of the optimal configurations determined with changes in the shoring surcharge applied (Figures 6.20, 6.21, 6.22).
a. Initial application and increase in inconvenience surcharge moves the utilities of the optimal configuration to the right (if there is space available to do so).

b. Further increase in the inconvenience surcharge just increases the optimal cost determined.

c. At some value of maximum inconvenience surcharge (200 to 500 K$ / Mile depending on the ROW width available), the surcharge gets large enough to change the orientation of the optimal solution by moving a utility to a deeper position in the corridor.

Figure 6.20: Initial Optimal Configuration Determined (Inconvenience)

Figure 6.21: Optimal Configuration Determined After Increasing Inconvenience Surcharge
The F-test value (176.7) and the P-value (0.00) from the ANOVA results table verify this factor's strong influence on the output of the heuristic.

*Sensitivity Index*: 0.24862, which accounts for about 30.25% of the variation in the optimal total cost.

3. *Shoring Surcharge Region* is the region starting from the edge of the pavement extending outwards (extent specified by the user) within which a utility has an inconvenience surcharge associated with it. The inconvenience surcharge model adds a surcharge that is maximum starting from the edge of the pavement and reduces linearly to zero at the end of the surcharge region. As seen in Figure 6.22,

*Change in the Inconvenience Surcharge Region*: From 0 to 3

*Change in Total Optimal Cost*: Increases from 1134 to 1224 (K$ / Mile)

The F-test value (552.5) and the P-value (0.00) from the ANOVA results table verifies this factor's moderately strong influence on the output of the heuristic.
Sensitivity Index: 0.23320, which accounts for about 28.37% of the variation in the optimal total costs.

![Main Effects Plot for Inconvenience Surcharge Region](image)

Figure 6.22: Main Effect Of Inconvenience Surcharge Region On The Total Optimal Costs

### 6.3.2 Installation Surcharge Models Factor Interactions

The only second order that is factor interaction influence noticed was the interaction between the inconvenience surcharge region and the shoring surcharge.

As seen in Figure 6.23,

*Change in Total Optimal Cost:* Increases from 1134 to 1252 (K$/Mile)

The F-test value (8.6) and the P-value (0.00) from the ANOVA results table verifies this factors moderate influence on the output of the heuristic.

Sensitivity Index: 0.03648, which accounts for about 4.44% of the variation in the optimal total costs.
6.4 General Conclusions

In his article “Verification, validation and confirmation of numerical models in the earth sciences” Oreskes [65] described Sensitivity Analysis as a tool to improve, verify, validate and corroborate a model by demonstration of agreement between observation and prediction. Sobol’ variance based sensitivity analysis used here is a global method in which the entire space of existence of the input factors is covered and all factors are varied simultaneously for analysis. The results derived (factor sensitivity indices) are informative (including both main and factor interaction effects), the computation is relatively inexpensive and the method is model independent (can be used in monotonic and non-monotonic models).
CHAPTER 7
MODEL OUTPUT EVALUATION AND ENHANCEMENT STUDY

The second part of the model analysis is an evaluation study (i.e. an assessment of the quality) of the final output of the heuristic. This chapter delves into the complexities of the present output determination technique of the heuristic, and based on certain observed shortcomings suggests an enhancement to be implemented with it. The enhancement called ‘the Ideal Configuration Selector’ addresses all the problems of the heuristic and implements a multi objective / criterion evaluation technique for utility configuration assessment and selection.

7.1 Problems With The Present Working Procedure

The output of the heuristic is a configuration of the utilities selected for placement in the ROW corridor having the least estimated total cost associated with it. The working structure of the heuristic, starting with the identification of configurations, their feasibility assessment, cost evaluation, and finally, selection of the best based on optimality explained in chapter 3 is very functional. However, a verification analysis of this working structure revealed the following problems.

1. Problems With The Configuration Identification Process

The heuristic is sometimes referred to as a “brute force” cost optimization model because of the discrete step operation of its mover program. The mover program moves
each utility, one at a time, by a specified step size within the corridor boundaries to find possible placement locations (configurations) for them. The movement step size, that is, the refinement for configurational search is specified in fractions of a foot (step size range is 0.1 to 1). Tests conducted on the heuristic however revealed the following implementation problems associated with the mover.

a. If the user decides on a very refined search (step size 0.2 or 0.1), the mover determines a very large number of configurations and, takes a long time to do so. The subsequent steps until the determination of an optimal solution are also computationally very expensive. An analysis with 3 utilities to be located in a ROW corridor having a cross-section of 6 x 6 feet employing a very refined search can take anywhere between 12 to 72 hours of processing time on a 2.8 GHz Pentium 4 processor to determine an optimal solution. The use of a coarse step size for the configurational search is not a solution to the problem either.

Figure 7.1 shows the positions assessed as feasible for utility placement by the mover in the ROW corridor at step size 1 and, Figure 7.2 shows the placement positions assessed while using a more refined step size of 0.5. It is obvious from these figures that the use of a coarse search step size results in an incomplete coverage of the available ROW corridor space thus eliminating possible good solutions.
b. Another problem with the use of the mover in the heuristic is, the variability observed in the final (optimal) outputs determined with different search step sizes. Experimental sweeps with reducing search step sizes showed an erratic variation in the total costs of the optimal solutions determined as illustrated in Figure 7.3 for an analysis with 3 utilities, Figure 7.4 (4 utilities) and Figure 7.5 (5 utilities) respectively.
Figure 7.3: Variation In The Total Costs Of Optimal Solutions For 3 Utility Experiment Using Varied Search Step Sizes

Figure 7.4: Variation In The Total Costs Of Optimal Solutions For 4 Utility Experiment Using Varied Search Step Sizes

Figure 7.5: Variation In The Total Costs Of Optimal Solutions For 5 Utility Experiment Using Varied Search Step Sizes
The cause of this variability is obvious. The mover uses discrete steps for utility movements in the corridor while finding possible placement configurations. However, this discretized search is being conducted over continuous cumulative cost functions generated by the cost models for each utility. The problem is this indicates that the best estimate for an optimal solution can be determined only by using the finest search step possible with the mover (step size 0.1) which poses problems of excessive computational time and large data files.

c. The final step in the working of the heuristic is the optimization of the estimated total costs of all the feasible utility configurations to determine the configuration associated with the least total cost. The problem arises when the analysis determines many configurations (somewhat similar or totally different) with the same least total costs (optimal solutions). If a “<” (less than) is used in the code for comparing total cost, the first configuration amongst the many with the same least total cost is selected and, if the “≤” (less than equal to) is used, the last configuration with the least total cost is chosen. This however does not always present the best solution, but only one amongst many possible optimal solutions.

2. *Problems With The Heuristics Output Quality*

   The purpose of the heuristic is to develop a good utility configuration assessment tool to help the Department of Transportation (DOT) make rational decisions on the placement allocation of utilities in ROW corridors. During conference presentations however, it was noticed that besides the department of transportation (DOT), a diverse group of stakeholders such as, the public (consumers), utility owners
(public and private,) and other corporate parties (contractors, services etc.) expressed interests in the development of a utility corridor organization scheme. Each stakeholder expressed certain requirements that the present single objective simulation does not address. For example,

a. Economic fairness for all utility companies. The displayed optimal solution (configuration) does not guarantee all the utilities being placed at inexpensive positions in the ROW.

b. Present utility installation techniques and procedures are not accurate and the solution does not provide information on the positioning flexibilities of the utilities in the selected configuration.

c. With the ever increasing demand for corridor space, for the placement of new utilities in the ROW or for extensions in the road ways, the present method does not evaluate configurations for renovation adaptability (i.e. the measure of the scope for addition of more utilities, and pavement extensions).

The proposed Ideal Configuration Selector (ICS) is designed to remedy the problems and shortcomings of the current output methodology used by the heuristic and also present a method for producing substantiated results (outputs) from it.

### 7.2 The Ideal Configuration Selector

The ICS is a utility configuration assessment tool which uses a multi-criterion decision making procedure called the Weighted Product Model (WPM) to assess and rank configurations according to their conformity to the desired configurational characteristics. The ICS uses a similar assessment procedure as the original heuristic
aided by a few experimental tools and techniques like, the Jiggle Sensitivity Tool (JST),
the Cost Dot Technique (CDT) and the Metric. The working structure of the ICS is as
shown in Figure 7.6 and explained in the following steps.

Figure 7.6: Working Structure Of The Heuristic With The Ideal Configuration Selector
Step 1: Identification Of Configuration Shape Sets

The ICS employs the original mover program to initially identify configurations using a moderately course step size (suggested range 0.6 to 0.4 from search pattern observation studies to ensure proper coverage of the ROW corridor space). Rather than assess all the configurations obtained, the ICS uses two experimental techniques namely the Cost Dot Technique (CDT) and the Metric to identify configuration shape (orientation) sets from the configurations determined. The working of the CDT is based on the fact that, the individual cost of a utility is a direct function of its location within the ROW. It uses this interaction between the utility cost functions and the constrained positioning possibilities of utilities in the ROW to group the configurations into sets of similar orientation as follows.

1. The CDT utilizes the individual costs of the utilities in a configuration as vector coefficients to determine the correlation between two configurations. (The correlation between two vectors is obtained by taking the dot product of the two cost vectors).

2. The correlation value is then used as a measure of the difference between the two configurations. (The correlation values lie between 0 and 1. Similar orientation configuration will have equal cost dot values).

In certain cases, like those involving large ROW or few utilities to be placed, it is possible for very different configurations to have the similar costs estimated for each utility. To determine and separately group these configurations the Metric is used in conjunction with the CDT. The Metric quantifies the difference between configurations with the help of the positional coordinates of the utilities that is, by the conventional
“sum of the square of differences” method. Detailed explanations of the CDT and the Metric are included in appendix D.

**Step 2: Optimization Of Shape Sets**

Once the configurational shape sets have been identified, another experimental tool called the Jiggle Sensitivity Tool (JST) is used to determine a configuration to represents the best possible (optimal) position for utilities in each shape set. The JST is a program that jiggles (moves) the utilities of a configuration by finite steps in specified directions (up, down, to the left and to the right) while monitoring,

1. The percentage change in the individual cost of the utility and, the percentage change in the total cost of the configuration,

2. The possibility for movement of a utility in a particular direction without violations to other utility clearances, corridor boundaries and utility stacking rules.

The detailed working of the JST is explained in appendix E.

The optimization of a shape sets is achieved with the following steps.

1. A configuration is selected from each shape set.

2. All the utilities in a configuration are jiggled (by 1 step = 1/12th of a foot) in all specified directions.

3. The configurational sensitivity for each of the 4n movements is analyzed and a positional change for a utility is accepted only if:
   a. it improves (reduces) the total cost of the configuration and,
   b. does not violate any rules (utility clearance, stacking and corridor boundary).
4. Steps 2 and 3 are repeated iteratively until:
   
a. No movement is possible for any utility. (Every utility is allowed a maximum of 6 steps in each direction to maintain configurational orientation and ensure complete coverage of ROW corridor space).
   
b. Jiggling of the utilities does not improve the total cost of the configuration.

**Step 3: Setup Of The Weighted Product Model (WPM)**

The ICS is formulated on a multi-criterion decision making procedure also known as the Weighted Product Model. The WPM is based on a numerical technique developed by Bridgman [58] and used later by Miller and Starr [61]. It is used here to select the shape configuration embodying most of the ideal configurational characteristics as the best solution. The WPM has the following components.

1. **Alternatives**: Alternatives represents the different options available for assessment.
   
The alternatives in the ICS are the shape configurations to be assessed.

2. **Attributes**: Attributes are referred to as goals or decision criteria. The decision criteria in the ICS are the desired characteristics of an ideal utility configuration (defined and determined in the next step) with respect to which the shape configurations will be assessed.

3. **Decision Weights**: The weights of importance of the decision criteria decided by the decision maker. The ICS suggest a nine point scale shown in Table 7.1 to the user for weighing the importance of each ideal configuration characteristic. The weights assigned are then normalized to sum up to 1 before being used in the WPM.
Table 7.1: Nine Point Scale For Characteristic Importance

<table>
<thead>
<tr>
<th>INTENSITY OF IMPORTANCE</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Weak Importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate Importance</td>
</tr>
<tr>
<td>5</td>
<td>Strong Importance</td>
</tr>
<tr>
<td>7</td>
<td>Demonstrated Importance</td>
</tr>
<tr>
<td>9</td>
<td>Absolute Importance</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between two judgments</td>
</tr>
</tbody>
</table>

4. *Decision Matrix*: A decision matrix as shown in Table 7.2 is an \((m \times n)\) matrix in which element \(c_{ij}\) indicates the performance of shape configuration \(C_i\) when evaluated in terms of ideal utility configuration characteristic \(Ch_j\).

Table 7.2: Decision Matrix For The Weighted Product Model

<table>
<thead>
<tr>
<th>ALTERNATIVES (Set Configurations)</th>
<th>ATTRIBUTES (Characteristics)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Ch_1)</td>
</tr>
<tr>
<td>WEIGHTS (Importance)</td>
<td>(w_1)</td>
</tr>
<tr>
<td>(C_1)</td>
<td>(c_{11})</td>
</tr>
<tr>
<td>(C_2)</td>
<td>(c_{21})</td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(\ldots)</td>
</tr>
<tr>
<td>(C_m)</td>
<td>(c_{m1})</td>
</tr>
</tbody>
</table>
Step 4: Quantifying Ideal Configuration Characteristics

A study was conducted to determine a set of ideal utility configuration characteristics to be used in the ICS for assessing utility configurations. Considering the requirements of the different parties concerned, the following characteristics were finally decided on.

1. Optimality in the total cost of the configuration.
2. Economic fairness for the utilities of the configuration.
3. Flexibility in the positioning of utilities of the configuration.
4. Low usage of corridor space by the configuration.

The explanations and quantifying measures for these ideal utility configuration characteristics are,

1. **Optimality in the total cost of the configuration**.
   
The total societal cost of the configuration selected should be at or close to the lowest possible value for the placement of utilities in the ROW. The optimal costs determined for each shape configuration is used directly in the WPM as performance measures for this characteristic.

2. **Economic fairness for the utilities of the configuration**.
   
Utility companies required that the configuration selection procedure ensure economic fairness to all the utilities in the ROW corridor. The coefficient used to represent economic fairness for the utilities of a configuration in the WPM is called the Balance Coefficient (BC). The BC is based on the premise, that if all utilities in the configuration were at or close to their individual minimum cost values, they would
definitely be located in equally fair (less expensive) positions. The BC for a configuration is determined as the maximum of the normalized differences from individual minimum costs of the utilities in a configuration. That is,

\[
\text{Balance Coefficient (BC)} = \max \left( \frac{IC_j - IC_{j\text{min}}}{IC_{j\text{min}}} \right) \quad \text{for } j = 1 \text{ to } n
\]

Since the WPM works on a minimization principle the shape configuration having the minimum of the maximum deviations of individual utility costs will be favored. This technique is derived from Chebychev’s Min Max Normalization Theory [64].

3. **Flexibility in the positioning of utilities of the configuration.**

The output of the heuristic is a positional configuration for the utilities to be placed within the ROW corridor. Utility installation procedures in use today are not very accurate and in most cases placement precision to the very last inch for all practical purposes can not be achieved. Thus it is very important to determine the positioning flexibility associated with each utility of a configuration before selecting it for implementation in a ROW corridor.

The flexibility of a configuration is the measure of the capability of the utilities in a configuration to be positioned finite distances away from their optimal position without violating placement rules (corridor boundaries and clearance constraints). The coefficient used to represent the flexibility of the utilities in a configuration in the WPM is called the Average Flexibility Coefficient (AFC), which is the average of the flexibility coefficients for all the utilities of a configuration.
The coefficient for flexibility of a utility in a configuration that is, the Flexibility Coefficient (FC) is defined as the number of valid positions for the utility (in the specified directions) around its position in the configuration. The JST is utilized to determine the validity of a utility’s position 6 mm in each direction (up, down, to the left and the right in 1 mm steps). A position is considered valid only if,

a. The rules for utility placement are not violated and,

b. The percentage change in the individual cost of a jiggled utility, that is, the positional sensitivity of that utility within the configuration does not exceed 10%.

4. **Low usage of corridor space by the configuration.**

With the ever increasing demand for space, be it for the placement of new utilities in the ROW or for extensions in the road ways, the measure of the scope for renovations that is, the addition of more utilities is a very important characteristic. The coefficient used to quantify this characteristic is the Corridor Space Usage Coefficient (CSUC), which is based on the premise that the measure of the utility addition capability of a configuration is a direct measure of the space available. The CSUC is calculated as the ratio of the area covered by the clearance boundaries of the utilities in a configuration to the total corridor space.

\[
\text{Corridor Space Usage Coefficient (CSUC)} = \frac{\text{Area covered by Utility Clearances}}{\text{Total Corridor Area}}
\]
Step 5: Ranking the Shape Configurations

The ranking of the alternatives (shape configurations) in the Weighted Product Model (WPM) involves comparing each shape configuration with the others by multiplying a number of ratios, one for each ideal utility configurational characteristic. Each ratio is raised to the power equivalent to the relative weight of the corresponding characteristic, that is, to compare two configurations $C_K$ and $C_L$, the following product (Bridgman [58] and Miller and Starr [61]) has to be calculated

$$R(C_K/C_L) = \prod_{j=1}^{n} \left( \frac{c_{K_j}}{c_{L_j}} \right)^{w_j}$$

Where,

- $n$ is the number of characteristics,
- $c_{ij}$ is the performance value of the $i^{th}$ configuration in terms of the $j^{th}$ characteristic, and
- $w_j$ is the weight of importance of the $j^{th}$ characteristic.

If the term $R(C_K/C_L)$ is less than one, then it indicates the shape configuration $C_K$ is more desirable than shape configuration $C_L$ (minimization problem). The best alternative is the one better than all other alternatives, that is, the utility configuration embodying most of the ideal configurational characteristics is selected as the best solution.

Step 6: Sensitivity / Criticality Of The Weights

The results obtained from the Ideal Configuration Selector are based entirely on the weights assigned by the user (decision maker) to each characteristic of the ideal
configuration in the WPM. To provide the decision maker with further insight into the selection procedure, the ICS provides a sensitivity / criticality analysis of the results to the weight decided on for each characteristic. The following procedure is followed for this purpose.

Suppose \( \tilde{\partial}_{k,i,j} \) (for \( 1 \leq i < j \leq m \) and \( 1 \leq k \leq n \)) denotes the minimum change in the current weight \( w_{k} \) of characteristic \( C_{k} \) such that the ranking of configurations \( C_{i} \) and \( C_{j} \) are reversed.

\[
\tilde{\partial}_{k,i,j} > K \quad \text{if } K \geq 0 \quad \text{and,}
\]

\[
\tilde{\partial}_{k,i,j} < K \quad \text{otherwise.}
\]

Where,

\[
K = \frac{\log \left( \prod_{y=1}^{n} \left( \frac{c_{iy}}{c_{jy}} \right)^{w_{y}} \right) \times 100}{\log \left( \frac{c_{ik}}{c_{jk}} \right)}
\]

and \( \tilde{\partial}_{k,i,j} \leq 100 \)

A critical degree of ideal utility configuration characteristic \( C_{k} \) denoted as \( D_{k}^{i} \) can be determined, which is, the smallest percent amount by which the current value of \( w_{k} \) must change, such that the existing ranking of the configurations will change.

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\[ D'_k = \min_{1 \leq i \leq j \leq m} \{ |\phi_{k,i,j}| \} \quad \text{for all } n \geq k \geq 1 \]

From this, a Sensitivity Coefficient of ideal configuration characteristic \( C_{h_k} \) denoted as \( \text{sens}(C_{h_k}) \) which is the reciprocal of the critical degree is determined.

\[
\text{sens}(C_{h_k}) = \frac{1}{D'_k} \quad \text{for any } n \geq k \geq 1
\]

If the critical degree is infeasible (i.e., impossible to change any configuration rankings with any weight change), then the sensitivity coefficient is set equal to zero.
CHAPTER 8
RESULTS AND CONCLUSIONS OF MODEL OUTPUT EVALUATION AND ENHANCEMENT STUDY

Chapter 7, ‘Model Output Evaluation & Enhancement Study’ highlighted certain problems associated with the working (implementation) and output determination methodology of the heuristic. Based on these shortcomings, it suggested an enhancement, the Ideal Configuration Selector (ICS) to be implemented with the heuristic. The ICS was specifically designed to tackle the problems of the heuristic and implement a multi-criterion configuration assessment procedure to substantiate the results presented by it. This chapter demonstrates the advantages of using the Ideal Configuration Selector with the heuristic.

8.1 Advantages Of Using The Ideal Configuration Selector

To demonstrate the functioning and advantages of the ICS, the following tests were conducted on the Standard Utility Placement Experiment 2 (Table B.3, appendix B) using the Standard Setup Parameters (Tables B.1) at step size 0.6 (moderately refined) as suggested in the ICS. Test runs were made on a Pentium IV, 2.8 GHz. 512 MB computer.

1. Speed: One of the problems highlighted with the use of the heuristic, was the computational time required for refined analysis. The ICS solves this problem by clustering (grouping) similar orientation configurations into sets and analyzing only
one optimal configuration from each shape set, thus reducing the number of configurations assessed and decreasing computational time. The speeding up of the heuristic is demonstrated from the timing shown below.

Analysis time using only the heuristic = 8:00:33 mins.

Analysis time using the ICS with the heuristic = 7:11:07 mins.

The important point to be noted here is that the heuristic was run at step size 0.6, where as the ICS refined the solutions obtained from runs at step size 0.6 by using the Jiggle Sensitivity Tool at jiggle size 0.1. The refinement in the solution is evident from results shown in Tables 8.1 (only heuristic) and Table 8.2 (heuristic with ICS).

2. **Refinement in Output**: Using different step sizes in configuration searches with the mover program in the heuristic resulted in, unpredictable variability in the total costs of the optimal solutions determined and in certain cases failure to identify possible good solutions. The ICS solves this problem by extracting one configuration from each shape (orientation) set identified and optimizing the positions of its utilities using the Jiggle Sensitivity Tool at jiggle size 0.1 before assessment. This procedure guarantees always determining the best possible solution.

![Figure 8.1: Optimal Configuration Determined Using The Heuristic](image)
Table 8.1: Optimal Solution Determined By The Heuristic

<table>
<thead>
<tr>
<th>UTILITY TYPE</th>
<th>HORIZ [in]</th>
<th>DEPTH [in]</th>
<th>COST [k$/mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER DIST</td>
<td>212</td>
<td>40</td>
<td>$463</td>
</tr>
<tr>
<td>RECLAIMED</td>
<td>189</td>
<td>41</td>
<td>$288</td>
</tr>
<tr>
<td>GAS DIST</td>
<td>155</td>
<td>39</td>
<td>$336</td>
</tr>
<tr>
<td>TELECOM</td>
<td>149</td>
<td>67</td>
<td>$455</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td><strong>$1,541</strong></td>
</tr>
</tbody>
</table>

Tables and Figures 8.1 and 8.2, detail the configuration determined as optimal by the heuristic the ICS respectively.

Table 8.2: Optimal Solution Determined By The ICS

<table>
<thead>
<tr>
<th>UTILITY #</th>
<th>HORIZ [in]</th>
<th>DEPTH [in]</th>
<th>COST [k$/mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER DIST</td>
<td>212</td>
<td>40</td>
<td>$463</td>
</tr>
<tr>
<td>RECLAIMED</td>
<td>153</td>
<td>41</td>
<td>$258</td>
</tr>
<tr>
<td>GAS DIST</td>
<td>177</td>
<td>62</td>
<td>$425</td>
</tr>
<tr>
<td>TELECOM</td>
<td>178</td>
<td>38</td>
<td>$335</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td><strong>$1,480</strong></td>
</tr>
</tbody>
</table>

Figure 8.2: Optimal Configuration Determined By The ICS
Table 8.3 shows the top 10 near optimal solutions determined by the ICS (all cheaper than that determined by the heuristic), highlighting the problem of lack of refinement in the heuristic’s results and the associated refinement benefits of using the ICS.

Table 8.3: List Of 10 Optimal Solutions Determined By The ICS

<table>
<thead>
<tr>
<th>CONFIGURATION RANKING</th>
<th>CONFIGURATION NUMBER</th>
<th>OPTIMAL TOTAL COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>964</td>
<td>1480.42</td>
</tr>
<tr>
<td>2</td>
<td>967</td>
<td>1481.08</td>
</tr>
<tr>
<td>3</td>
<td>3697</td>
<td>1481.09</td>
</tr>
<tr>
<td>4</td>
<td>3699</td>
<td>1481.75</td>
</tr>
<tr>
<td>5</td>
<td>18967</td>
<td>1481.75</td>
</tr>
<tr>
<td>6</td>
<td>18969</td>
<td>1482.41</td>
</tr>
<tr>
<td>7</td>
<td>12644</td>
<td>1484.23</td>
</tr>
<tr>
<td>8</td>
<td>12645</td>
<td>1484.89</td>
</tr>
<tr>
<td>9</td>
<td>5695</td>
<td>1485.11</td>
</tr>
<tr>
<td>10</td>
<td>5696</td>
<td>1485.77</td>
</tr>
</tbody>
</table>

3. **Customization of Output:** The optimization routine in the heuristic compares the total costs of all the feasible configurations to determine an optimal solution. However, when several configurations have the same total costs the routine selects either the first or the last configuration depending on the program code. The single objective nature of the heuristic produces outputs (utility configurations) which aren’t very
flexible, that is, they can not be adapted to specific requirements. The ICS implements a multi objective utility configuration assessment and selection procedure which firstly eliminates the ambiguity from the output determination and presents the user (decision maker) with the option of customizing the outputs. The user can select and weigh the characteristics that he or she is looking for in a configuration for a particular ROW corridor. For example:

a. **Better Utilization of Corridor Space**: If the user (decision maker) is designing a ROW corridor which will be upgraded by addition of new utilities, he will obviously want to implement the best possible (safe and economically efficient) utility configuration which utilizes the least amount of corridor space to facilitate future expansions. With the ICS, the user can select and emphasize the importance of this characteristic, to customize the heuristic’s output.

Table 8.4 and Figure 8.3 details the configuration determined by the ICS for best corridor space utilization. The space utilized by this configuration is just 20.99% of the total available corridor space.

Table 8.4: Solution Determined By The ICS For The Best Corridor Space Utilization

<table>
<thead>
<tr>
<th>UTILITY #</th>
<th>HORIZ [in]</th>
<th>DEPTH [in]</th>
<th>COST [k$/mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER DIST</td>
<td>212</td>
<td>40</td>
<td>$463</td>
</tr>
<tr>
<td>RECLAIMED</td>
<td>189</td>
<td>41</td>
<td>$288</td>
</tr>
<tr>
<td>GAS DIST</td>
<td>213</td>
<td>68</td>
<td>$492</td>
</tr>
<tr>
<td>TELECOM</td>
<td>192</td>
<td>67</td>
<td>$485</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>$1,727</strong></td>
</tr>
</tbody>
</table>
b. Better Positioning Flexibility for Utilities: If corridor space is not a constraint, and the user wants to reduce the installation costs and avoid the hassles of accurate positioning of utilities in the corridor, he has the option of selecting a configuration which has high positioning flexibilities for its constituent utilities by weighing the utility flexibility option accordingly.

Table 8.5 and Figure 8.4 details the configuration determined by the ICS for highest flexibility in utility positioning. The average flexibility coefficient for this configuration was 0.24 which indicates an average of 6 steps of flexibility for each utility with less than 10% increase in individual costs.

Table 8.5: Solution Determined By The ICS For Flexibility In Utility Positioning

<table>
<thead>
<tr>
<th>UTILITY #</th>
<th>HORIZ [in]</th>
<th>DEPTH [in]</th>
<th>COST [k$/mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER DIST</td>
<td>204</td>
<td>40</td>
<td>$467</td>
</tr>
<tr>
<td>RECLAIMED</td>
<td>152</td>
<td>57</td>
<td>$300</td>
</tr>
<tr>
<td>GAS DIST</td>
<td>213</td>
<td>62</td>
<td>$455</td>
</tr>
<tr>
<td>TELECOM</td>
<td>178</td>
<td>39</td>
<td>$336</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>$1,559</td>
</tr>
</tbody>
</table>
c. *Balance / Fairness in Utility Costs*: If the user requires a configuration which is economically fair to all utility companies (a major requirement with utility companies), selecting and weighing the balance cost option assesses and determines the best solution with the most balance in individual costs.

Table 8.6 and Figure 8.5 details the configuration determined by the ICS for economic fairness to all utility. The balance coefficient determined for this configuration is 0.77 which indicates that the maximum variation of the individual cost of the utilities of this configuration is 77% from their minimum possible individual costs.

**Table 8.6: Solution Determined By The ICS For Fairness In Individual Utility Costs**

<table>
<thead>
<tr>
<th>UTILITY #</th>
<th>HORIZ [in]</th>
<th>DEPTH [in]</th>
<th>COST [k$/mi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER DIST</td>
<td>211</td>
<td>59</td>
<td>$532</td>
</tr>
<tr>
<td>RECLAIMED</td>
<td>153</td>
<td>41</td>
<td>$258</td>
</tr>
<tr>
<td>GAS DIST</td>
<td>213</td>
<td>39</td>
<td>$366</td>
</tr>
<tr>
<td>TELECOM</td>
<td>178</td>
<td>57</td>
<td>$393</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>$1,549</td>
</tr>
</tbody>
</table>
Figure 8.5: Configuration Determined By The ICS For Fairness In Individual Utility Costs

4. **Substantiation of Results**: The ICS performs a sensitivity / criticality analysis of the importance weights assigned by the user (decision maker) to the desired configuration characteristics. This analysis is conducted on the 10 top ranked solutions to provide the user with useful information on other configurations that nearly meet his requirements.

Table 8.7: Top 10 Configuration Obtained With The ICS

<table>
<thead>
<tr>
<th>CONFIG. RANKING</th>
<th>CONFIG. NUMBER</th>
<th>OPTIMAL TOTAL COSTS</th>
<th>BALANCED INDIVIDUAL COSTS</th>
<th>PERCENTAGE SPACE UTILIZED</th>
<th>UTILITY POSITIONAL FLEXIBILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18865</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>19720</td>
<td>1512.41</td>
<td>0.91</td>
<td>32.72</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>28680</td>
<td>1486.43</td>
<td>0.91</td>
<td>35.19</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>5696</td>
<td>1587.81</td>
<td>0.89</td>
<td>38.07</td>
<td>0.24</td>
</tr>
<tr>
<td>5</td>
<td>19719</td>
<td>1485.77</td>
<td>0.91</td>
<td>35.19</td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>23225</td>
<td>1546.40</td>
<td>0.91</td>
<td>32.72</td>
<td>0.28</td>
</tr>
<tr>
<td>7</td>
<td>28679</td>
<td>1562.18</td>
<td>0.77</td>
<td>38.48</td>
<td>0.28</td>
</tr>
<tr>
<td>8</td>
<td>28907</td>
<td>1621.23</td>
<td>0.89</td>
<td>38.07</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Table 8.7 (Continued)

<p>| | | | | | |</p>
<table>
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<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>9</td>
<td>28906</td>
<td>1595.60</td>
<td>0.77</td>
<td>38.48</td>
<td>0.28</td>
</tr>
<tr>
<td>10</td>
<td>16535</td>
<td>1611.05</td>
<td>1.05</td>
<td>33.13</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Table 8.8: Sensitivity / Criticality Of The Results

<table>
<thead>
<tr>
<th>CRITICALITY BETWEEN</th>
<th>WEIGHT FOR OPTIMAL TOTAL COSTS</th>
<th>WEIGHT FOR BALANCED INDIVIDUAL COSTS</th>
<th>WEIGHT FOR PERCENTAGE SPACE UTILIZED</th>
<th>WEIGHT FOR UTILITY POSITIONAL FLEXIBILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 AND 2</td>
<td>93.56</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 3</td>
<td>98.14</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 4</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 5</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 6</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 7</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>1 AND 8</td>
<td>98.70</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
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<tr>
<td>1 AND 9</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
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<tr>
<td>1 AND 10</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
<td>NF</td>
</tr>
<tr>
<td>SENSITIVITY</td>
<td>0.010688</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8.8 details the criticality between the output configurations detailed in Table 8.7. An increase of 93.56% in the weights assigned to the optimality criterion will cause the rankings between configurations 1 and 2 to change. The sensitivity of the result to the optimality characteristic is 0.01. The sensitivity of the output to the other characteristics is zero which indicates that changing the importance weights for these characteristics will not change the result.
8.2 General Conclusions

*Multi Criteria Decision Making* has been one of the fastest growing problem areas during the last two decades. In business, decision making has changed from a single (the Boss!) and single criteria (profit), decision environment to a multi person and multi criteria situation. For problems with discrete decision spaces, i.e. with countable few decision alternatives, the Weighted Product Model (WPM) is very useful for making justifiable decisions. What makes this technique so valuable is that even though the analyses are very rigorous, the results are described very clearly and are understandable even to non specialists.
CHAPTER 9  
FUTURE WORK

‘Uncertainty is not an accident of the scientific method, but its substance.’

The ongoing research project titled, “Optimal Placement of Utilities within FDOT Right-of-Way”, sponsored by the Florida Department of Transportation (FDOT), and currently being investigated at the University of South Florida [6], presents a decision-making heuristic aimed at developing a safe and economically efficient utility placement allocation system for transportation ROW corridors.

When a model is used to drive a choice or a decision, it becomes imperative to assess the importance of its associated uncertainties to ensure its relevance and guarantee the validity of its outputs. The above mentioned heuristic finds suitable (optimal cost) locations for the utilities in the ROW corridors with the help of utility cost assessment models while adhering to the rules and regulations of safety, relocation, and clearance for utility placement set by AASHTO. From this it is obvious that the cost assessment models and the AASHTO utility placement rules heavily influence the outcome of the heuristic.

This thesis, has partly analyzed the uncertainties associated with the input factors affecting the cost assessment models of the heuristic. The following uncertainties and questions still need to be evaluated to complete the analysis of the heuristic.
9.1 Sensitivity Analysis Of The AASHTO Utility Placement Rules

The rules for utility placement (utility clearance, stacking, and safety) are set by the AASHTO to ensure overall safety of the utilities placed within the ROW corridor. While the rules are well defined, their applicability is subject to a variety of interpretations, giving rise to doubts and uncertainties. For example,

a. Mandatory clearance required between utilities (varying with types) is defined in terms of inches, horizontally and vertically. However how this clearance is to be implemented is subject to interpretation. Question like,
   - Do you consider a rectangular, circular or elliptical boundary? and
   - What are the cost ramifications of considering different types of boundaries? need to be answered.

b. Placement of utilities very close to the pavement poses problems of disruption to traffic and increased possibility of accidents. The AASHTO utility placement rules defines a clear zone starting from the edge of the pavement within which no utility can be placed. However it would be interesting to determine:
   - The cost ramifications of implementing such a constraint.
   - The optimal extent for a clear zone.

c. Mandatory no stacking rules are applied to certain utilities. The rule for stacking again is open for interpretation. Questions like:
   - How do you define a no stacking boundary?
   - What is the cost ramifications of a no stacking constraint applied to a utility? need to be assessed.
9.2 Development Of The Damage Model

The data available on damage events is not very accurate and hence a simple linear damage model is used in the heuristic to estimate damage costs associated with a utility. The model assumes that the number of accidental damage incidents is proportional to the expected number of access events and that excavating to conduits buried deep within a corridor will more likely result in damage to the utility itself and other utilities in the corridor. While these are all valid assumptions the following issues raise serious doubts about the validity of the model.

a. The probability of damage not only depends on the depth of location and frequency of access to a utility but also on the presence, nature (type) and location (proximity) of other utilities within the corridor.

b. A linear model varying with depth might not fully represent the damage cost of a utility because damaging utility line at any depth should essentially cost the same.

c. The assumption of fraction of events resulting in damage incidents, arbitrarily taken as 1% in the damage model would be better modeled as distribution derived from better data.
REFERENCES

Civil & Transportation


Sensitivity Analysis


**Multi-Objective / Criteria Decision Making**


Bibliography


General


APPENDICES
Appendix A: Variance Sensitivity Indices (SOBOL' 1990b)

The method adopted for the sensitivity studies on the factors of the heuristic is a variance based technique, also called ANOVA (analysis of variances) like sensitivity method.

Let \( f(x) \) denote the model function where \( x = (x_1, \ldots, x_n) \) is the set of input variables, and, let \( I \) denote the unit interval \([0,1]\), \( I^n \) – the input factor space as an \( n \)-dimensional unit hypercube and \( x \in I^n \).

The integrable function can be defined as,

\[
\sum_{s=1}^{n} \sum_{i_1 < \ldots < i_s} f_{i_1, \ldots, i_s} (x_{i_1}, \ldots, x_{i_s})
\]

Where, the interior sum is over all sets of \( s \) integer’s \( i_1, \ldots, i_s \), that satisfy \( 1 \leq i_1 < \ldots < i_s \leq n \).

Formula (1) means that

\[
f(x) = f_0 + \sum_{i=1}^{n} f_i (x_i) + \sum_{1 \leq i < j \leq n} f_{ij} (x_i, x_j) + \ldots + f_{12\ldots n} (x_1, x_2, \ldots, x_n)
\]

The idea used by SOBOL was to decompose the function \( f(x) \) into summands of increasing dimensionality. The general decomposition of equation (1) is non informative, and for equation (1) to hold, \( f_0 \) must be constant and the integrals of every summands over any of its own variables must be zero.

\[
\int_{0}^{1} f_{i_1, \ldots, i_s} (x_{i_1}, \ldots, x_{i_s}) dx_{i_s} = 0 \quad \text{for} \quad k = i_1, \ldots, i_s
\]

130
Appendix A (Continued)

Equation (1) satisfying equation (2) is called decomposition into summands of different dimensions. In this case each member $f_{i_1, \ldots, i_s}$ is responsible for the joint distribution of the variables $X_{i_1}, \ldots, X_{i_s}$ to the variability of $f(x)$ in $I^n$.

The integrals below are as a rule from 0 to 1 for each variable and $dx = dx_1 \ldots dx_n$.

Integrating equation (1) over $I^n$ we obtain

$$\int f(x)dx = f_0$$

Integrating equation (1) over all variables except $x_i$ we obtain

$$\int f(x) \prod_{k \neq i} dx_k = f_0 + f_i(x_i)$$

thus define $f_i(x_i)$. Similarly, integrating (1) over all variables except $x_i$ and $x_j$ we obtain

$$\int f(x) \prod_{k \neq i, j} dx_k = f_0 + f_i(x_i) + f_j(x_j) + f_{ij}(x_i, x_j)$$

and define $f_{ij}(x_i, x_j)$. We continue the procedure until all $(n-1)$ dimensional summands are defined, and then the last member $f_{12, \ldots, n}(x_1, x_2, \ldots, x_n)$ is found from identity (1).

Since $f(x)$ is a square integral, so are all the $f_{i_1, \ldots, i_s}$, therefore constants

$$V_{i_1, \ldots, i_s} = \int f_{i_1, \ldots, i_s}^2(x_{i_1}, \ldots, x_{i_s})dx_{i_1} \ldots dx_{i_s}$$

called ‘partial variances’ can be introduced as well as the ‘total variance’ $V$ of $f(x)$.
Appendix A (Continued)

\[ V = \int f^2(x)dx - f_0^2 \]

Squaring equation (1) and integrating over \( I^n \) we obtain

\[ V = \sum_{s=1}^{n} \sum_{i_1 < \ldots < i_s}^{n} V_{i_1 \ldots i_s} \]

This means,

\[ V = \sum_{i=1}^{n} V_i + \sum_{1 \leq i < j \leq n} V_{ij} + \ldots + V_{1,2,\ldots,n} \quad (3) \]

The origin of this term is clear if \( x \) were a random point uniformly distributed \( I^n \), then \( f(x) \) and all \( f_{i_1,\ldots,i_s}(x_{i_1},\ldots,x_{i_s}) \) would be random variables, and \( V \) and \( V_{i_1\ldots i_s} \) their variances. The term ANOVA comes from Analysis of Variances.

The ratios \( S_{i_1\ldots i_s} = \frac{V_{i_1\ldots i_s}}{V} \) are called sensitivity indices for \( 1 \leq i_1 < \ldots < i_s \leq k \).

The indices are non-negative and their sum is 1.

\[ \sum_{i=1}^{n} S_i + \sum_{1 \leq i < j \leq n} S_{ij} + \ldots + S_{1,2,\ldots,n} = 1 \]

\( S_i \) is called the first order sensitivity index for factor \( x_i \), which measures the main effect of \( x_i \) on the output. \( S_{ij} \) for \( i \neq j \) is called the second order sensitivity index which measure the interaction effect of the variation in \( f(x) \) due to \( x_i \) and \( x_j \).
Appendix B: Standard Utility Placement Experiments

The sensitivity studies conducted on the heuristic involve running the standard utility placement experiments, using ‘nominal’ values for the setup factors. Two extreme values are proposed to represent the range of likely values for each setup factor and the nominal value is taken midway between the two extremes values. The initial setup for the standard experiments is shown in Tables B.1.

Table B.1: Standard Utility Placement Experiments Initial Setup

<table>
<thead>
<tr>
<th>INPUT PARAMETERS / FACTORS</th>
<th>UNITS</th>
<th>NOMINAL VALUE</th>
<th>RANGE</th>
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<tr>
<td>Right of Way Width</td>
<td>Ft.</td>
<td>18</td>
<td>12 - 40</td>
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<tr>
<td>Maximum Depth</td>
<td>Inches</td>
<td>72</td>
<td>120</td>
</tr>
<tr>
<td>Number of Initial Lanes</td>
<td>#</td>
<td>2</td>
<td>2 - 6</td>
</tr>
<tr>
<td>Lane Width</td>
<td>Ft.</td>
<td>12</td>
<td>12 - 15</td>
</tr>
<tr>
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<td>Years</td>
<td>20</td>
<td>10 - 50</td>
</tr>
<tr>
<td>Design Year Average Daily Traffic</td>
<td>K Cars / Day</td>
<td>20</td>
<td>5 - 40</td>
</tr>
<tr>
<td>Design Year</td>
<td>Years</td>
<td>10</td>
<td>1 - 20</td>
</tr>
<tr>
<td>Design Speed</td>
<td>MPH</td>
<td>50</td>
<td>30 - 75</td>
</tr>
<tr>
<td>Default Cover</td>
<td>Inches</td>
<td>36</td>
<td>24 - 48</td>
</tr>
<tr>
<td>Traffic Growth Rate</td>
<td>%</td>
<td>10</td>
<td>0 - 20</td>
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</table>
Appendix B (Continued)

The utilities considered for placement in the standard experiment 1 are:

Table B.2: Standard Utility Placement Experiment 1

<table>
<thead>
<tr>
<th>UTILITY TYPE</th>
<th>DIA.</th>
<th>STACK</th>
<th>AG DIA.</th>
<th>AG FAC.</th>
<th>#/MILE</th>
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</thead>
<tbody>
<tr>
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<td>6</td>
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<td>POTABLE</td>
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<td>0</td>
<td>NO</td>
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<td>NO</td>
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</table>

The utilities considered for placement in the standard experiment 2 are:

Table B.3: Standard Utility Placement Experiment 2

<table>
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<tr>
<th>UTILITY TYPE</th>
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<th>STACK</th>
<th>AG DIA.</th>
<th>AG FAC.</th>
<th>#/MILE</th>
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<tr>
<td>POWER DIST</td>
<td>8</td>
<td>NO</td>
<td>4</td>
<td>CYLINDER</td>
<td>2</td>
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<td>RECLAIMED</td>
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<td>GAS DIST</td>
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<td>0</td>
</tr>
<tr>
<td>TELECOM</td>
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<td>NO</td>
<td>0</td>
<td>NO</td>
<td>0</td>
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</tbody>
</table>
### Appendix C: Analysis Of Variances Tables

Table C.1: Analysis Of Variances (ANOVA) Of Accident Model Factors

<table>
<thead>
<tr>
<th>SOURCE OF VARIATION</th>
<th>DF</th>
<th>ADJ. S.S.</th>
<th>ADJ. M.S.</th>
<th>F</th>
<th>P</th>
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<td>30716300000</td>
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</tr>
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<td>17056602</td>
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<td>58703333333</td>
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</tr>
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<td>6975730807</td>
<td>10066.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Design Year &amp; Design Speed</td>
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<td>7067618940</td>
<td>336553283</td>
<td>485.7</td>
<td>0.00</td>
</tr>
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<td>177945145</td>
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<td>12</td>
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<td>0</td>
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<td>1.00</td>
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### Table C.1 (Continued)

<table>
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<tbody>
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<td>13703285</td>
<td>19.8</td>
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<td>1137107</td>
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<td>0.24</td>
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<td>0.00</td>
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<td>4120132</td>
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<td>0.39</td>
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<td>14120184425</td>
<td>1176682035</td>
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<td>692941</td>
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<td>Total</td>
<td>92159</td>
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Appendix C (Continued)

Table C.2: Analysis Of Variances (ANOVA) Of Damage Model Factors

<table>
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<tr>
<th>SOURCE OF VARIATION</th>
<th>DF</th>
<th>ADJ. S.S.</th>
<th>ADJ. M.S.</th>
<th>F</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>Maximum Damage</td>
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<td>8079341</td>
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<td>Default Cover</td>
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<td>Maximum Depth</td>
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<td>1822891</td>
<td>182289</td>
<td>5622.2</td>
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<tr>
<td>Damage Fraction</td>
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<td>5508641</td>
<td>612071</td>
<td>18877.5</td>
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</tr>
<tr>
<td>Maximum Damage &amp; Default Cover</td>
<td>60</td>
<td>5379</td>
<td>90</td>
<td>2.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Maximum Damage &amp; Maximum Depth</td>
<td>100</td>
<td>729156</td>
<td>7292</td>
<td>224.9</td>
<td>0.00</td>
</tr>
<tr>
<td>Maximum Damage &amp; Damage Fraction</td>
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<td>2203457</td>
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<td>Default Cover &amp; Maximum Depth</td>
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Table C.3: Analysis Of Variances (ANOVA) Of Installation Surcharge Model Factors

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<th>SOURCE OF VARIATION</th>
<th>DF</th>
<th>ADJ. S.S.</th>
<th>ADJ. M.S.</th>
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<td>873494</td>
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<td>1846753</td>
<td>184675</td>
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### Table C.3 (Continued)

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<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
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</thead>
<tbody>
<tr>
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<td>9032</td>
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<td>0.000</td>
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<tr>
<td>Shoring Surcharge &amp; Inconvenience Surcharge</td>
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<td>409</td>
<td>0.4</td>
<td>1.000</td>
</tr>
<tr>
<td>Inconvenience Surcharge Region &amp; Inconvenience Surcharge</td>
<td>30</td>
<td>219873</td>
<td>7329</td>
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<td>0.000</td>
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<tr>
<td>Error</td>
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Appendix D: Configuration Differentiation And Clustering Techniques

The Ideal Configuration Selector uses two experimental techniques namely the Cost Dot Technique (CDT) and the Metric to differentiate between and cluster (group) configurations into shape sets based on similarity in orientation.

D.1 Cost Dot Technique (CDT)

The Cost Dot Technique uses the individual cost of the utilities for quantifying the difference between configurations. The idea used in the CDT is that any feasible configuration has \( N \) utilities with individual costs. Since the individual cost of a utility is a direct function of its location within the ROW, the individual cost of utilities can be used to differentiate between two configurations.

The CDT employs the individual costs of the utilities in a configuration as vector coefficients. The correlation between the vectors of two configurations is taken as the measure of the difference between those two configurations. The correlation is calculated as the dot product of those two vectors.

Consider an example with 3 utilities, if the individual utility costs of the \( 0^{th} \) configuration are \((C_{o1}, C_{o2}, C_{o3})\) and the individual utility costs of the \( i^{th} \) configuration are \((C_{i1}, C_{i2}, C_{i3})\), the coefficients for the first configurational vector will be,

\[
\left( \frac{C_{o1}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}}, \frac{C_{o2}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}}, \frac{C_{o3}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \right)
\]

and the vector will be represented as,
Appendix D (Continued)

\[
\overline{C}_o = \frac{C_{o1}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \overline{i} + \frac{C_{o2}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \overline{j} + \frac{C_{o3}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \overline{k}
\]

The coefficient for the \(i^{th}\) configurational vector will be,

\[
\left( \frac{C_{i1}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}}, \frac{C_{i2}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}}, \frac{C_{i3}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} \right)
\]

and the vector will be,

\[
\overline{C}_i = \frac{C_{i1}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} \overline{i} + \frac{C_{i2}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} \overline{j} + \frac{C_{i3}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} \overline{k}
\]

The correlation coefficient or Cost Dot Coefficient (CDC) is calculated as the dot product of the two vectors which is,

\[
\text{CDC} = \overline{C}_o \cdot \overline{C}_i = \frac{C_{o1}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \times \frac{C_{i1}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} + \frac{C_{o2}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \times \frac{C_{i2}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}} + \frac{C_{o3}}{\sqrt{C_{o1}^2 + C_{o2}^2 + C_{o3}^2}} \times \frac{C_{i3}}{\sqrt{C_{i1}^2 + C_{i2}^2 + C_{i3}^2}}
\]

The range of the Cost Dot Coefficient is between 0 and 1. Similar orientation configurations have equal cost dot coefficients.
Appendix D (Continued)

D.2 The Metric

The metric quantifies the difference between two configurations with the help of the positional coordinates of the utilities. The idea is that any feasible solution can be identified as a 2N vector, describing the configuration of N utilities with x and y coordinates. The difference between two configurations (i.e. the Metric value $M_{oi}$) is quantified by the “sum of the square of differences” method, represented in the equation below and depicted in Figure D.1.

$$M_{oi} = \sum_{j=1}^{N} (x_{ij} - x_{oj})^2 + (y_{ij} - y_{oj})^2$$

Figure D.1: Quantifying Configurational Differences Using The Metric
Appendix D (Continued)

The Ideal Configuration Selector (ICS) applies the Metric to the orientation clustering process after shape (orientation) set have been determined by the Cost Dot Technique. The Metric helps determine configurations of different orientation having similar individual costs for their constituent utilities, a rare occurrence which is not identified by the CDT. Configurations varying by more than a 1000 metric value points are considered to be configurationally different. The functioning of the Cost Dot Technique and the Metric for differentiating between configurations is demonstrated for the configurational sweep search results shown in Figures D.2 and Figure D.3.

Figure D.2: Cost Dot And Metric Value Plots For Differentiating Between Configurations In A 3 Utility Step Size Sweep

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Figure D.2 illustrates the configurational difference in the optimal solutions obtained using different step sizes in the analysis. Optimal configuration obtained for step sizes 0.3 and 0.5 are similar, so are the configurations for step size 0.4 and 0.8, 0.2 and 0.7, 0.6 and 0.9. Figure D.3 shows configurations with step size 0.3, 0.5 and 0.8 are similar using the CDT. The need for the Metric in the ICS’s clustering process is highlighted with the identification of an orientationally different configuration for step size 0.5, not detected by the CDT.
Appendix E: Jiggle Sensitivity Tool (JST)

The Jiggle Sensitivity Tool is a program employed in the Ideal Configuration Selector to jiggle (move) the utilities of a configuration by finite steps in specified directions (up, down, to the left and to the right) as shown in Figure E.1 while monitoring the following,

1. The percentage change in the individual cost of a jiggled utility represents the positional sensitivity of that utility within the configuration and,

\[
\text{Positional Sensitivity}_j = \frac{\text{Percentage Individual Cost Change}}{\text{Utility Positional Change}} = \frac{\% (\Delta IC)}{\Delta (x_j) \text{ or } \Delta (y_j)}
\]
Appendix E (Continued)

2. The percentage change in the total cost of the configuration with the jiggling of a utility is the configurational sensitivity of the configuration with respect to that particular utility.

\[
\text{(Configurational Sensitivity)}_j = \frac{\text{Percentage Total Cost Change}}{\text{Utility Positional Change}} = \frac{\%(\Delta TC)}{\Delta(x_j) \text{ or } \Delta(y_j)}
\]

3. The validity of the movement of each utility at every jiggled step for,
   a. Violations to the clearance boundaries of other utilities.
   b. Violations to the ROW corridor boundaries (i.e. ROW width, maximum depth, and default cover).
   c. Violations to utility placement constraints (clear zone, below pavement, and stacking).