CHAPTER 5–MULTI-CRITERIA DECISION ANALYSIS SOFTWARE

INTRODUCTION

Through quantitative evaluation of the data and information compiled in the literature review and survey, an explicitly defined list of alternatives and decision criteria to evaluate rehabilitation alternatives was developed for culverts 122 centimeter (48 inch) in diameter or smaller. Relative weights of each criterion were assigned in comparison to the defined alternatives, thereby allowing a dynamic interaction between criteria and alternatives as the decision maker varies preferences. Results were input into a Microsoft® Excel workbook. Using a Multi-Criteria Decision Analysis (MCDA) technique, the user-friendly workbook minimizes the cognitive effort of the decision maker. An MCDA workbook allows the user to customize the decision aid model to a situation to select the appropriate culvert-lining method. A simplified graphical representation of the successive decision analysis steps was provided in the form of a user flow chart in the Microsoft® Excel workbook. Development of the MCDA was assisted by Dr. Darrell G. Fontane, Professor, CSU.

BACKGROUND

Often engineers are faced with making a choice among various options. The selection of the most appropriate culvert-rehabilitation technique is a good example of this. If the only consideration were cost, economic principles could be used to guide our selection. However, the choice of a culvert-rehabilitation strategy involves costs and non-economic measures such as structural integrity provided. In general, the considerations might include both quantitative and qualitative measures. In such cases, a process must be used to approximately "quantify" all measures on a similar, numerical scale so that mathematical calculations can be performed. Initially, the scope of Task 2 encompassed building a decision tree for determination of a trenchless-technology technique for culvert rehabilitation. Decision trees are useful tools for well-defined problems but are limited in the ability of providing decision guidelines. For example, a designer could use a decision tree to determine an alternative that provides the greatest cost benefit or the greatest structural integrity, but would be restricted in determining an outcome if both guidelines were of equal importance. For the decision problem presented by the FHWA, a more sophisticated method of decision-making was needed. Multi-Criterion Decision Analysis is a numerical process to compare or "score" alternatives on a comparable scale.

MCDA is a systematic process used for analyzing discrete decision problems where the circumstances are not clearly defined. MCDA is based on the concept of deriving an overall score for the decision option, or alternative, being analyzed. A primary advantage to MCDA is the provision of a highly structured decision-making technique. Within a decision problem, objectives (criteria) are used to evaluate the performance of an alternative. The decision maker defines the relative importance factors of criteria as they pertain to a specific project. Relative importance factors are numerical representations of the preference of the decision maker, commonly based on background information and experience. MCDA provides a numerical score, or rating, assigned to a given alternative with respect to each criterion. In decision-making scenarios there may exist disagreement between varying decision makers as to the relative importance given to criteria. It is possible, with MCDA techniques, to easily examine many scenarios and provide simple tools for comparison. Various combinations of relative importance factors can be examined, determining new alternative rankings. By developing a Microsoft® Excel-based MCDA tool, the user is provided with a method to document and audit the various decision-making processes. In the Excel workbook, the decision-making process is an iterative procedure that can easily be adapted to illustrate new situations or include additional information.

MCDA DEVELOPMENT

Determination of Relevant Criteria and Alternatives

In the scope of work defined by the FHWA, one task was to develop a methodology providing ease of determination of culvert rehabilitation through trenchless-technology techniques. Understanding of these techniques was furnished in the literature compilation, providing a setting within which the problem could be solved. CSU, in conjunction with the FHWA, developed a list of inputs, alternatives, and criteria to serve as the basis of the MCDA process. Selection of criteria was based on information gathered during the literature review pertaining to the characteristics of trenchless-technology techniques that allowed judgment of performance of one alternative in comparison to another. Criteria allow the decision maker to adapt the scenario to personal preference. Inputs were chosen for their ability to provide field-evaluation tools that tailor the MCDA workbook to the specific decision-making situation. Each trenchless-technology technique included in the decision-making process is deemed an alternative solution to the problem. In order to provide the specificity required to individualize a given scenario, each alternative was evaluated within the context of the model inputs. Inputs, presented below, provide evaluation tools specific to alternative attributes in the context of the decision-making model:

1. Length of existing culvert
2. Diameter of existing culvert
3. Diameter change or discontinuity within the existing culvert
4. Structural integrity of existing culvert

Limitations of alternatives used in development of the MCDA, in the context of user inputs, are presented in Table 50. During alternative analyzation, it became apparent that information pertaining to several alternatives was incomplete specific to the culvert characteristics under examination. Table 50 does not include swagelining/drawdown and rolldown methods, which were originally investigated in the literature review, due to the deficient information. Reasons for the exclusion of the swagelining/drawdown and rolldown methods are explained in the following section.

Table 50. Alternative Limitations of Model Inputs.

Input	Alternative								
	Sliplining		Close-fit lining		Spirally wound lining	Cured-in-place lining		Spray-on lining	
	Segmental Method	Continuous Method	Deformed/ Reformed Method	Fold and Form Method		Inversion Method	Pulled-in-place Method	Cement-mortar System	Epoxy System
Applicable Length	< 300 m[1] (985 ft)[2]	< 300 m (985 ft)	< 800 m (2,625 ft)	< 210 m (689 ft)	< 300 m (985 ft)	< 900 m (2,955 ft)	< 150 m (495 ft)	< 450 m (1,475ft)	< 450 m (1,475 ft)
Diameter Limitation	7.6-122 cm[3] (3-48 in.)[4]	10-122 cm (4-48 in.)	10-40.6 cm (4-16 in.)	10-61 cm (4-24 in.)	10-122 cm (4-48 in.)	10-122 cm (4-48 in.)	10-122 cm (4-48 in.)	7.6-122 cm (3-48 in.)	7.6-122 cm (3-48 in.)
Diameter Change/ Discontinuity	Severe Prohibits[5]	Severe Prohibits	Allowable	Allowable	Allowable	Allowable	Allowable	Allowable	Allowable
Structural Integrity	RI[6]	RI	NA[7]	NA	RI	RI	RI	DE[8]	DE

[1]m – meter, [2]ft – feet, [3]cm – centimeters, [4]in. – inches, [5]Prohibits – Existence of prohibits the use, [6]RI – Restores structural integrity, [7]NA – Not applicable to structurally deteriorated culverts, [8]DE – Does not enhance structural integrity

Alternative attributes were then analyzed in the context of the predetermined criteria. Criteria were intended to provide a tool for determining the user-established preference in relation to the alternatives. Evaluation of alternative attributes in the context of the criteria proved to have elements of uncertainty and imprecision. Analysis was anticipated to provide sufficient information to quantitatively weigh each alternative within the context of each criterion. Criteria used for analysis were:

1. Design life of lining method
2. Capacity reduction of the existing culvert after installation
3. Resistance to abrasion and corrosion of lining method
4. Time required for installation
5. Requirement for flow bypass of the flow during installation
6. Extent of digging required during installation

7. Cost of lining method
8. Safety of crew during installation
9. Existence of water quality concerns after installation of lining

Examination of alternatives, in the context of model inputs and analysis criteria, suggested that insufficient information applicable to the culvert rehabilitation decision-making process was available for several alternatives. Swagelining/drawdown and rolldown methods were eliminated from the decision-making model because limited information was available on cost of installation. In addition, insufficient information was available on installation details such as safety of workers during installation and amount of required digging for installation.

The final culvert lining alternatives incorporated into the MCDA model were:

1. Segmental Sliplining
2. Continuous Sliplining
3. Close-fit Lining Deformed/Reformed
4. Close-fit Lining Fold and Form;
5. Spirally Wound Lining
6. Cured-in-place pipe Lining, Inversion
7. Cured-in-place pipe Lining, Pulled-in-place
8. Spray-on lining, Cement-mortar
9. Spray-on lining, Epoxy

Alternative Ratings

Using information obtained during the literature review and survey, alternatives were rated to allow the MCDA to identify how well an alternative satisfies a criterion. Rating scales were developed for each criteria dependant of the variability of the alternatives. Range of the rating scales was arbitrary, rating scales needed only to appropriately reflect the differences among alternatives. Operation of the MCDA is based on a predetermined set of alternative ratings. A summary of the alternative ratings used in the MCDA is presented in Table 51.

Table 51. Alternative Rating Scales.

Criteria	Alternative								
	Sliplining		Close-fit lining		Spirally Wound Lining	Cured-in-place lining		Spray-on lining	
	Segmental Method	Continuous Method	Deformed/ Reformed Method	Fold and Form Method		Inversion Method	Pulled-in-place Method	Cement-mortar System	Epoxy System
Design Life	4	4	4	3	3	5	5	1	2
Capacity Reduction	2	2	5	5	5	5	5	4	4
Abrasion and Corrosion Resistance	3	3	3	4	4	4	4	1	2
Installation Time	5	3	3	3	4	2	2	1	1
Flow Bypass Requirements	4	4	1	3	4	1	1	1	1
Digging Requirements	5	1	3	3	3	2	2	5	5
Cost	4	4	3	3	2	1	1	5	5
Safety	4	3	3	3	3	3	3	5	5
Environmental Concerns	4	4	3	3	4	1	1	1	1

Design Life

Design life was rated based on the design life of the common liner materials presented in the literature review. Design life of the material used in the nine alternatives included in the decision analysis ranged from 20 to 100 years. The spray-on lining cement-mortar system had the shortest design life and the cured-in-place inversion installation methods had the longest. Presented below is the rating scale for the design life criterion:

100 years	5
75 years	4
50 years	3
30 years	2
20 years	1

Capacity Reduction

Each alternative was rated based on the reduction of the capacity of the culvert after installation of the liner. Capacity reduction was fairly significant for the two (2) sliplining methods, while the other methods produced minimal to almost zero reduction. Presented below is the rating scale for capacity reduction:

Significant	1
Potential	3
Minimal	5

Abrasion and Corrosion Resistance

Abrasion and corrosion resistance was rated on the ability of the common liner materials presented in the literature review to resist corrosion and abrasion. The spray-on lining cement-mortar system provided the worst resistance to abrasion and corrosion; where as, the fold and form, spirally wound lining, cured-in-place inversion installation method, and cured-in-place pulled-in-place method were all rated equally as the best alternatives for abrasion and corrosion resistance. Presented below is the rating scale for abrasion and corrosion resistance:

Worst	1
Best	4

Installation Time

Installation time was rated on the length of time required to install a culvert liner. Installation time included consideration of machinery setup, amount of digging required if applicable, required time of installment, and necessary monitoring and testing after installation is complete. Spray-on liners required the least amount of time to install, and segmental slipliners require the longest amount of time to install. Presented below is the rating scale for installation time:

Longest	1
Moderate	2
Minimal	3
Shortest	4

Flow Bypass Requirements

Flow bypass requirements were rated on whether an alternative required circumvention of the flow to a secondary channel during installation. Though no alternative required bypassing the flow at all times, segmental sliplining and spirally wound lining typically did. It is rarely necessary to bypass the flow for the deformed/reformed method for close fit lining, the cured-in-place methods, and the spray-on lining methods. Presented below is the rating scale for flow bypass requirements:

Always Required	1
Usually Required	3
Not Required	5

Cost

Cost was rated based on the average cost given by case studies and survey results presented in the literature review. Spray-on lining methods were the least expensive, and the cured-in-place lining methods were the most expensive. Presented below is the rating scale for the cost criterion:

Most Expensive	1
Least Expensive	5

Safety

Safety ratings were based on the safety of the installers. Consideration was given to the machinery involved and whether installer entry was required during the installation process. Presented below is the rating scale for the safety criterion:

High Risk	1
Low Risk	5

Environmental Concerns

Environmental concern was rated based on the necessity of chemical use, such as chlorine or resins, during installation. Spray-on lining methods and the cured-in-place lining methods were considered to have the greatest environmental concerns. Presented below is the rating scale for environmental concerns:

Major	1
Minimum	5

Methods of Determining Alternative Ranking

There are many MCDA methods with the basic difference between them illustrated by the scoring process. There are two (2) general categories of methods: value-based methods and outranking-based methods. Value-based methods assign a rating (or score) to an alternative based upon how well that alternative satisfies a specific criterion. For example, assume a 1 to 5 rating scale is implemented with 5 representing the best value. In a value-based method, a rating of 4 is exactly twice as good as a rating of 2. The range of the rating scale is arbitrary and can be selected to meet the desires of the decision makers. However, once a rating scale is defined, rating values assigned to each of the alternatives for a specific criterion need to be carefully applied so that scores appropriately reflect the differences in the alternatives. In contrast, the ratings assigned in outranking methods place little value on how well an alternative satisfies a specific criterion. What is important is only whether one alternative is preferred (or better) than another. The degree of preference is not necessarily considered (although in some outranking methods it can be). In an outranking method, the preferred alternative tends to be the one that has the highest performance in the largest number of criteria.

Three (3) MCDA alternative ranking methods were included in this project. The Weighted Average Method and the Discrete Compromise Programming Method are value-based methods and the PROMETHEE method is an outranking method. Users can select a method of their choice or they can compare the results of all three (3) methods. By comparing the results of all three (3) methods, the impact of the type of MCDA method on the solution can be determined. Usually the results of all three (3) MCDA methods will be similar with only minor differences in the alternative rankings. It is recommended that the Weighted Average Method be the first choice in this application for culvert-rehabilitation strategies since it is a simple decision process. If the process produces alternatives with equal ranks, the Discrete Compromise Programming method will usually be able to provide more discrimination and produce a non-equal ranking. Finally, the PROMETHEE method should be considered if the basic data is not very precise.

Weighted Average Method

The Weighted Average Method (WAM) is a value-based method where the actual value of the performance measure is used to assign the alternative ranking. A 1 to 5 rating scale is used in the WAM, with a value of 1 indicating the worst performance and a value of 5 the best performance. The relative importance of each criterion is determined using relative importance factors assigned by the decision maker. Relative importance factors are then normalized to produce a set of normalized criterion weights. Each designated alternative rating is then multiplied by the normalized weight. The equation in Figure 25 is used to determine the overall score for each alternative.

$$S_j = \sum_{i=1}^{4} W_i * R_{i,j}$$

where,

S = overall score for alternative j

W = weight

R = relative importance of criterion i

Figure 25. Equation. S subscript j.

Since the summation of the normalized weights must equal 1, the overall score will be in the range of 1 to 5. Alternatives are ranked based on the resulting score with the highest score given a rank of 1.

Discrete Compromise Programming Method

A value-based method, Discrete Compromise Programming Method (CP), uses a rating scale of 0 to 1, with a value of 1 representing the best performance and a value of 0 the worst. CP converts the 1 to 5 scale from the WAM to the necessary 0 to 1 scale. CP uses the equation in Figure 26 to weight the relative importance factors.

$$R_{i,j} = \left[\frac{Actual_{i,j} - Worst_i}{Best_i - Worst_i} \right]^p$$

where,

R = CP rating metric;

$Actual$ = actual rating of alternative;

$Worst$ = worst rating of any alternative for a specified criterion;

$Best$ = best rating of any alternative for a specified criterion; and

p = exponent determining the additional emphasis on the CP metric rating value.

Figure 26. Equation. R subscript i,j.

The exponent *p* can be a value of either 1 or 2. When *p* equals 1 each rating metric rescales the original rating scale to a 0 to 1 scale. When *p* equals 2, however, greater significance is given to the largest CP rating metric values. Overall scores for each alternative are computed as described in the WAM. Alternatives are then ranked based on the resulting score.

PROMETHEE Method

The PROMETHEE Method is based on determination of preference and indifference. Every alternative is compared pairwise to each of the other alternatives. A preference value of 1 is assigned if 1 alternative is better than (or preferred to) the performance of another, with respect to a specific criterion, without considering the magnitude of the performance difference. A preference value of 0 is assigned if the alternative is equal or inferior to the other alternative. In PROMETHEE the decision maker is considered to have a strict preference for the action of highest value.[(100)] Preference values determined from the pairwise comparisons are then analyzed to develop an overall rating value for each alternative. These overall rating values are on a scale of +1 to -1. An overall rating of +1 means that an alternative is strictly preferred to all other alternatives while an overall rating of -1 implies that an alternative is inferior to all other alternatives. Compared with the Weighted Average Method and Discrete Compromise Programming Method, the PROMETHEE method is less influenced by the actual magnitude of the basic data. A disadvantage to the PROMETHEE method is that the pairwise comparisons and the process to calculate overall rating values may be harder to understand by the decision maker.

Methodology

Once the culvert characteristics are determined, the relative importance factors defined, and the method of alternative ranking selected, the MCDA employs the appropriate alternative ranking equation and a scoring of alternatives is presented. The methodology used in the culvert-lining decision analysis to determine an alternative score is displayed in the flow chart presented in Figure 27. In Figure 27, the right-angle-cornered boxes contain functions that required user action; the round-cornered boxes represent functions inherent to the MCDA program.

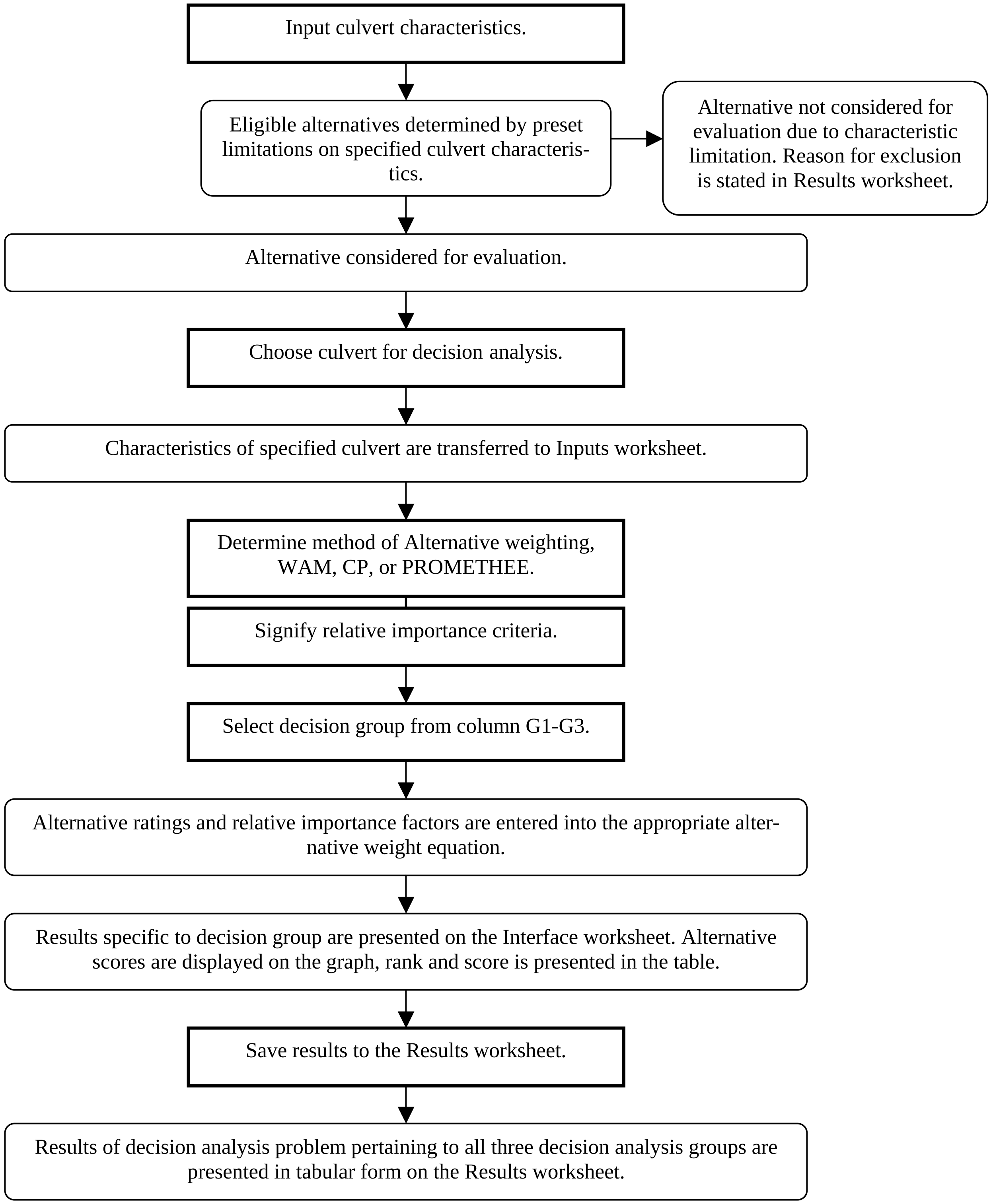

Figure 27. Flow Chart. MCDA Methodology.

Summary

A methodology providing ease of determination of culvert rehabilitation through trenchless-technology techniques was developed using MCDA principles. Using information provided by the literature review, a discrete list of culvert-rehabilitation alternatives and relative importance criterion were developed. Rating scales for each alternative were created dependant on the ability of an alternative to satisfy a specific criterion. Three (3) alternative ranking methods were included in the MCDA. The Weighted Average Method and the Discrete Compromise Programming Method are value-based methods and the PROMETHEE method is an outranking method. The Weighted Average Method is easily explained and understood. It is recommended that the weighted average method be the first choice in this application for culvert-rehabilitation strategies since it is a familiar decision process. Discrete Compromise Programming will usually provide more discrimination and produce a non-equal ranking. The PROMETHEE method is most valuable when the basic data are not very precise. Additionally, a methodology was presented of how the MCDA inputs the alternative ratings and relative importance factors into alternative ranking equations to output an alternative score.

APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS

A workbook was created in Microsoft® Excel to facilitate the MCDA process. Users enter culvert characteristics on the Culvert Characteristics worksheet. In addition to information pertinent to operation of the MCDA, room is provided on the Culvert Characteristics worksheet to create a culvert database. Information pertaining to six (6) culverts can be entered. On the Inputs worksheet, the user chooses one (1) of the six (6) culverts to be analyzed. Once a culvert is selected, the four (4) culvert characteristics necessary for operation of the MCDA are displayed on the Inputs worksheet. Relative importance of criteria and method of alternative ranking are selected by the user on the Interface worksheet. Three (3) relative importance scenarios can be entered, potentially representing three (3) varying decision scenarios or decision makers. When a user selects a method of alternative ranking, Excel activates the worksheet pertaining to the selected method. Alternative ratings are saved in the Basic Data worksheet and appear in the alternative ranking worksheets. Results of the alternative ranking computation may be viewed in two (2) places. Results appear on the Interface worksheet in graphical and tabular forms. Additionally, results pertaining to the three (3) relative importance of criteria scenarios are saved to the Results worksheet. Also displayed on the Results worksheet is a table detailing exclusions, if any, of alternatives and the reasons for exclusion. User direction can be accessed on the Directions worksheet.

Note: In the Microsoft® Excel workbook, the Security Level should be set on “Medium” or “Low” (Tools → Macro → Security). If the Security Level is set on “High,” the macro will not run.

Application Procedure

An application procedure was developed for decision maker use of the Culvert Liner Decision Analysis Microsoft® Excel workbook. The following steps are intended as a guideline for use of the decision-analysis model. All measurements should be recorded in feet and inches, where specified.

1. A field-site survey should be performed to assess culvert characteristics. Four (4) culvert characteristics, presented in Section 5.3.1, are imperative for the decision-analysis model. Culvert length and diameter are needed. Additionally, knowledge of existence of changes in diameter and/or discontinuities along the culvert is required. It is also necessary to discern if the culvert requires restoration of structural integrity.
2. Open the “Culvert Rehabilitation Decision Analysis” Microsoft® Excel workbook. Begin on the Home worksheet. The Home worksheet guides the user through the MCDA process and should be returned to after completion of a designated action.

3. Click on the first box, titled “Begin by entering the culvert characteristics on the Culvert Characteristics Worksheet. Click this box to go to the Culvert Characteristics Worksheet.” This will take the user to the Culvert Characteristics worksheet. Figure 28 presents the Home Worksheet and draws attention to the first box.

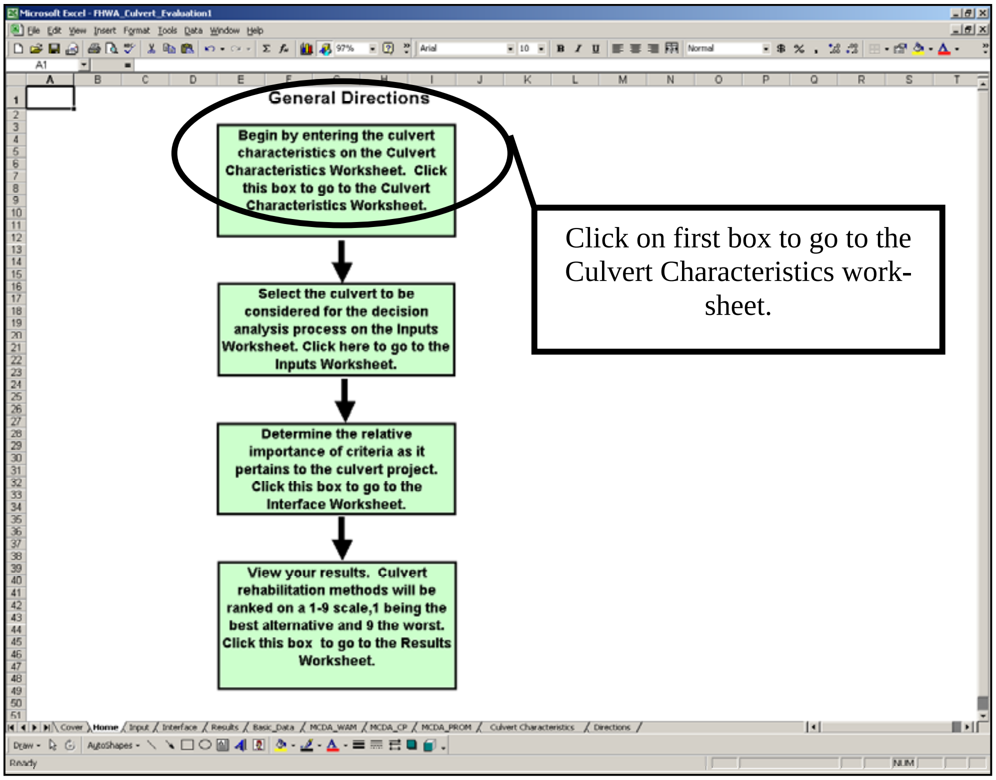

Figure 28. Screenshot. MCDA Home Worksheet, Navigates to Culvert Characteristics Worksheet.

4. Six (6) distinct culverts, and thereby six (6) individual decision problems, can be analyzed in the workbook. It is not necessary to enter information pertaining to six (6) culverts. Begin by entering the information pertaining to the first culvert into the area titled “Culvert A” and continue entering information in the areas titled “Culvert B-F,” or leave the area blank if no further culverts are to be included in the analysis.

5. In the Culvert Characteristics worksheet, presented in Figure 29, the user is required to fill in the four (4) characteristics pertinent to the operation of the model. Highlighted in Figure 29 are the Culvert A data entry area, the areas of required input, and the Return to Home Worksheet button. Cells requiring input necessary for the function of the MCDA are highlighted in green on this worksheet. Other culvert characteristic information is included on the worksheet to allow the user to develop a database if desired. First, the user enters the length of the culvert under examination, which must be answered in feet. Second, the user enters the diameter of the culvert, which must be answered in inches. Dropdown boxes are provided to answer the third and fourth questions. Selections are made by clicking the highlighted box, then clicking on the down arrow and selecting the appropriate answer.

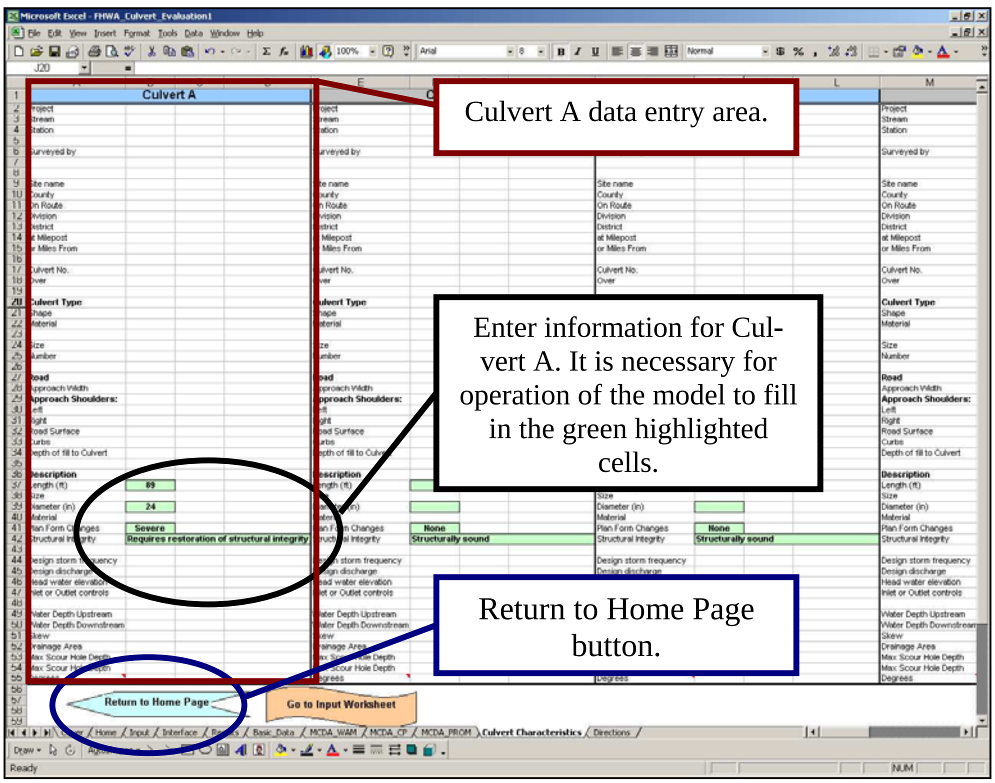

Figure 29. Screenshot. MCDA Culvert Characteristics Worksheet, Navigates to the Inputs Worksheet.

6. Once finished entering pertinent culvert characteristics, click the "Return to Home Worksheet" button to continue with the analysis.
7. Click on the second box on the Home Worksheet, titled "Select the culvert to be considered for the decision analysis process on the Inputs Worksheet. Click here to go to the Inputs