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A multiattribute decision analysis methodology for the life-cycle of production facilities

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A Multiattribute Decision Analysis Methodology for the Life-Cycle of Production Facilities

by

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Thesis Advisor

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1. Abstract

The need for simple, yet powerful design methodologies for production facilities that take into account life-cycle considerations has been widely expressed. Today's design goals are to consider both cost and performance over the life of an engineering project. To date, little has been accomplished towards fulfilling these goals. This shortcoming, in large measure, is due to the fact that designing for the life cycle is complex. How does one minimize cost while at the same time maximize performance over the life-cycle of a facility? What is the "best" balance between cost and performance in a production facility? And most importantly; which is the "best" production facility alternative? The development of a methodology that ranks alternatives based on both cost and performance criteria is a complex task that has origins in many disciplines: Civil Engineering, Industrial Engineering, Computer Engineering, Decision Sciences, and Logic.

The goal of this research project is to create and implement a methodology that will develop rankings from which the "best" production facility (process plant) can be selected. Both performance and cost criteria over the life-cycle of a representative case study will be considered in the selection process. Thomas Saaty's Analytic Hierarchy Process (AHP) is a useful and proven tool that allows for consideration of both cost and

performance in the evaluation of alternatives. The AHP will be employed to create a methodology that will augment the life-cycle engineering of production facilities. A modified AHP which takes into account inter-relationships between the attributes of a production facility, and deviations from the representative case, will be designed and demonstrated in the development for this case study of a process plant.

2. Introduction

2.1 The Problem

2.1.1 Definition of Life-Cycle Engineering

The term "life-cycle engineering" has become a catch phrase in the civil engineering discipline. That is, it is commonly agreed upon that life-cycle engineering is the best way to design, but the consensus also reflects the trend of gross under-utilization of life-cycle engineering. To design for the life-cycle is to consider both cost and performance over the entire life of a project. That is, life-cycle engineering provides a balanced view of the expenditures of resources and the benefits of the implementation of a design. This ideally means that conceptual design decisions through decommissioning should be accounted for in a project which is properly life-cycle engineered. The ultimate goal of this ideal is to maximize performance while minimizing life-cycle cost. However, this is an extremely complex and difficult process which is currently being under-utilized (Construction Industry Institute, 1997).

To a limited extent, computer models and decision-support software may be employed to aid decision makers, project managers, and engineers in successfully designing for the life-cycle of a project. The problem with this notion is that these tools are not yet in wide-spread use. This is partially due to the complex nature of a life-cycle analysis, and partially due to the lack of data required to make a proper life-cycle analysis.

2.1.2 Production Facilities

The Construction Industry Institute (CII) Task Force #122 on Life-Cycle Analysis for Projects was founded with the intent to study the life-cycle of production facilities. This Task Force has compiled data that relates the decisions made about the design, construction, operation, maintenance, and required performance of a production facility to the various costs, throughout the life-cycle. These data are valuable because they may be used as the basis of a decision-support system that successfully models life-cycle cost and performance factors of a production facility. The availability of the data enables the implementation of a conceptual rational model through the use of decision science methods, yielding a prototype to aid in the life-cycle engineering of production facilities.

2.2 The Need

It is a commonly accepted premise that every new facility should be designed to provide an owner with the lowest life-cycle cost possible. Thus, few would disagree that the benefits of life-cycle engineering can be substantial. It is therefore troubling to find that most personnel who are involved with the project delivery of production facilities agree that life-cycle engineering is not done systematically, if at all (CII, 1997). Efficient utilization of resources; such as capital, materials, and labor, requires that they be allocated in a manner which results in an acceptable level of performance at minimum cost over the entire life of an asset. The approach employed in this thesis is based on recognition that, although decisions made early in the life of a production facility about the design and operation of the project should consider life-cycle cost and performance factors, *such factors are frequently not considered in today's design methodologies.*

Life-cycle engineering is a comprehensive, systematic methodology which treats all stages of life of a facility as part of an integrated process of evaluation. It considers both cost and performance throughout the planning horizon of a facility. Thus it supports a more balanced view of investment considering design, construction, maintenance, renewal, and decommission issues. Consideration of all stages in the life-cycle brings to light future problems and issues that can occur downstream and, therefore, supports intelligent and informed decision making so that overall life-cycle costs will be reduced.

2.2.1 Problems With Developing a Rational Model

A major problem in the development of a rational model for the life-cycle of a production facility is the apparent need for an exhaustive knowledge base. A rational model is a concept, developed with a compilation of relevant experience and implemented with a systematic framework, that represents the important characteristics or attributes of an existing "real-life" or potential "real-life" entity. The better the rational model, the more objective it is. Sometimes the "relevant experience" part of the rational model is understood as "exhaustive knowledge base," and this can steer people away from developing a functioning rational model for the life-cycle of production facilities because of the amount of data that apparently needs to be collected.

An exhaustive knowledge base is not always necessary if a smaller, yet systematic and comprehensive, knowledge base of relevant information can be created and validated by a team of experts. The best method to determine what is relevant to a model, and hence what type of data should be focused upon for collection, is to determine what questions the decision maker wants answered. For example, how much will it cost to deconstruct a production facility 25 years from now? Should this cost be discounted to account for the time value of money? If the equipment in the facility only lasts 20 years, is it rational to design the production facility for a 25 year life? These questions need to be answered if a project is to be properly designed for the life-cycle, but each of these questions requires a different kind of knowledge base. That is, in order to be able to make estimates of deconstruction costs, one requires histories of past deconstruction costs. This data differs from the knowledge base required to study the relation between equipment life and facility design life.

Another problem with developing a rational model for the life-cycle of production facilities is the lack of accepted methodologies for doing so. For example, problems like the specification of a level of detail arise. Should a model be developed around an element (or component), sub-system, or system? That is, should detailed design, such as decisions on pipe sizing, be part of the model? What about the schematic decisions higher up the hierarchy, such as the utility type? What about considering decisions or constraints that have downstream impacts on other decisions or constraints? For example, excess capacity will be more valuable if there is a steep positive product demand. If there existed a set of standard design methodologies, questions like these could be dealt with rationally and methodically.

Once methodologies for designing for the life-cycle have become accepted and standardized, designing for the life-cycle will become feasible.

2.2.2 The Myth of Life-Cycle Engineering

The CII Task Force #122 has determined that the current use of life-cycle engineering is more of a myth than it is reality (CII, 1997). That is, decision makers and project managers are either mis-using or under-utilizing the power of life-cycle engineering. The authors of this CII document, after extensive surveys, have determined and clearly stated that the personnel involved with the conceptual (that is, "big picture") decisions about a project do not consider the life-cycle during this stage of design. The lack of life-cycle engineering is partially due to its complex nature, and partially due to the lack of standard, accepted methodologies.

2.3 The Objectives of This Research Project

The first objective of this research project is to design, implement, and verify a decision support system that serves as a processing algorithm in choosing the best alternative from a finite set of alternatives for production facilities. A schematic of this objective is given, on the following page, in Figure 2.3.1.

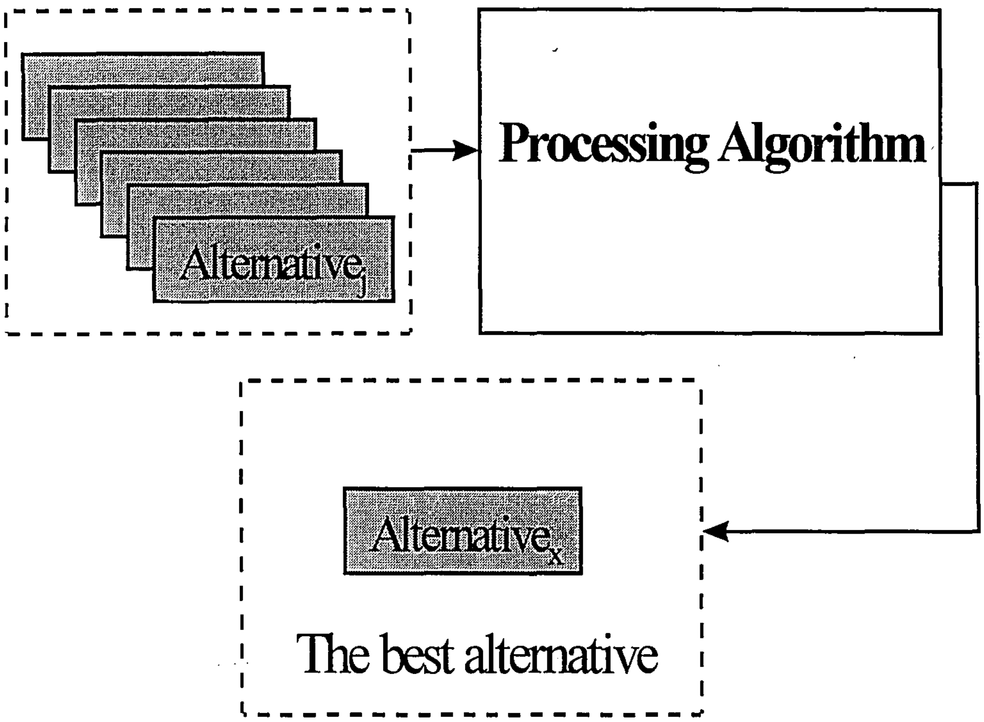
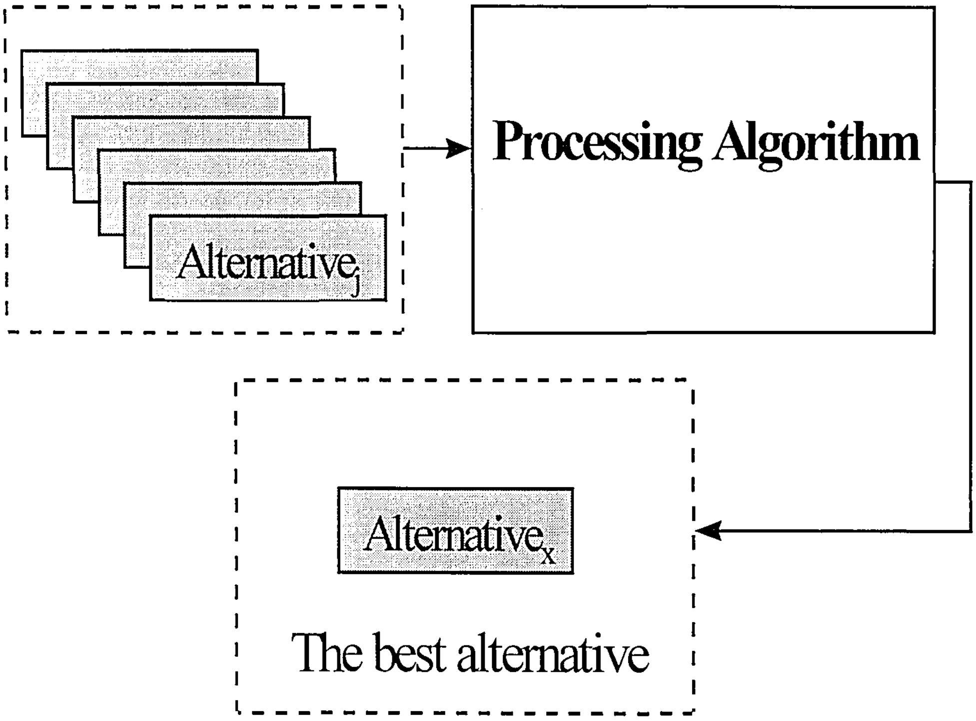


Figure 2.3.1. The role of the processing algorithm in selecting the best alternative

For example, if one production facility has a compressed facility layout while another has no excess capacity, which one performs better, if all other attributes are equal? That is, given a set of design alternatives for a proposed production facility, which set maximizes performance while minimizing cost? In doing this, techniques that consider both cost and performance over the life-cycle of a project may be demonstrated for use in the civil engineering discipline.

The second objective of this research is to extend one of the most widely accepted methodologies used to select the best alternative from a finite



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For example, if one production facility has a compressed facility layout while another has no excess capacity, which one performs better, if all other attributes are equal? That is, given a set of design alternatives for a proposed production facility, which set maximizes performance while minimizing cost? In doing this, techniques that consider both cost and performance over the life-cycle of a project may be demonstrated for use in the civil engineering discipline.

The second objective of this research is to extend one of the most widely accepted methodologies used to select the best alternative from a finite set of alternatives so that it more accurately models situations as complex as production facilities. The modified methodology has potential applications in other civil engineering projects.

2.4 A Brief Introduction to Multiattribute Decision Analysis

Multiattribute Decision Analysis (MADA) refers to the scientific methodology of selecting the best alternative from a finite set of differing alternatives. Thomas Saaty's Analytic Hierarchy Process (AHP) is an example of a MADA methodology (Saaty, 1980). The AHP is a mathematical tool that assists a decision maker in ranking alternatives based on both cost and performance criteria. The AHP and will be used extensively in this thesis. It will be utilized and extended to create a practical tool that ranks production facility alternatives based on both cost and performance criteria. The use of AHP allows the subjective creation of a valuable knowledge base without the need for a vast compilation of detailed data. Additionally, AHP provides a proven, rational methodology for the consideration of the multiple attributes that are important in the design of production facilities. These two properties of the AHP overcome two of the major hurdles (lack of methodologies and lack of data) of applying life-cycle engineering to civil engineering projects.

The AHP will be extended to more accurately model the complex nature of production facilities, relative to a "traditional" application of the AHP. This modified AHP will be demonstrated on a small, yet representative, scale by considering a production facility on a coarse-grained level of detail.

2.5 Contents of the Remainder of This Thesis

Chapter 3 will describe the background on the AHP, as well as the state of MADA as practiced in civil engineering. The current state of design of production facilities will also be discussed, as will be the ideal design practice.

Chapter 4 will provide the actual method of the AHP. That is, Chapter 4 will show how the AHP works. A detailed example will be provided.

Chapter 5 will describe, in detail, the extensions of the AHP to create a proposed multiattribute decision analysis. The proposed multiattribute decision analysis will model the inter-relationships between attributes. Again, a detailed example will be provided.

Chapter 6 will cover the details about the data collection for the AHP analysis. Chapter 7 will present the AHP analysis, and demonstrate the extended AHP method on a representative case study of a production facility.

Chapter 8 will discuss the results and conclusions. Chapter 9 is the bibliography.

3. Background and Literature Review

3.1 Prior Research

3.1.1 Life-Cycle Engineering in Civil Engineering

Civil engineering projects are costly and they are expected to be in service for many years, so careful and systematic consideration of both costs and performance over the life-cycle of a project can be beneficial. That is, life-cycle engineering lends itself to application in large-scale civil engineering projects because of the high costs and importance of an acceptable level of performance that are required from these projects. Life-cycle engineering, by its nature, should implemented in civil engineering projects in order to minimize these life-cycle costs while maximizing performance of these projects.

After an extensive literature search, several research publications concerning life-cycle engineering in the civil engineering discipline may be found. It should be noticed that most of these applications are implemented from the *research* side of civil engineering, rather than the *practical* side. That is, rather than existing as standard practice, these applications exist as theoretical ideals. For example, Mohammadi, Guralnick, and Yan (Mohammadi et. al., 1995) attempt to model the life-cycle cost of highway bridges. The model is highly theoretical, it requires precise knowledge of abstract concepts, such as present-worth value and value indices. This makes practical application difficult for decision makers.

A number of papers exist purely to encourage designers to consider the life-cycle during the early stages of design. David Novick, senior vice-president of Parsons, Brinckerhoff, Quade, and Douglas, Inc., states that the "short term perspective may result in a useful life for the facility that is too short," in his article "Life-Cycle Considerations in Urban Infrastructure Engineering" (Novick, 1992). He also points out that "early examination of all possible alternatives allows decision makers to recognize the full range of solutions and at least identify the desired approach."

The important aspect to realize is that there are very few sources that offer standardized and rational methodologies for civil engineers that assist in designing for the life-cycle. Methods that calculate life-cycle costs are readily available in many text books (Kirk and Dell'isola, 1995) and can be easily applied in situations where the important variables are both limited in quantity and easily defined.

For example, life-cycle cost analysis was implemented in the design of a lighting system for a production facility (Kirk and Dell'isola, 1995). The fact that the useful life of only the lighting system is relatively short, in addition to the fact that cost and performance data of the alternatives that were considered were known and well documented, make complete life-cycle cost analysis possible. But for civil engineering projects, such as a complete production facility, these methods are exceedingly difficult to implement. This is due, in part, to the complexity of these projects. Therefore, for these large projects, different design methodologies which account for life-cycle considerations, both cost and performance, need to be developed and implemented.

3.1.2 Multiattribute Decision Analysis in Civil Engineering

There have been a few instances where multiattribute decision analysis (MADA) has been successfully implemented within the discipline of civil engineering (Goicoechea et. al., 1992). The nature of MADA facilitates the organization of the data and knowledge that is required for a life-cycle analysis of complex or large-scale alternatives. That is, MADA methodologies require a systematic organization of data. This facilitates the application of life-cycle engineering in civil engineering because one of the major hurdles of life-cycle engineering is the amount and nature of data that is required to design for the life-cycle. The use of MADA clearly defines what data is required for an analysis, and life-cycle considerations may be included in these analyses.

Furthermore, at the early stages of a civil engineering project, several design alternatives are feasible. The question is, which one is best? MADA is a logical choice as a method to evaluate and then select the best alternative from a set of alternatives.

Lin and Teng (Goicoechea et. al., 1992) used MADA methods in the selection of freeway interchange locations in Taiwan. Criteria in this model included benefits to local industry and regional development (Goicoechea et. al., 1992). The result was a decision support system that assists transportation planners and engineers in the selection of freeway interchange locations.

Parent and Lebdi (Goicoechea et. al., 1992) used MADA methodologies to design a water resource system in France. MADA methods were used to optimize the balance between water quality and demand. Reliability criteria were considered in the development of this model. The result was a decision support system that assists decision makers in allocating water such that it meets a combination of criteria.

It can be seen from these examples that MADA and AHP have been applied in civil engineering projects. Yet, the current use of MADA is not yet wide-spread within this discipline. The lack of MADA applications in civil engineering may be partially due to the current state of disregard for life-cycle considerations. As mentioned in the Introduction, the personnel who are responsible for making key decisions, with respect to production facilities, are not fully aware of the life-cycle implications of their decisions. In addition, the lack of MADA applications in civil engineering may be due to the lack of knowledge of MADA. By and large, MADA is not taught to civil engineering students as part of a standard college curriculum.

3.2 Current Practice

3.2.1 The Desire and Means for a Rational Methodology of Life-Cycle Engineering in the Design of Production Facilities

As stated in the Introduction, the CII Task Force #122 has found that life-cycle engineering is not adequately used, if used at all, in the current design practice of production facilities. Resources are not as widely available as they have been in the past, so careful consideration must be given in allocation, and the benefits of the utilization of these resources. In other words, the role of production facilities in today's society dictates a balanced view of the life-cycle during design, and the CII has found that this is not being done in the conceptual design of production facilities.

The fact that organizations, such as the CII, are conducting research on life-cycle engineering is evidence that there is a need for some sort of standardization when it comes to civil engineering design for the life-cycle. The goals of this CII Task Force are to promote the consideration of cost and performance throughout all stages of the life-cycle in the design of production facilities by developing a conceptual model for life-cycle engineering and a decision-support tool. By implementing that tool, in the form of windows-based software, the CII will set a precedent in the standardization of rational and systematic life-cycle engineering methodologies.

3.2.2 The Use of Multiattribute Decision Analysis in Civil Engineering

The use of MADA in civil engineering is increasing, but it is not yet wide-spread. This may be due, in addition to the complex level of analysis and lack of data, to the lack of understanding of MADA and a clear distinction between MADA and multi*objective* decision analysis (MODA). As stated before, MADA is the technique of selecting the best alternative from a finite set of alternatives. MADA can also be used to rank alternatives based on cost and performance criteria. The alternatives in MADA are established through the decision maker's knowledge base of the cost and performance of each alternative.

MODA is the technique of designing the single best alternative from an indefinitely large set of alternatives. That is, the single best alternative in a MODA analysis is designed, or specified, by the analysis. This is done with the utilization of linear programming and constraint functions (NIST, 1995). For example, statements such as, "The first 10,000 units of output produced will cost $0.70 each, while each additional unit will cost $0.60 each" are used to define constraints that minimize cost while maximizing performance.

When civil engineers talk about designing for the life-cycle of a project, they are usually thinking in terms of MODA. MODA can be an extremely involved process on the scale required for civil engineering projects. A more practical solution would be to use MADA since civil engineering solutions are often selected from a set of proposals where constraints are so rigid that, in general, only a small set of alternatives are even suitable for a project. For example, PennDot is currently designing an interchange between I-95 and the Pennsylvania turnpike. Six different alternatives have been designed. Each one re-routes traffic between the two highways, but along different paths. Each alternative requires the relocation of different residences and businesses. In this case, these six designs are the only designs that are considered to perform satisfactorily within cost constraints. So why use the complex nature of MODA to design the very best one from scratch when MADA may implemented to directly select between these six designs?

3.3 The Ideal

The ideal practice in the design of production facilities includes a balanced view of all cost and performance issues throughout the entire life-cycle of a production facility. As mentioned in the Introduction, part of the reason why these issues are not considered during design is that there is a lack of standardized methodologies. Also mentioned in the Introduction was that the main objective of this thesis is to create a practical methodology for use in the design of production facilities that accounts for life-cycle decisions. The future of the engineering design of production facilities includes life-cycle engineering. This thesis is a step towards realizing and achieving this ideal.

4. Multiattribute Decision Analysis Methodologies

The purpose of this chapter is to provide a detailed understanding of the methodologies utilized in this thesis. This chapter contains a detailed description of the technique of the analytic hierarchy process. Sections 4.1.1 and 4.1.2 provide some brief introductory remarks to multiattribute decision analysis. Sections 4.1.3 and 4.1.4 present both ends of the dichotomy that is in the calculations of the analytic hierarchy process. Sections 4.1.5 and 4.1.6 present the technique of the calculations, and 4.1.7 provides a detailed example. Section 4.2 presents several other multiattribute decision analysis methodologies, and Section 4.3 provides a summary of this Chapter.

4.1 The Analytic Hierarchy Process

The analytic hierarchy process (AHP) is an example of a multiattribute decision analysis (MADA) method. MADA methods are used to assist a decision maker in choosing or ranking different alternatives based on the values of attributes. In this case, an alternative is a proposed design for a production facility. The attributes are what describe the important parameters of each production facility. For example, "facility layout" is an attribute of a production facility. "Compressed" or "normal" are the possible values, or choices, of the attribute "facility layout" for a given alternative. The AHP utilizes a hierarchical structure. A hierarchy is used to organize data so that different production facility alternatives may be compared. Figure 4.1.1 shows the hierarchical relationship between an object, it's attributes, and the values of those attributes.

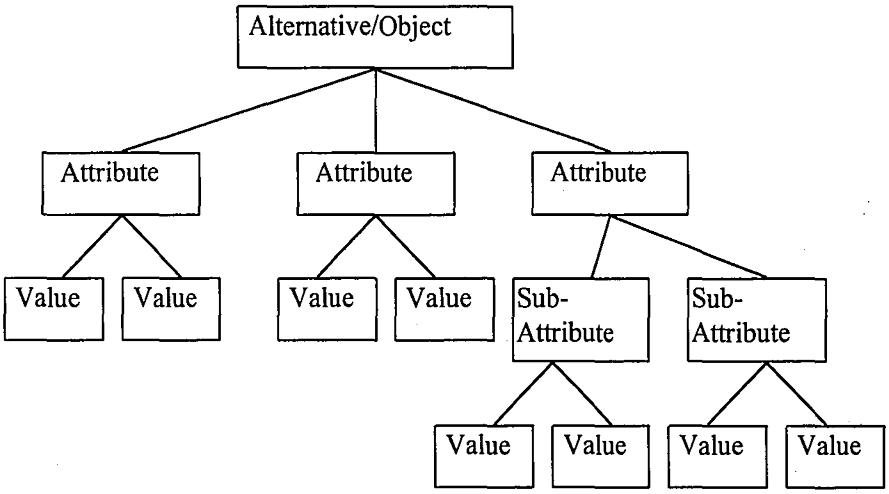


Figure 4.1.1. The Object/Attribute/Value Hierarchy

The highest element in the hierarchy is the object, or the alternative. The alternative is defined by its attributes. An attribute of a production facility may be facility layout, or facility size, etc. The attributes are defined by their values. For example, the possible values of facility size may be large or small, and the possible value of facility layout may be normal or compressed. Figure 4.1.2, on the following page, shows some of the relationships in an object/attribute/value hierarchy for a production facility.

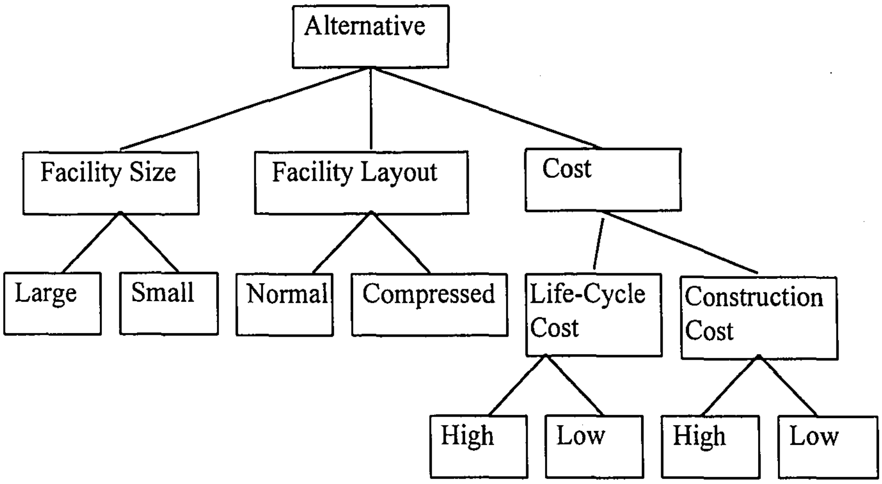


Figure 4.1.2. An Abbreviated Object-Attribute-Hierarchy for a Production Facility

As seen in Figures 4.1.1 and 4.1.2, sub-attributes may be used to facilitate the organization of the hierarchy, but it is a necessary condition that the highest element in the hierarchy (i.e. the root node) is the alternative, and all of the lowest elements (i.e. the leaf nodes) are values.

4.1.1 Cardinal vs. Ordinal Scales

The AHP is used to rank different alternatives on a cardinal scale. This means the ranks for each alternative reflect how desirable the alternative is, relative to other alternatives. Ordinal scales do not give any information with respect to relative desirability. For example, temperature is given on an ordinal scale. If it is 5 degrees centigrade in Bethlehem, and 30 degrees centigrade in Miami; it makes no sense to say that Miami is 6 times warmer than Bethlehem. That is, if the numbers were transformed into degrees farenheight Miami would no longer be “6 times” as warm as Bethlehem, yet the actual amount of heat in both cities would remain unchanged when using these different scales. In the case of temperature, “6 times” would be an inaccurate relative measure. But, if Bethlehem covers 50 square miles and Miami covers 500 square miles; it makes perfect sense to say that the area of Miami is ten times greater than the area of Bethlehem. This is because no matter the unit of measurement (square miles, acres, square meters, etc.), there is ten times as much land in Miami, relative to Bethlehem. In the case of area, “10 times” is an effective relative measure. In other words, area is given on an ordinal scale, and population is given on a cardinal scale.

Part of the usefulness of the AHP is that it gives results on a cardinal scale. This gives the decision maker information as to *how much more* desirable one alternative will be relative to other alternatives.

4.1.2 Compensatory vs. Non-Compensatory Ranking Schemes

The AHP utilizes what is known as a compensatory ranking scheme. A compensatory ranking scheme is one that allows poor performance with respect to one attribute to be balanced by high performance by another attribute. That is, the poor performance of a high initial cost may be justified by a high performance of a high product demand. Non-compensatory ranking schemes, such as maximin and minimax (Resnick), do not allow high-performing attributes to make up for deficiencies in other attributes. Non-compensatory ranking schemes are, in general, less sophisticated tools that are sometimes used as "screening" devices to weed out poorly-performing alternatives before proceeding to more involved, fully compensatory, MADA methodologies.

4.1.3 Attribute Importances

4.1.3.1 The Matrix of Pairwise Comparisons

The AHP, like other MADA methods, requires the decision maker to assign importance values to each individual attribute. Importance values reflect how important one attribute is relative to other attributes. For example, life-cycle cost will be much more important than facility layout when considering overall desirability of a production facility, so the importance value of life-cycle cost would be some degree higher than the importance value of facility layout. Specifically, the AHP requires the attributes to be cardinally ranked by importance. Given a large set of attributes, it would be difficult to simply rank attributes so that the final ranking follows a cardinal scheme because it would be hard to visualize the exact nature of the cardinal relationship between all the attributes simultaneously.

The ranking can be facilitated by the utilization of a matrix of pairwise comparisons (MPC). The MPC allows each attribute to be compared to a single other attribute, one at a time, to make importance judgments. Each element in the MPC represents a simple pairwise comparison between two attributes. That is, element $MPC_{i,j}$ is a reflection of how much more important the attribute in row i is with respect to the attribute in column j. Figure 4.1.3.11, on the following page, is a schematic of a matrix of pairwise comparisons.

	Attribute 1	**Attribute 2**	**...**	**Attribute *i***	**Attribute *j***	**...**	**Attribute *n***
Attribute 1	1	Importance of Attribute 1 relative to Attribute 2	...	Importance of Attribute 1 relative to Attribute i	Importance of Attribute 1 relative to Attribute j	...	Importance of Attribute 1 relative to Attribute n
Attribute 2	Importance of Attribute 2 relative to Attribute 1	1	...	Importance of Attribute 2 relative to Attribute i	Importance of Attribute 2 relative to Attribute j	...	Importance of Attribute 2 relative to Attribute n
...	...	...	1	...	...	...	...
Attribute *i*	Importance of Attribute i relative to Attribute 1	Importance of Attribute i relative to Attribute 2	...	1	Importance of Attribute i relative to Attribute j	...	Importance of Attribute i relative to Attribute n
Attribute *j*	Importance of Attribute j relative to Attribute 1	Importance of Attribute j relative to Attribute 2	...	Importance of Attribute j relative to Attribute i	1	...	Importance of Attribute j relative to Attribute n
...	...	...	...	...	...	1	...
Attribute *n*	Importance of Attribute n relative to Attribute 1	Importance of Attribute n relative to Attribute 2	...	Importance of Attribute n relative to Attribute i	Importance of Attribute n relative to Attribute j	...	1

Figure 4.1.3.1.1. A Matrix of Pairwise Comparisons

For example, consider the performance of a production facility. If facility size is 5 times as important as facility design life, relatively speaking, then element $MPC_{\text{facility size, facility design life}}$ would be 5.

If the element in column j is more important than the element in row i, then the value of $MPC_{i,j}$ is inverted. For example, if it is determined that facility design life is 5 times more important than facility size, then the element $MPC_{\text{facility size, facility design life}}$ would be 1/5.

Since *importance* is being compared across attributes, attributes with different units may be compared. That is, *it is possible to compare the proverbial "apples and oranges" with respect to importance.* Facility size may be measured in square meters, and facility design life may be measured in years; but someone with relevant experience can determine that facility size is some specific degree more or less important than facility layout with respect to performance over the life-cycle of a production facility.

When constructing the MPC, Saaty (Saaty, 1980) suggests to consider a representative case study, or a "typical alternative." That is, for the "typical" production facility, a specific attribute such as facility size is some degree more or less important than facility design life when considering performance of an alternative. This concept of a typical production facility will be discussed in Chapter 5.

4.1.3.2 The Nine-Point Scheme in the MPC

NIST suggests the use of a five-category scheme with associated numerical values for the determination of the importance factors for an AHP analysis. This scheme is called the nine-point scheme. The goal of using the nine-point scheme is to facilitate data acquisition. The nine-point scheme is a list of fuzzy descriptors that attach a numerical value to verbal judgments like "extremely more important." That is, it is relatively easy for someone to say that life-cycle cost is "extremely more important" than facility layout. It would be somewhat difficult for someone to say that life-cycle cost is roughly 9 times more important than facility layout.

The scale of the numerical equivalents is 1 through 9, but can be varied for sensitivity analyses. It should be noted that outcomes can differ depending on the scale of the numerical equivalents. If scale makes significant changes in the final ranking scheme, a more detailed analysis should be performed. Table 4.1.3.2.1 presents a list of the verbal judgments and the corresponding numerical equivalents most commonly used in AHP analysis.

Verbal Judgment	Numerical Equivalent
Extremely More Important	9
Very Strongly More Important	7
Strongly More Important	5
Moderately More Important	3
Equally as Important	1

Table 4.1.3.2.1. The fuzzy scheme used in the MPC

This means that a numerical equivalent is attached to a fuzzy qualitative phrase. For example, "extremely more important" is translated to "9 times more important."

4.1.3.3 The MPC in Practice

There are several simplifications that can facilitate data collection for the MPC. The first is that all the elements along the main diagonal of the matrix are equal to one, since any element is equally as important as itself.

The second simplification is that only the upper half of the matrix needs to be completed (see Figure 4.1.3.1.1). For element $MPC_{i,j}$ that is known, element $MPC_{j,i}$ is equal to the inverse of $MPC_{i,j}$. That is:

$$MPC_{i,j}=1/\,MPC_{j,i}$$

For example, if facility size is 5 times as important as facility design life, then $MPC_{\text{facility size, facility design life}}$ is equal to 5, and $MPC_{\text{facility design life, facility size}}$ is equal to 1/5.

A third simplification would be to only complete one row of the MPC, and extrapolate the rest of the MPC from the logical relations within that row. For example, if facility size is 5 times as important as facility design life, and facility design life is 2 times as important as utility type; then facility size would be 10 times as important as utility type.

It should be noted that this third simplification should **not** be used in practice. Though it does lead to a perfectly consistent matrix, there are several problems with this notion. First, misjudgments are amplified. A single mistake or misjudgment is reflected throughout the entire MPC. That is, "any subjective judgment process such as pairwise comparisons has an inherent possibility for error or bias" (NIST, 1995). Secondly, it does not allow the decision maker to express all the nuances of the analysis in the MPC. That is, any error in a given specific element would eventually be canceled out (NIST, 1995). The canceling out is done in the eigenvector based method for calculating the actual attribute weights. This technique will be discussed in the following section.

Consistency checks are used to check the logical consistency of the MPC, as mentioned above. Saaty (Saaty) defines the consistency ratio (**CR**) as:

$$\mathbf{CR = a/(n-1)}$$

where **a** is equal to the eigenvalue that corresponds to the principal eigenvector, and n is equal to the number of attributes. Eigenvalues and eigenvectors will be discussed in the following sub-section. A perfectly consistent MPC would have a **CR** = 0. According to Saaty (Saaty, 1980), values of **CR** up to 0.1 are acceptable. In practice, the MPC may be iterated until the **CR** is very small. This is done by creating a MPC, and checking the **CR**. If the **CR** is higher than desired, then the decision maker goes back into the MPC to look for any logical inconsistencies, and adjusts them to more accurately model the problem and to resolve any conflicts of consistency.

4.1.3.4 The Principal Eigenvector Technique

The calculations of MADA methods require a cardinally ranked set of attributes, not an entire matrix of pairwise comparisons in order to rank alternatives. Saaty suggests that the best way to get a vector of importance ratios would be to use the principal eigenvector of the MPC (Saaty, 1980). Kreyszig offers the following definition for an eigenvector (Kreyszig, 1993):

> Let **A** = $[a_{jk}]$ be a given n x n matrix and consider the vector equation:
>
> $$\mathbf{Ax} = \lambda\mathbf{x}$$
>
> where λ is a number. It is clear that the zero vector $\mathbf{x} = \mathbf{0}$ is a solution of (this equation) for any value of λ. A value of λ for which (this equation) has a solution $\mathbf{x} \neq \mathbf{0}$ is called an eigenvalue or characteristic value of the matrix **A**. The corresponding solutions $\mathbf{x} \neq \mathbf{0}$ of (this equation) are called eigenvectors of characteristic vectors of **A** corresponding to that eigenvalue λ.

The principal eigenvector corresponds to the highest real value of λ, the principal eigenvalue.

In any perfectly consistent matrix of pairwise comparisons with **n** attributes, all the eigenvalues will be equal to zero, except one. The remaining eigenvalue, the principal eigenvalue, will be equal to **n**. Small deviations in a MPC correspond to small deviations in the eigenvalues (Saaty, 1980). This means that the principal eigenvalue will always be close to **n**, and the remaining eigenvalues will be small, or imaginary. The eigenvector associated with the principal eigenvalue, the principal eigenvector, is then used in the calculation of the attribute weights. The remaining eigenvectors will contain either imaginary numbers, or negative numbers.

The numbers in the principal eigenvector correspond to the relative weights of the attributes. This vector must be normalized before it is used in any calculations so that vectors are comparable across alternatives. Normalization techniques are described in Section 4.1.5.

There are various numerical methods available to assist in the "hand calculation" of eigenvectors, but the availability of high-powered computing software enables the principal eigenvector to be easily calculated.

4.1.4 Attribute Preferences

After the relative *importance* of each attribute has been determined via the principal eigenvector technique, the relative *preference* of each value of each attribute needs to be specified. That is, how much more or less preferred is a compressed facility layout relative to a normal facility layout? A value is preferred over another if it has an advantage over the other value with respect to performance. For example, if a normal facility layout can produce twice as much output as a compressed facility layout, then a normal facility layout is preferred. For the AHP, the *degree* of the preference must be specified. This will be discussed later in this section. When determining attribute preferences, all other attributes are kept constant, including cost.

In the case of this model for production facilities, there are only a few choices for each attribute. So it is relatively easy to determine the scores for each attribute's values, even if the choices are qualitative in nature. That is, since the only values of facility layout are "normal" and "compressed;" it is easy to state that a normal facility layout is some degree more or less preferable than a compressed layout. If, for example, a normal facility layout is twice as preferable as a compressed facility layout, then the preference ratio is 2 to 1. Again, these numbers need to be normalized before any calculations occur, and the normalization techniques are presented in chapter 4.1.5. Details on the data collection techniques used in the analysis of production facilities will be given in Chapter 5.

In cases where there is a larger set of attribute values, MPC's may be created to determine relative preferences. The key difference is that the MPC is now one of *preference* instead of importance. The calculations to determine the preference ratios, including the principal eigenvector technique and consistency ratio, are all analogous to the calculations described above for the MPC for relative importances.

4.1.4.1 Quantitative Attribute Preferences

In the case where the performance of an attribute can be measured quantitatively, a more direct method of computing attribute preference ratios may be used. For example, if alternative A's facility size is 20,000 square feet and alternative B's facility size is 40,000 square feet; then it may be interpreted that alternative B performs twice as well as alternative A with respect to size. That is, the actual magnitudes of the attributes become the preference ratios. This is the case for *performance* attributes. That is, performance attributes are attributes for which larger values imply better performance.

For *cost* attributes, that is attributes for which lower values imply better performance, the values are simply inverted before determining relative attribute performance. For example, if the life-cycle cost of alternative A is \$20,000 and the life-cycle cost of alternative B is \$40,000; it can be said that alternative A performs twice as well as alternative B with respect to cost.

This method implies a direct, one to one, relationship between magnitude of the attribute and performance of the attribute, which may not always be accurate. For example, due to attributes like facility layout, it is not clear that a 40,000 square foot facility will perform twice as well as a 20,000 square foot facility.

This method of evaluating quantitative attribute preference values is not used in this research project due to the qualitative level of analysis.

4.1.4.2 Cost Attributes Considered in this Model

The cost attributes considered in this analysis are: 1) life-cycle cost, 2) initial cost, and 3) annual cost. The CII task force has compiled a list of approximately 20 elements of life-cycle cost for a production facility. These elements are categorized by cost-phase: 1) Planning and Design, 2) Construction and Equipment, 3) Maintenance, 4) Operations, and 5) Decommissioning. Ideally, all the cost elements sum to the total life-cycle cost of the production facility. So it would make sense to consider life-cycle cost as the only cost element; as life-cycle cost is, in effect, the "bottom line." Initial cost and annual cost are included because some decision makers are willing to trade off a high life-cycle cost for decreased initial or annual costs.

Since life-cycle, initial, and annual costs are difficult to determine precisely at the time when an AHP analysis is most useful, qualitative choices for the values of these attributes are given. For example, "very expensive" is used instead of "$10,000,000." This allows the decision maker to express the notion that one alternative will be some specific degree more or less expensive relative to another alternative, rather than being concerned with exact dollar amounts. After all, the nature of the AHP dictates that the relative preferences are what are important in the calculations, not exact dollar amounts.

4.1.5 Normalization Techniques

The principal eigenvector and all the preference ratios need to be normalized so that different alternatives may be compared on the same scale. There are two commonly accepted methods of normalizing vectors: division by sum (DBS), and division by maximum (DBM) (NIST, 1995).

In DBS, a given vector is normalized by the sum of the elements in that vector. That is, each element is divided by the sum of the elements in that vector. The sum of the elements in the normalized vector is equal to one.

In DBM, a given vector is normalized by the maximum value within that vector. That is, each element is divided by the maximum element within that vector. The new maximum value within the normalized vector is equal to one.

The availability of the two different normalization schemes give some flexibility to a decision maker. According to NIST (NIST, 1995), "DBS is the preferred approach in AHP except when the analysis is concerned only with identifying the highest-ranked alternative rather than establishing a cardinal ranking among all alternatives, or when several alternatives exhibit very similar performance with respect to several attributes." The best results would be obtained by utilizing both normalization schemes, and investigating how results differ by utilizing a sensitivity analysis. This allows a sensitivity study between normalization schemes.

4.1.6 Calculating the Desirability Scores

There is a single desirability score, or desirability index, calculated for each alternative. This is determined by summing the products of attribute weight times attribute performance. Equation 4.1.6.1 is used to calculate the desirability score in an AHP analysis.

$$DesirabilityScore_j = \sum_{i=1}^{n}(weight_i)*(score_i)$$

Equation 4.1.6.1. The equation for desirability score in the AHP.

Where j represents a single alternative, i represents a single attribute, and n represents the number of attributes. The desirability scores for each alternative reflect a cardinal ranking of alternatives where a higher desirability score reflects better performance over the life-cycle of the production facility. A hypothetical example is presented in the following sub-section.

4.1.7 An Example of the AHP

Consider the purchase of a new car. For the sake of simplicity, only account for three attributes: size, color, and initial cost. The values of size are: small, medium, and large. The values of color are: red, blue, and yellow. The values of cost are: inexpensive, moderate, and expensive. Granted, this is a gross over-simplification, but it will serve as an example.

The first step is to create the matrix of pairwise comparisons for the attributes. Using the nine-point scheme, suppose the MPC is:

	Size	Color	Cost
Size	1	5	1/3
Color	1/5	1	1/9
Cost	3	9	1

The first element in the first row of the MPC, element MPC $_{size,size}$ relates the importance of size to the importance of size. Since any attribute is equally as important as itself, all elements along the main diagonal are equal to one. The second element in the first row of the MPC relates the importance of size to the importance of cost. Considering size is "strongly more important" than color, this element is equal to 5. The third element in the first row relates the importance of size to the importance of cost. Since cost was determined to be "moderately more important" than size, this element is equal to 1/3. This value is inverted because the column attribute is more important than the row attribute. Note that the values in the first *column* in the MPC are equal to the inverses of the first *row* in the MPC.

Mathcad calculates the principal eigenvector as:

Size	0.36
Color	0.09
Cost	0.93

After normalizing the principal eigenvector by DBS, the weights of the attributes, as shown on the following page, are:

Size	0.27
Color	0.06
Cost	0.67

Note that the sum of the weights is equal to one. DBM is not utilized in this example, as the end goal is a simple ranking of alternatives.

Now the preference ratios must be determined. For size, say "large" is four times as preferable as "medium." And "medium" is twice as preferable as "small." This leads to the following preference ratios for size:

Size	
Small	1
Medium	2
Large	8

After normalizing by DBS, the preference scores for each value of size are:

Size	
Small	0.09
Medium	0.18
Large	0.73

Again, note that the sum of the scores is equal to one.

Similarly, the scores for color and cost may be expressed as:

Color	
Blue	0.67
Red	0.26
Yellow	0.07

Cost	
Inexpensive	0.58
Moderate	0.28
Expensive	0.14

Note that now it is a trivial problem to design the "best" alternative. Just pick the highest scoring value for each attribute. For this example, the "best" car would be large, blue, and inexpensive. The problem arises when this set of attribute values does not exist as an alternative. Suppose there are three alternatives:

	Alternative A	Alternative B	Alternative C
Size	Large	Medium	Small
Color	Yellow	Blue	Red
Cost	Moderate	Expensive	Inexpensive

Now all that is needed is the calculation of the desirability score for each alternative. This is done be summing the products of weight times score:

	Alternative A	Weight* Score(A)	Alternative B	Weight* Score(B)	Alternative C	Weight* Score(C)
Size	Large	(0.26)*(0.73)	Medium	(0.26)*(0.18)	Small	(0.26)*(0.09)
Color	Yellow	(0.06)*(0.07)	Blue	(0.06)*(0.67)	Red	(0.06)*(0.27)
Cost	Moderate	(0.67)*(0.29)	Expensive	(0.67)*(0.14)	Inexpensive	(0.67)*(0.57)
Desirability Score		0.39		0.19		0.42

According to this analysis, the "best" performing alternative is alternative C with a desirability score of 0.42. It should be noted that alternative A is almost as desirable as alternative C. In fact, alternative C is only (0.42/0.39) = 1.08 times as desirable as alternative A, since the desirability scores are on a cardinal scale. Since these desirability scores are approximately the same, a more detailed analysis may be performed. This will be done in the example section of Chapter 5.

4.2 Other MADA Methods

There are several other MADA methods. Most are based on the AHP due to its intuitive nature.

The weighted product method (NIST, 1995) is very similar to the AHP. The weights and scores are determined similarly. The desirability score is calculated by summing the scores taken to the power equal to the weight. Equation 4.2.1 is used to calculate the desirability score in the weighted product method.

$$DesirabilityScore_j = \sum_{i=1}^{n} (weight_i)\wedge(score_i)$$

Equation 4.2.1 The equation used to calculate the desirability score in the weighted product method

According to NIST (NIST, 1995), the weighted product method "tends to penalize poor performance on one attribute more heavily" than AHP.

The Nontraditional Capital Investment Criteria (NCIC) method (NIST, 1995) is also based on the AHP. At least one attribute must be defined in monetary terms, and the performance of other attributes are defined in terms of monetary gains with respect to the initial attribute.

The TOPSIS method (NIST, 1995) ranks alternatives based on deviation from an ideal alternative. That is, an alternative that deviates the least from the ideal is the highest ranked alternative.

AHP is used in this thesis due to its wide-spread use and acceptance in industry, as shown in Chapter 3.

4.3 A Summary of Chapter 4.

Chapter 4 presented a description and the technique of the analytic hierarchy process. A simplified example was given in order to demonstrate the implementation of the methodology. Other MADA methodologies were also briefly mentioned.

5. A Proposed Multiattribute Decision Analysis Methodology

The AHP can be modified to more accurately model production facilities and other large-scale projects within the civil engineering discipline. This is because some of the attributes are inherently inter-related, and these inter-relationships are not modeled in a traditional AHP analysis. For example, a steep product demand makes excess capacity more valuable than if there were a volatile product demand. This nuance is not reflected in the AHP, as the MPC and performance ratios are determined for a representative case study, or the "typical" case. The "typical" case may or may not have a steep product demand, and the importance of excess capacity largely relies on the value of product demand. A modified AHP analysis would take into account these inter-relationships, and model them accordingly.

There are MADA methodologies that account for attribute inter-relationships, but these are extremely complex. For example, the NCIC method requires the development of a unique MPC for each *possible* alternative. Analyses using the NCIC method can grow to an unmanageable size and, therefore, is not usually considered feasible as a practical decision-support tool.

5.1 Attribute Inter-Relationships

An inter-relationship ($\mathbf{I}_{i,j}$) occurs when the value of one attribute (attribute **i**) has an impact on the importance or preference values of another attribute (attribute **j**). For example, it is clear that for production facilities, excess capacity and product demand are inter-related. That is, the value of product demand has an impact on the importance and performance of excess capacity.

The calculations of desirability indices in the AHP are made for a baseline, or representative, production facility. This may be acceptable, if one is simply ranking a set of alternatives whose attributes are, for the most part, independent of each other. In the case of production facilities, and other complex civil engineering projects, a significant number of attributes are inter-related. In this case, the use of AHP may or may not provide an "adequate," or sufficiently robust analysis.

For a modified AHP analysis, specific elements in the MPC as well as the performance ratios of each attribute should be modeled as a functions of the values of all inter-related attributes. That is, any deviations from the typical case are accounted for within the model. The challenge in this situation is how one incorporates these inter-relationships into a MADA methodology.

5.2 The Technique of the Proposed Modified AHP

5.2.1 Specifying Inter-Related Attributes

The establishment of inter-related attributes may be facilitated with the use of an attribute inter-dependence matrix (IDM). Figure 5.2.1.1 is a schematic of an IDM.

	Attribute 1	**Attribute 2**	**...**	**Attribute *i***	**Attribute *j***	**...**	**Attribute *n***
Attribute 1	N/A	...	...	...	...	...	...
Attribute 2	...	N/A	...	√	√	...	...
...	...	...	N/A	...	...	...	...
Attribute *i*	...	√	...	N/A	...	...	√
Attribute *j*	...	√	...	...	N/A	...	...
...	...	...	...	...	...	N/A	...
Attribute *n*	...	...	...	√	...	...	N/A

Figure 5.2.1.1. A Schematic Inter-Dependency Matrix (IDM)

This matrix has the attributes listed in both the rows and the columns, similar to the MPC. In this case, check marks are placed in the elements where inter-relationships exist. The IDM is used to assist in the establishment and tabulation of inter-related attributes.

For example, the element $IDM_{\text{excess capacity, product demand}}$ would have a check mark, since excess capacity and product demand have been determined to be inter-related. It should be noted that only the upper half of this matrix needs to be completed since any inter-relationship only needs to be identified once.

5.2.2 The Inter-Related Importances

Since the modified MPC must now account for inter-relationships between attributes, each element in the modified MPC is a not only a function of the relative importances of the two "base" attributes, but also a function of all the values of the attributes that are inter-related with the two "base" attributes.

The steps for creating a modified MPC are:

1. Create the MPC for the "typical" case, as in the traditional AHP. Identify a pairwise comparison to work with.

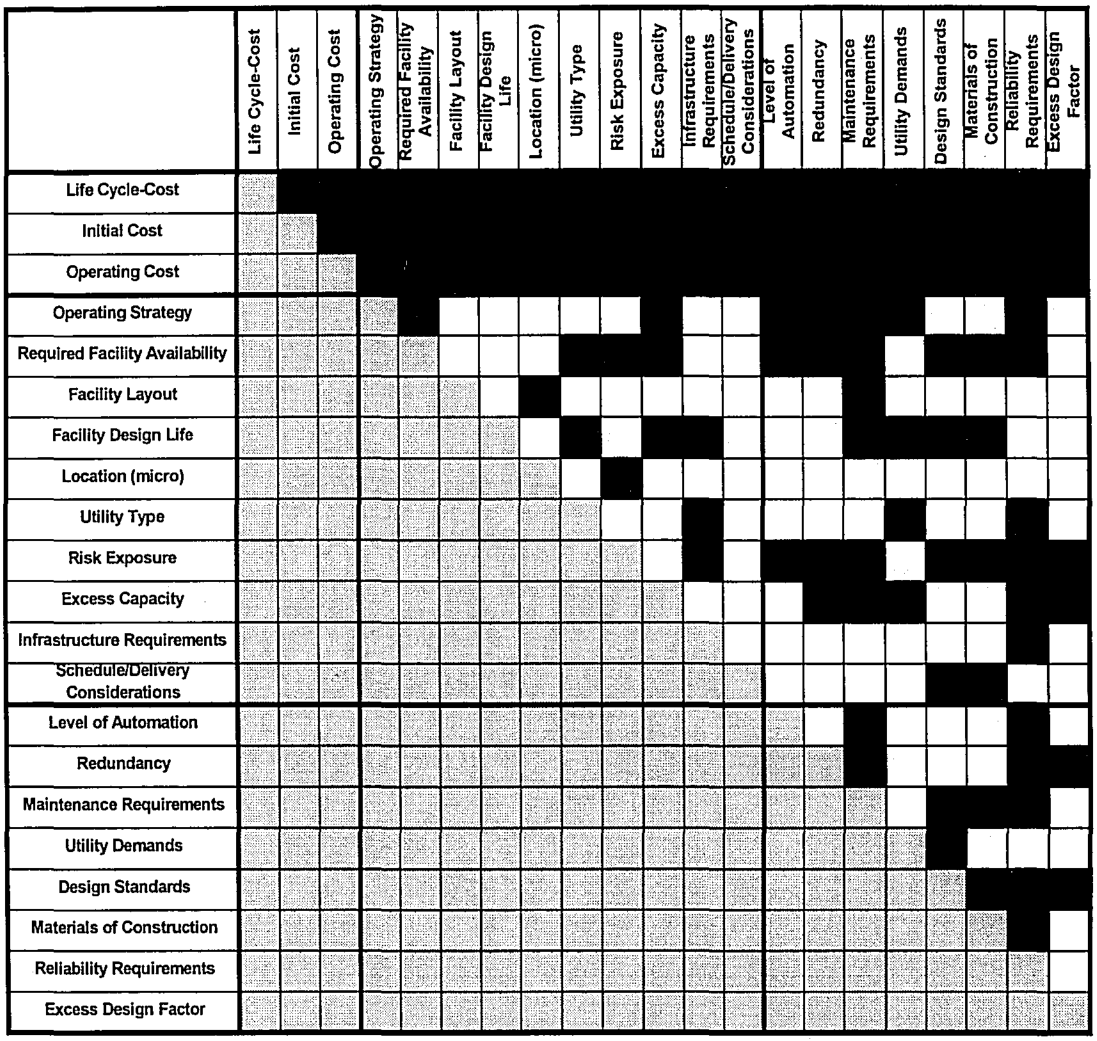
2. List the attributes for which modification functions are needed. That is, create and utilize the IDM. Modification functions are needed for the two

"base" attributes of the pairwise comparison (attributes **i** and **j**) in addition to all the attributes inter-related with those two base attributes.

3. Determine the values of the modification functions.

4. Compile the modification functions in the modified MPC, and calculate the values in the MPC for each alternative.

For a working example, consider the element MPC $_{\text{facility layout, excess design factor}}$. *Note that these two attributes are not inter-related.* Figure 5.2.2.1, shown on the following page, is the IDM used in this analysis. Only the upper half of this matrix was completed, as any inter-relationship needs to be identified only once. The inter-relationships are identified by a black element above the diagonal.



	Life Cycle-Cost	Initial Cost	Operating Cost	Operating Strategy	Required Facility Availability	Facility Layout	Facility Design Life	Location (micro)	Utility Type	Risk Exposure	Excess Capacity	Infrastructure Requirements	Schedule/Delivery Considerations	Level of Automation	Redundancy	Maintenance Requirements	Utility Demands	Design Standards	Materials of Construction	Reliability Requirements	Excess Design Factor
Life Cycle-Cost	▨	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Initial Cost	▨	▨	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Operating Cost	▨	▨	▨	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Operating Strategy	▨	▨	▨	▨	■	□	□	□	□	□	■	□	□	■	■	■	■	□	□	■	□
Required Facility Availability	▨	▨	▨	▨	▨	□	□	□	■	■	■	□	□	■	■	■	□	■	■	■	□
Facility Layout	▨	▨	▨	▨	▨	▨	□	■	□	□	□	□	□	□	□	■	□	□	□	□	□
Facility Design Life	▨	▨	▨	▨	▨	▨	▨	□	■	□	■	■	□	□	□	■	■	■	■	□	□
Location (micro)	▨	▨	▨	▨	▨	▨	▨	▨	□	■	□	□	□	□	□	□	□	□	□	□	□
Utility Type	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	■	□	□	□	□	■	□	□	■	□
Risk Exposure	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	■	□	■	■	■	□	■	■	■	■
Excess Capacity	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	■	■	■	□	□	■	■
Infrastructure Requirements	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	■	□
Schedule/Delivery Considerations	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□	■	■	□	□
Level of Automation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	■	□	□	□	■	□
Redundancy	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	□	□	□	■	■
Maintenance Requirements	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	■	■	■	□
Utility Demands	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	□	□	□
Design Standards	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■
Materials of Construction	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	□
Reliability Requirements	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□
Excess Design Factor	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure 5.2.2.1. The IDM used in this analysis

In the traditional AHP model developed, it was stated that facility layout is strongly more important than excess design factor. In the nine-point scheme, this means that MPC $_{\text{facility layout, excess design factor}} = 5$. When attribute inter-relationships are considered, MPC $_{\text{facility layout, excess design factor}}$ is a function of the values of facility layout, excess design factor, and all the attributes that are inter-related with these two attributes. The inter-related attributes as seen in the IDM are location (micro), maintenance requirements, risk exposure, excess capacity, redundancy, and design standards.

Therefore, the $\text{MPC}_{\text{facility layout, excess design factor}}$ within the model is $\text{MPC}_{\text{facility layout, excess design factor}}$*(**f**(facility layout) * **f**(excess design factor) * **f**(location-micro) * **f**(maintenance requirements) * **f**(risk exposure) * **f**(excess capacity) * **f**(redundancy) * **f**(design standards)) where each **f**(attribute) is a numerical value that depends on the choice for that attribute that accounts for an inter-relationship within the model. Or:

$\textbf{MPC(modified)}_{\textbf{facility layout, excess design}}$ =

$\textbf{MPC(typical)}_{\textbf{facility layout, excess design}}$ * Πf(values of "base" attributes) *

Πf(values of inter-related attributes)

Where the functions of the inter-related attributes (modification functions) modify the original MPC element to reflect the attribute inter-relationships and where Π is the multiplicative function.

The multiplicative function is used to model the inter-relationship because it has been successfully used to model deviations from "known" or "representative" cases in the past. For example, in fracture mechanics, the stress intensity factor (K) for a central through crack in an infinite plate is well known:

$$K = \sigma * \sqrt{\pi * a}$$

Where σ is the normal stress, and a is half the crack width. Where the mathematical derivations for a crack in an infinite plate are relatively simple, the derivation for stress intensity factors in finite-dimensioned plates is extremely difficult. Fisher proposes the use of "correction factors to modify $\sigma * \sqrt{\pi * a}$ (for the idealized case) to account for the effects of free surface,... finite width,... nonuniform stresses acting on the crack,... and crack shape" (Fisher, 1984) in the calculation of stress intensity factors for finite-dimensioned plates. The stress intensity factor for finite-dimensioned plates may be expressed as:

$$K = F_e * F_s * F_w * F_g * \sigma * \sqrt{\pi * a}$$

Where the F_e, F_s, F_w, and F_g, are determined by empirical formulas which account for the effects of free surface, finite width, nonuniform stresses acting on the crack, and crack shape, respectively. In other words, these functions are used to account for a deviation from a known, or baseline case.

In this thesis, the modification functions are numerical values that account for the choices of the inter-related attributes. For example, the choices for location are remote or accessible. If a *remote* location causes facility layout to become *even more* important than excess design factor, then f(location) for location equal to remote is equal to some number greater than 1, since a number greater than one increases the importance of facility layout relative to the excess design factor. This number is determined by an expert in the field of analysis using an experience base and subjective judgment. For this working example, assume this number is 1.2 (the scale and magnitude of the modification functions is discussed in Section 5.2.5). A modification factor equal to 1.2 will reflect the inter-dependency, with respect to importance. If, however, an *accessible* location causes facility layout to become *relatively additionally less* important than excess design factor, then f(location) for is equal to some number less than 1. Again, this number is determined by an expert using experience and subjective judgment. For this case, assume this number is 0.8. Therefore, in this case,

f(location) = 1.2 if location = remote,

or 0.8 if location = accessible.

The functions for the remaining relevant attributes for the modified MPC are also calculated. The key scenario to remember is, "Attribute X is inter-related with the pairwise comparison in question. Value Y of attribute X may cause the dominant attribute of the pairwise comparison to become some degree additionally more or additionally less important, relative to the "typical" case. What is this degree?"

The inter-related attribute functions are not necessarily equivalent for different elements in the MPC, since the effect of the value of attribute X on attribute Y may differ from the effect of the value of attribute X on attribute Z.

It should be noted that for a choice equal to a typical case, the modification function of that attribute should not change the MPC. Therefore, in this case, the modification function is equal to 1. This is due to the fact that the original MPC was developed for the typical case, and should remain unaffected for the "typical case" scenario. For example, the choices for risk exposure are low, normal, and high. Assuming that the choice: "normal" is the typical case of risk exposure, any **f**(risk exposure) when risk exposure is equal to normal is equal to 1.

After all the inter-relationship functions are specified, and a particular alternative is specified, the principal eigenvector of the modified MPC may be calculated, and normalized. The MPC is now different for each alternative. It follows that the principal eigenvectors and normalized weights will differ across alternatives too, so that the principal eigenvector must be calculated for each alternative when the desirability scores are being calculated.

5.2.3 The Inter-Related Attribute Preferences

The preference values for each attribute's choices must also reflect the inter-relationships that occur within a problem. This is done analogously to the modified MPC. That is, the values in the vector of preference ratios are multiplied by functions of the values of the inter-related attributes. This vector is then normalized so that the desirability score may be calculated.

For example, consider the values of the attribute facility layout. The choices for facility layout are compressed or normal. Assume that, for a typical case, a normal facility is twice as preferable as a compressed facility. The normalized (DBS) vector of preference ratios for a typical production facility would be:

Choice	**Value**
Normal	0.667
Compressed	0.333

since a normal facility layout is twice as preferable than a compressed facility. The facility layout has been determined to be inter-related with location, and maintenance requirements (see the IDM in section 5.2.2). Therefore, a modification factor is needed for the values of facility layout, which is a function of these attributes. The modified (pre-normalization) vector of preference ratios are:

Choice	**Value**
Normal	0.667***f1**(location)***f1**(maintenance requirements)
Compressed	0.333***f2**(location)***f2**(maintenance requirements)

Again, since facility layout is inter-related with location and maintenance requirements, they must be modeled in the vector of preference values. Note that the modification functions for each inter-related attribute are modeled independently of each other. Again, the modification functions are determined by an expert in the field. Take, for example, the inter-relationship between facility layout and location. As stated before, the choices for facility layout are normal or compressed. The choices for location are remote or accessible. If an accessible production facility location diminishes the value of a normal facility layout. Then **f1**(location), when location is accessible, would be a number less than one. Assume for illustrative purposes here that this number is 0.9. This value is determined by an expert. Analogously, **f2**(location), when location is accessible, would be a number greater than one. This is because an accessible location increases the value of a compressed layout, relative to a normal layout. Assume this number is 1.2. These numbers reflect the nuance that when the location is accessible, a normal layout may not be as preferable, relative to the typical case.

5.2.4 The Calculation of Desirability Indices in the Proposed MADA

Since the inter-related MPC and inter-related attribute values are determined before normalization, the calculation of the desirability scores is the same as in AHP, once the modification factors have been applied. There are a few key differences though.

As mentioned before, the principal eigenvector of the MPC must be calculated, and normalized, for each alternative. This is because the MPC is different for each alternative, leading to different attribute weights for each alternative.

Similarly, the attribute weights must be calculated, and normalized, for each alternative. Again, this is due to the fact that the attribute weights vary across alternatives.

Once all the principal eigenvectors and preference vectors are calculated, the desirability score for each alternative may be calculated. The nature of this calculation remains unchanged. That is, the desirability score for each alternative is still the sum of the products of weight and score. Equation 5.2.4.1 is used to calculate the desirability score for the proposed multiattribute decision analysis.

$$DesirabilityScore_j = \sum_{i=1}^{n} (weight_i) * (score_i) \cdot$$

Equation 5.2.4.1. The formula for calculating the desirability score in the AHP and the proposed multiattribute decision analysis method

5.2.5 A Fuzzy Scheme for the Modification Functions

In the AHP, the MPC is frequently constructed with a fuzzy nine-point scheme where verbal judgments are given a quantifiable numerical equivalent (Saaty). These values are given on the following page in Table 5.2.5.1.

Verbal Judgment	**Numerical Equivalent**
Extremely More Important	9
Very Strongly More Important	7
Strongly More Important	5
Moderately More Important	3
Equally as Important	1

Table 5.2.5.1. A fuzzy scheme for the MPC

An analogous nine-point scheme may be used to create the preference ratios for the attribute choices. In this case, the term "preferred" is substituted for "important." It should be noted that NIST has shown that variation in the numerical equivalents can affect the ranking of the alternatives (NIST). If this is the case, then a more detailed analysis is required.

After the representative case study, or "typical case," MPC is created with the nine-point scheme mentioned above, the modification functions may be determined. Modification functions, as mentioned before, are the functions which numerically account for any deviation of a particular alternative from the "typical case" scenario. They can be utilized in two places, in the MPC and in the various preference ratios.

In order to model inter-relationships in the MPC, each element is multiplied by functions of the "base" pairwise attributes it models, and all the attributes which are inter-related with both the "base" attributes. For each of the modification functions for a pairwise comparison, the following scenario is postulated; "Attribute X is inter-related with the pairwise comparison in question. Value Y of attribute X causes the dominant attribute of the pairwise comparison to become some degree additionally more or additionally less important, relative to the "typical" case. What is this degree?" The dominant attribute is the more important attribute. Attribute X may be one of the "base" attributes, or one of the inter-related attributes. To ease data collection, another fuzzy scheme may be used, analogous to the fuzzy scheme mentioned above. This fuzzy scheme is presented in Table 5.2.5.2.

Verbal Judgment	Numerical Equivalent
Extremely Additionally More Important	1.7
Very Strongly Additionally More Important	1.5
Strongly Additionally More Important	1.3
Moderately Additionally More Important	1.1
Equally as Important	1

Table 5.2.5.2. A fuzzy scheme used to model inter-relationships in the MPC

If the dominant attribute in the MPC becomes some degree "*less*" additionally important than the baseline, or "typical," case, then the appropriate value of the numerical equivalent (substituting "less" for "more") is simply inverted. The numerical equivalents become the values of the modification function for the case when attribute X has the value Y. These numerical equivalents are then tabulated for all values of all the base and inter-related attributes.

The development of the modification functions for the preference ratios is analogous. When developing the modification functions for attribute A, consider the following scenario: "Attribute A is inter-related with attribute B. Value X of attribute B causes the value Y of attribute A to be some degree additionally more or less preferable, relative to the "typical" case. What is that degree?" Again, a fuzzy scheme is employed. This fuzzy scheme is presented in Table 5.2.5.3.

Verbal Judgment	Numerical Equivalent
Extremely Additionally More Preferable	1.7
Very Strongly Additionally More Preferable	1.5
Strongly Additionally More Preferable	1.3
Moderately Additionally More Preferable	1.1
Equally as Preferable	1

Table 5.2.5.3. A fuzzy scheme used to model inter-relationships in the vector of preferences

Again, the numerical equivalents are inverted if the value Y of attribute A becomes some degree "less" preferable, instead of "more" preferable.

5.2.6 The Automation of the Modified AHP

The user interface of a program that automates the modified AHP would appear identical to an unmodified AHP because no additional information is required from the user. Only the method of calculation differs. That is, the principal eigenvectors and preference ratio vectors for each alternative may be calculated without any additional information required from the user.

It follows that a modified AHP analysis may be run in parallel with an unmodified AHP analysis, for verification and sensitivity analyses.

5.2.7 Problems in Data Acquisition

The data acquisition for a modified AHP analysis is much more involved than for a traditional AHP analysis. The expert is faced with isolating complex relationships, and modeling the relationships by assigning them a numerical value. This problem may be partially resolved by the utilization of additional fuzzy schemes, similar to the nine point scheme, that ease data acquisition with little loss of accuracy.

It is also essential that the expert involved has a clear understanding of the relationships that are being modeled.

5.3 An Example of the Proposed Multiattribute Decision Analysis Method

Again, consider the purchase of a new car. Refer to the example in section 4.1 for a traditional AHP analysis of the purchase of a new car. This example will illustrate the modified AHP. Consider three attributes, size, color, and cost. The values of size are: small, medium, and large. The values of color are: red, blue, and yellow. The values of cost are: inexpensive, moderate, and expensive. Assume that the MPC and preference values for the "typical" case is the same as the example in section 4.1.

Step 1: Establish the inter-related attributes

The first step is to establish which attributes are inter-related. Assume some colors affect cost. That is, color is inter-related with cost. Also assume that cost is inter-related with size. Then the IDM would look like:

	Size	Color	Cost
Size	▨		x
Color	▨	▨	x
Cost	▨	▨	▨

That is, cost is inter-related with both size and color.

Step 2: Create the modified MPC

The original MPC in Section 4.1 was:

	Size	Color	Cost
Size	1	5	1/3
Color	1/5	1	1/9
Cost	3	9	1

The modified MPC is now:

	Size	Color	Cost
Size	1	5*$f_{1,2}$(size)*$f_{1,2}$(color)*$f_{1,2}$(cost)	(3*$f_{1,3}$(size)*$f_{1,3}$(cost)*$f_{1,3}$(color))^-1
Color	(5*$f_{1,2}$(size)*$f_{1,2}$(color)*$f_{1,2}$(cost))^-1	1	(9*$f_{2,3}$(size)*$f_{2,3}$(cost)*$f_{2,3}$(color))^-1
Cost	3*$f_{1,3}$(size)*$f_{1,3}$(cost)*$f_{1,3}$(color)	9*$f_{2,3}$(size)*$f_{2,3}$(cost)*$f_{2,3}$(color)	1

Note that the modification functions have subscripts. This is because the modification functions are not necessarily the same for each relationship.

That is, the value of an attribute will impact the importances and preference of other attributes differently.

Step 3: Determine the modification functions for the MPC

The modification functions must now be determined. Consider the relationship between color and size. In the "typical" case, size is "strongly more important" than color. That is, size is 5 times more important than color. The modification functions modify the "five times more important" with respect to the values of size, color, and cost. Cost is included since it is inter-related with size (and color). Now look at how the value of size impacts the relationship between size and color. For example, does the size of a large car make the size of the car even more, or less important than color for the typical case. Assume that a large car does, in fact, make the importance of the size of the car moderately additionally less important than color, relative to the typical case. So **$f_{1,2}$(size)** is equal to some number less than 1 for size equal to large. According to the fuzzy scheme presented in section 5.2.5, **$f_{1,2}$(size) = (1/1.1) = 0.91** when size is equal to large. That is, according to the fuzzy scheme presented earlier, when size is equal to large, size becomes moderately additionally less important than color. For size equal to medium, **$f_{1,2}$(size) = 1**. This is because medium is the typical case scenario. For size equal to small, the say that the color becomes moderately additionally more important. So, in this case, **$f_{1,2}$(size) = 1.1** for size equal to small.

Now consider the effect of color on the relationship between color and size. Does a blue car make size even more or less important than color? Assume that for color equal to blue, **$f_{1,2}$(color) = (1/1.3) = 0.77**. That is, a color equal to blue makes color strongly additionally more important than size, relative to the typical case. Assume that color equal to red is the typical case. Then **$f_{1,2}$(color) =1.3**, for color equal to red. For color equal to yellow, size becomes strongly additionally more important, relative to the typical case. Then **$f_{1,2}$(color)** for color equal to yellow is equal to **1.3**.

Next, consider the effect of cost on the relationship between color and size. Assume that for an inexpensive cost, size becomes moderately additionally more important, relative to the typical case. This means that **$f_{1,2}$(cost) = 1.1**. Assume that for an expensive cost, size becomes moderately additionally less important, relative to the typical case. That is, $f_{1,2}$**(cost) = 0.91** when cost is equal to expensive. Similar to before, a moderate cost would be the typical case, so **$f_{1,2}$(cost)** for cost equal to moderate is equal to one.

The functions of $MPC_{1,2}$ can be summarized in a table:

Size	**f1,2(size)**	**Color**	**f1,2(color)**	**Cost**	**f1,2(cost)**
Small	1.1	Blue	0.77	Inexpensive	1.1
Medium	1	Red	1	Moderate	1
Large	0.91	Yellow	1.3	Expensive	0.91

Similarly, the values of the functions for $MPC_{1,3}$ and $MPC_{2,3}$ may be determined and tabulated as such:

Size	f1,3(size)	Color	f1,3(color)	Cost	f1,3(cost)
Small	1.3	Blue	0.91	Inexpensive	1.1
Medium	1	Red	1	Moderate	1
Large	0.77	Yellow	1.1	Expensive	0.91

Size	f2,3(size)	Color	f2,3(color)	Cost	f2,3(cost)
Small	1.3	Blue	0.77	Inexpensive	1.5
Medium	1	Red	1	Moderate	1
Large	0.77	Yellow	1.3	Expensive	0.67

notice that the functions are unique for each case. This means that the MPC must be computed for each alternative.

Step 4: Determine the modification functions for the preference ratios

The next step is to determine the preference ratios for each attribute. Recall the preference ratios for size:

Size	
Small	0.09
Medium	0.18
Large	0.73

These ratios are now modified to account for the values of inter-related attributes. Since size has been determined to be inter-related with cost, only a function of cost needs to be considered, so that the vector of preference ratios now, as shown on the next page, is:

Size	
Small	0.09*f1(cost)
Medium	0.18*f2(cost)
Large	0.73*f3(cost)

Consider the effect of cost on the performance of size. For example, if the cost is low, the decision maker may not be too picky about size. So the differences between the values of size should be diminished. For cost equal to inexpensive; a small sized car is extremely additionally more preferable, a medium sized car is moderately additionally less preferable, and a large sized car is strongly additionally less preferable. That is, for cost equal to inexpensive; **f3(cost) = 0.77, f2(cost) = 0.91, and f1(cost) = 1.7**. This reflects the notion that the decision maker is willing to deal with a smaller car, if it is inexpensive. Conversely, for a high-priced car, the decision maker wants to be sure that the size is large. In this case, the performance of a large size should be amplified relative to the other sizes. So for an expensive car; a large car is extremely additionally more preferable, a medium sized car is moderately additionally more preferable, and a small car is strongly additionally less preferable. That is, for cost equal to expensive; **f3(cost) = 1.7, f2(cost) = 1.1, and f1(cost) = 0.77**. For cost equal to moderate, the typical case, all the modification functions are equal to one, as nothing has deviated from the typical case. The modification factors for size can be tabulated, as shown on the following page:

The impact of cost on the preference of size:

	f1(cost)	f2(cost)	f3(cost)
Expensive	1.7	1.1	0.77
Moderate	1	1	1
Inexpensive	0.77	0.91	1.7

Cost is also inter-related with color. The modification functions for the effect of cost on the performance of color may be tabulated as:

The impact of cost on the preference of color:

	f1(cost)	f2(cost)	f3(cost)
Expensive	1.5	1.3	0.91
Moderate	1	1	1
Inexpensive	0.91	1	1.7

Note again that the modification functions for color are not the same as the modification functions for size.

Now the modification functions for the performance of cost must be determined. Since there are two attributes inter-related with cost, there are two modification functions for each of the choices of cost. That is, the vector of relative performances looks like:

	Cost
Inexpensive	0.57*f1(size)*f1(color)
Moderate	0.28*f2(size)*f2(color)
Expensive	0.14*f3(size)*f3(color)

The determination of these functions is analogous, and they may be tabulated as shown on the following page:

The impact of size on the preference of cost:

	f1(size)	f2(size)	f3(size)
Small	1.5	1.1	0.77
Medium	1	1	1
Large	0.67	1	1.7

The impact of color on the preference of cost:

	f1(color)	f2(color)	f3(color)
Blue	1.5	1.3	0.91
Red	1	1	1
Yellow	0.91	1	1.7

Step 5: Calculate the desirability scores for each alternative

Now that all the modification factors have been tabulated, the individual alternatives may be considered. Again, look at the three alternatives that were considered in the first example:

	Alternative A	Alternative B	Alternative C
Size	Large	Medium	Small
Color	Yellow	Blue	Red
Cost	Moderate	Expensive	Inexpensive

The MPC for alternative A looks like:

	Size	Color	Cost
Size	1	$5*f_{1,2}(size)*f_{1,2}(color)*f_{1,2}(cost)$	$(3*f_{1,3}(size)*f_{1,3}(cost)*f_{1,3}(color))$^-1
Color	$(5*f_{1,2}(size)*f_{1,2}(color)*f_{1,2}(cost))$^-1	1	$(9*f_{2,3}(size)*f_{2,3}(cost)*f_{2,3}(color))$^-1
Cost	$3*f_{1,3}(size)*f_{1,3}(cost)*f_{1,3}(color)$	$9*f_{2,3}(size)*f_{2,3}(cost)*f_{2,3}(color)$	1

Since the values are specified, the functions may be determined, as shown on the following page:

	Size	Color	Cost
Size	1	5*0.91*1.3*1	(3*0.77*1*1.1)^-1
Color	(5*0.91*1.3*1)^-1	1	(9*0.77*1*1.3)^-1
Cost	3*0.77*1*1.1	9*0.77*1*1.3	1

The resulting MPC for alternative A is:

	Size	Color	Cost
Size	1	5.92	0.394
Color	0.167	1	0.122
Cost	2.54	8.23	1

The resulting principal eigenvector of this matrix is:

Size	0.43
Color	0.09
Cost	0.89

The normalized weights are:

Size	0.30
Color	0.07
Cost	0.63

Note that the weights sum to one, and are different than in the original AHP analysis.

Next the preferences must be calculated. The modified preference ratios for size are:

Size	
Small	0.09*f1(cost)
Medium	0.18*f2(cost)
Large	0.73*f3(cost)

The modification functions were determined above. With these values, the vector of preferences, for alternative A is:

Size	
Small	0.09*1
Medium	0.18*1
Large	0.73*1

Since the cost is the typical case (moderate), the modification functions are all equal to one (see above for explanation), and the vector of preferences for alternative A remains unchanged:

Size	
Small	0.09
Medium	0.18
Large	0.73

The modification functions for color are:

Color	
Blue	0.67*f1(cost)
Red	0.26*f2(cost)
Yellow	0.07*f3(cost)

Again, since the cost is equal to the typical case (moderate) for this alternative, the modification functions are all equal to one. The normalized vector of preferences is:

Color	
Blue	0.67
Red	0.26
Yellow	0.07

The modification factors for cost, as shown on the next page, are:

Cost	
Inexpensive	0.58*f1(size)*f1(color)
Moderate	0.28*f2(size)*f2(color)
Expensive	0.14*f3(size)*f3(color)

For this alternative, the vector of preference ratios is:

Cost	
Inexpensive	0.58*0.67*0.91
Moderate	0.28*1*1
Expensive	0.14*1.7*1.7

Normalized, this vector is:

Cost	
Inexpensive	0.34
Moderate	0.27
Expensive	0.39

This is the vector of preferences that will be used in the calculation of the desirability score for alternative A.

The principal eigenvectors and preference ratios are calculated analogously for the other two alternatives, so that the final desirability scores are:

	Alternative A	Weight* Score(A)	Alternative B	Weight* Score(B)	Alternative C	Weight* Score(C)
Size	Large	(0.30)*(0.73)	Medium	(0.30)*(0.22)	Small	(0.20)*(0.048)
Color	Yellow	(0.07)*(0.067)	Blue	(0.10)*(0.71)	Red	(0.04)*(0.27)
Cost	Moderate	(0.63)*(0.27)	Expensive	(0.60)*(0.095)	Inexpensive	(0.76)*(0.67)
Desirability Score		0.39		0.19		0.53

Notice that the attribute weights are different for each alternative (as one goes across columns). This is due to the fact that the MPC varies depending on the specification of the attributes. Also notice that the ordinal rankings have not changed. That is, alternative C is still the alternative that performs the best. The consideration of inter-relationships makes it even clearer that Alternative C is the most desirable, relative to the traditional AHP analysis. Alternative B clearly should not be considered in further analyses, since it's desirability score is even lower (relative to alternatives A and C) than before.

5.4 A Summary of Chapter 5

The technique and methodology of the analytic hierarchy process was presented, along with a demonstrative example, in Chapter 4. It was pointed out that modifications could be made to more accurately model alternatives as complex as production facilities, and other large-scale civil engineering projects. The technique and methodologies of these modifications were made in Chapter 5, where an attempt was made towards utilizing the systems approach in civil engineering decision making, where complex procedures are systematically and comprehensively explored. This, in turn, allows the development of a model of inter-related attributes at the element, sub-system, and system level.

6. Data Collection and Analysis

The data for this research project was primarily collected in collaboration with the members of CII Task Force #122. Data specific to the analytic hierarchy process and the modified analytic hierarchy process was collected by a survey which was distributed to a select sub-set of members from the Task Force.

6.1 The Attributes and Values of a Production Facility

The attributes of a production facility, for this analysis, were determined by the CII task force on life-cycle engineering. These attributes are listed on the next page in Table 6.1.1.

Cost Attributes	Life Cycle-Cost Initial Cost Annual Cost
Conceptual Design Attributes	Operating Strategy Required Facility Availability Facility Layout Facility Design Life Location Utility Type Risk Exposure Excess Capacity Infrastructure Requirements Schedule/Delivery Considerations
Schematic Design Attributes	Level of Automation Redundancy Maintenance Requirements Utility Demands Design Standards Materials of Construction Reliability Requirements Excess Design Factor

Table 6.1.1. The list of attributes considered in this analysis

The definitions of these attributes may be found in Appendix A. There are three cost attributes: life-cycle cost, initial cost, and annual cost. Three different types of costs were considered in order to express the differences between them with respect to importance. That is, high initial costs may be compensated by low annual or life-cycle costs. The conceptual design attributes are attributes that are determined early in the life of the project. The schematic attributes reflect the construction and operation of a production facility, where a decision maker has a high degree of flexibility with respect to design across alternatives.

These attributes may be compared to NIST's list of attributes for buildings (NIST). The attributes are not the same, but for the most part, they are analogous. The attributes presented here represent those design decisions frequently encountered in process plant design.

The values of these attributes are presented in Tables 6.1.2, 6.1.3, and 6.1.4.

Phase	Attribute	Values
Cost Attributes	Life Cycle-Cost	Very Expensive
		Expensive
		Moderate
		Inexpensive
		Very Inexpensive
	Initial Cost	Very Expensive
		Expensive
		Moderate
		Inexpensive
		Very Inexpensive
	Annual Cost	Very Expensive
		Expensive
		Moderate
		Inexpensive
		Very Inexpensive

Table 6.1.2. The table of cost attributes and choices considered in this analysis

Phase	Attribute	Values
Conceptual Design Attributes	Operating Strategy	Continuous
		Non-Continuous
	Required Facility Availability	Low
		Medium
		High
	Facility Layout	Normal
		Compressed
	Facility Design Life	Less Than 10 Years
		10 to 20 Years
		Greater than 20 Years
	Location	Easy Access
		Difficult Access
	Utility Type	Convert
		Purchase
	Risk Exposure	Low
		Medium
		High
	Excess Capacity	No
		Yes
	Infrastructure Requirements	Existing Infrastructure
		Moderate Additional Infrastructure
		Extensive Additional Infrastructure
	Schedule/Delivery Considerations	Compressed
		Normal

Table 6.1.3. The table of conceptual attributes and choices considered in this analysis

Phase	Attribute	Values
Schematic Design Attributes	Level of Automation	Low
		Medium
		High
	Redundancy	None
		Selective
		Full
	Maintenance Requirements	Low
		Normal
		High
	Utility Demands	Normal
		Minimized
	Design Standards	Project Specific
		Corporate Standard
		Industry Standard
	Materials of Construction	Standard
		High Performance
	Reliability Requirements	Normal
		High
	Excess Design Factor	None
		Usual
		High

Table 6.1.4. The table of schematic attributes and choices considered in this analysis

The values for the conceptual and schematic design decisions were compiled by the CII Task Force. Values for the cost attributes were specified by the author simply by creating a logically consistent MPC. That is, a “less expensive” facility is always preferable to a “more expensive” facility, all other attributes kept constant. Since the cost attributes are among the most important attributes, a wider variety of choices was given in an attempt to give the user an opportunity to express the differences between similarly performing alternatives. The values for costs are specified by the user on a qualitative level because exact costs are difficult to specify at the time when this analysis would be most effective. The calculations for these preference values may be found in Appendix B.

6.1.1 The Cost Elements

The CII task force has specified a set of elements of life-cycle cost. These elements are parts that sum to life-cycle cost. There are approximately 20 elements of life-cycle cost specified, which span from planning and design through decommissioning. The list of cost elements was developed as part of the knowledge base used in the CII project, but they are not all relevant to an AHP analysis. This list may be found in Appendix C.

Life-cycle cost is considered in this analysis, as life-cycle cost is the "bottom line" measure of cost of a production facility. Initial cost and annual cost are also considered to give a decision maker the opportunity to account for the possibility that a production facility may have a low life-cycle cost, but initial cost may by high. For example, high initial costs may steer decision makers away from a particular design alternative, even if life-cycle costs are low, so the value of low initial cost should be accounted for in the AHP model.

6.1.2 Constraints of the Model

The CII task force has also specified a series of "pre-established objectives and constraints." These are constraints that are placed upon the design of the production facility. For example, the cost of capital is a pre-established constraint because it is relevant to the design problem over the life-cycle of the project, yet the design team has no control over it's value. Table 6.1.2.1 lists the pre-established objectives and constraints.

Pre-Established Objectives and Constraints	Cost of Capital
	Product Demand
	Product Margin
	Date Required
	Location (macro)
	Facility Flexibility
	Facility Capacity
	Technology Life
	Process Requirements
	Construction Equipment Availability
	Construction Labor Availability

Table 6.1.2.1. The list of pre-established objectives and constraints created by the CII Task Force

The pre-established objectives and constraints were not considered as attributes in the AHP analysis. This is because they are assumed to be constant across alternatives, and hence not impacting the desirability indices relative to each other. That is, if the value of cost of capital is 10% for one alternative, it will be 10% for all alternatives, or it will not differ significantly enough to affect calculations.

6.2 The Collected Data

The raw data that was collected for this AHP analysis may be found in Appendix D. Several experts were surveyed, with differing results. The experts were asked to complete a MPC, and a table of preference ratios for all the attributes. As should be expected, the consistency indices were not ideal. In general, they were above the normally acceptable tolerances. This may be partially due to the unfamiliarity of the experts surveyed with MADA techniques, and partially due to the actual size of the MPC involved.

It should be kept in mind that the goal of the use of a MPC is a vector of importance ratios, not a perfectly consistent matrix. That is, if the vector of importance ratios is verified, then even a high consistency ratio is acceptable. In this case, the vector of importance ratios was verified by the members of the CII Task Force.

The vector of importance ratios used in this analysis was revised after the MPC was created. That is, when this vector was sent out for verification, some changes were made. The preference vectors for each attribute reflect a synthesis of each of the expert's results.

6.3 The Desirability Scores

The desirability scores may now be calculated for any production facility alternative. As mentioned in Section 6.2, the weights and performance ratios presented in Tables 6.3.1 through 6.3.4 were calculated from the survey of the Construction Industry Institute Task Force #122. The consistency ratio of the MPC used to generate this vector of weights was 3.8%, which is acceptable since it less than 10% (Saaty, 1980).

	Attribute	Weight
Cost Attributes	Life Cycle-Cost	.117
	Initial Cost	.053
	Annual Cost	.053
Conceptual Design Attributes	Operating Strategy	.117
	Required Facility Availability	.012
	Facility Layout	.053
	Facility Design Life	.023
	Location	.0068
	Utility Type	.011
	Risk Exposure	.023
	Excess Capacity	.117
	Infrastructure Requirements	.053
	Schedule/Delivery Considerations	.053
Schematic Design Attributes	Level of Automation	.023
	Redundancy	.011
	Maintenance Requirements	.053
	Utility Demands	.105
	Design Standards	.024
	Materials of Construction	.024
	Reliability Requirements	.024
	Excess Design Factor	.012

Table 6.3.1. The list of attributes and their weights considered in the AHP analysis

Phase	Attribute	Choices	Value
Cost Attributes	Life Cycle-Cost	Very Expensive	0.033
		Expensive	0.063
		Moderate	0.13
		Inexpensive	0.26
		Very Inexpensive	0.51
	Initial Cost	Very Expensive	0.033
		Expensive	0.063
		Moderate	0.13
		Inexpensive	0.26
		Very Inexpensive	0.51
	Annual Cost	Very Expensive	0.033
		Expensive	0.063
		Moderate	0.13
		Inexpensive	0.26
		Very Inexpensive	0.51

Table 6.3.2. The list of cost attributes and values considered in the AHP analysis

Phase	Attribute	Choices	Value
Conceptual Design Attributes	Operating Strategy	Continuous	0.88
		Non-Continuous	0.12
	Required Facility Availability	Low	0.11
		Medium	0.33
		High	0.56
	Facility Layout	Normal	0.75
		Compressed	0.25
	Facility Design Life	Less Than 10 Years	0.14
		10 to 20 Years	0.43
		Greater than 20 Years	0.43
	Location	Easy Access	0.75
		Difficult Access	0.25
	Utility Type	Convert	0.75
		Purchase	0.25
	Risk Exposure	Low	0.56
		Medium	0.33
		High	0.11
	Excess Capacity	No	0.17
		Yes	0.83
	Infrastructure Requirements	Existing Infrastructure	0.56
		Moderate Additional Infrastructure	0.33
		Extensive Additional Infrastructure	0.11
	Schedule/Delivery Considerations	Compressed	0.75
		Normal	0.25

Table 6.3.3. The list of conceptual attributes and values considered in the AHP analysis

Phase	Attribute	Choices	Value
Schematic Design Attributes	Level of Automation	Low	0.11
		Medium	0.33
		High	0.56
	Redundancy	None	0.14
		Selective	0.43
		Full	0.43
	Maintenance Requirements	Low	0.64
		Normal	0.27
		High	0.09
	Utility Demands	Normal	0.25
		Minimized	0.75
	Design Standards	Project Specific	0.56
		Corporate Standard	0.11
		Industry Standard	0.33
	Materials of Construction	Standard	0.17
		High Performance	0.83
	Reliability Requirements	Normal	0.17
		High	0.83
	Excess Design Factor	None	0.33
		Usual	0.56
		High	0.11

Table 6.3.4. The list of conceptual attributes and values considered in the AHP analysis

The desirability score for each alternative is calculated by summing the products of weight and appropriate value, as presented in Chapter 4.

6.4 Collection of the Modified AHP Data

Data was collected in order to demonstrate the proposed multiattribute decision analysis method. This data was verified through contact with a select subset of members within the CII Task Force, and will be presented in

Chapter 7. The proposed multiattribute decision analysis method will be demonstrated in Chapter 7 on a subset of the most important attributes. An MPC will be created that accounts for the inter-relationships between this subset of attributes.

The attributes used to demonstrate the proposed multiattribute decision analysis method were chosen because the Task Force determined these to be the most important attributes of a production facility (process plant).

6.5 A Summary of Chapter 6

Chapter 6 presented the data used in the analysis. The attributes of a production facility were given in Section 6.1. Sections 6.1.1 and 6.1.2 mentioned other data relevant to the evaluation of production facilities, but not in an AHP analysis. All the information required to calculate the desirability score for an alternative was presented in Section 6.3, and information on the data collection for the proposed MADA method was given in Section 6.4.

7. Implementation and Verification

7.1 The Traditional AHP Analysis

The data collected from the panel of experts from the CII Task Force was compiled and verified. In addition to the task force, the list of attributes was verified by roughly 30 project managers in the production facility (process plant) industry. Companies surveyed include Eli Lilly, Lockwood Greene, and TPA, Inc. These companies were asked to respond to this stage of the verification as part of the Task Force's project.

The data for the importance MPC and preference vectors was acquired from a select subset of the Task Force. Each expert on the Task Force who created an MPC received their specific normalized principal eigenvector to review. The consistency ratios of these matrices varied from under 0.04 to nearly 0.40. The experts, for the most part, agreed with the cardinal ranking of attributes as given by their specific principal eigenvector. Some changes were made to these vectors, such as slight increasing or decreasing the cardinal ranking of a few attributes, or the "swapping" of cardinal rank of two attributes. But, in general, the members of the CII Task Force who were asked to complete the MPC agreed with the ranking of attributes by importance.

7.1.1 Presentation of Complied Data

The compiled data may be found in the Tables 7.1.1.1 through 7.1.1.3. For each attribute, the weight of that attribute is given in the third column. The preference value is given for each choice in the fifth column. The sixth column is the product of attribute weight and preference value, so this is given for each attribute's choice.

Phase	Attribute	Weight	Choices	Value	Weight* Value
Cost Attributes	Life Cycle-Cost	0.117	Very Expensive	0.033	0.0039
			Expensive	0.063	0.0074
			Moderate	0.13	0.015
			Inexpensive	0.26	0.03
			Very Inexpensive	0.51	0.06
	Initial Cost	0.053	Very Expensive	0.033	0.0018
			Expensive	0.063	0.0033
			Moderate	0.13	0.0069
			Inexpensive	0.26	0.014
			Very Inexpensive	0.51	0.027
	Annual Cost	0.053	Very Expensive	0.033	0.0018
			Expensive	0.063	0.0033
			Moderate	0.13	0.0069
			Inexpensive	0.26	0.014
			Very Inexpensive	0.51	0.027

Table 7.1.1.1. The weights, preference values, and their products for the cost attributes.

Phase	Attribute	Weight	Choices	Value	Weight* Value
Conceptual Design Attributes	Operating Strategy	0.117	Continuous	0.88	0.1
			Non-Continuous	0.12	0.014
	Required Facility Availability	0.012	Low	0.11	0.0013
			Medium	0.33	0.004
			High	0.56	0.0067
	Facility Layout	0.053	Normal	0.75	0.04
			Compressed	0.25	0.013
	Facility Design Life	0.023	Less Than 10 Years	0.14	0.0032
			10 to 20 Years	0.43	0.0099
			Greater than 20 Years	0.43	0.0099
	Location	0.0068	Easy Access	0.75	0.0051
			Difficult Access	0.25	0.0017
	Utility Type	0.011	Convert	0.75	0.0083
			Purchase	0.25	0.0028
	Risk Exposure	0.023	Low	0.56	0.013
			Medium	0.33	0.0076
			High	0.11	0.0025
	Excess Capacity	0.117	No	0.17	0.02
			Yes	0.83	0.097
	Infrastructure Requirements	0.053	Existing Infrastructure	0.6	0.032
			Moderate Additional	0.33	0.018
			Extensive Additional	0.067	0.0035
	Schedule/Delivery Considerations	0.053	Compressed	0.75	0.04
			Normal	0.25	0.013

Table 7.1.1.2. The weights, preference values, and their products for the conceptual attributes.

Phase	Attribute	Weight	Choices	Value	Weight* Value
Schematic Design Attributes	Level of Automation	0.023	Low	0.11	0.0025
			Medium	0.33	0.0076
			High	0.56	0.013
	Redundancy	0.011	None	0.14	0.0015
			Selective	0.43	0.0047
			Full	0.43	0.0047
	Maintenance Requirements	0.053	Low	0.64	0.034
			Normal	0.27	0.014
			High	0.09	0.0048
	Utility Demands	0.105	Normal	0.25	0.026
			Minimized	0.75	0.079
	Design Standards	0.024	Project Specific	0.56	0.013
			Corporate Standard	0.11	0.0026
			Industry Standard	0.33	0.0079
	Materials of Construction	0.024	Standard	0.17	0.0041
			High Performance	0.83	0.02
	Reliability Requirements	0.024	Normal	0.17	0.0041
			High	0.83	0.02
	Excess Design Factor	0.012	None	0.33	0.0037
			Usual	0.55	0.0066
			High	0.11	0.0013

Table 7.1.1.3. The weights, preference values, and their products for the schematic attributes.

The desirability index for each alternative is calculated by summing the appropriate elements from the "Weight*Value" column. That is, for each attribute, select one choice for each attribute, and sum the values in the "Weight*Value" column. The desirability indices represent a cardinal ranking of attributes, with respect to desirability. In other words, the attribute with the highest desirability index is the most desirable.

7.2 Demonstration of the Proposed Multiattribute Decision Analysis

A demonstration of the proposed MADA will now be given. The attributes of this demonstration will be life-cycle cost (LCC), Facility Layout (FL), Operating Strategy (OS), Excess Capacity (EC), and Utility Demand (UD). These attributes were chosen since they were determined to be the most important attributes, with respect to the life-cycle of a production facility. The Task Force has specified inter-dependencies between some of these attributes. Refer to the Inter-Dependency Matrix (IDM) in Figure 5.2.2.1. This will illustrate the inter-dependencies that the Task Force have identified. Given these inter-dependencies, the MPC for the proposed MADA is presented in Figure 7.2.1.

	LCC	**FL**	**OS**	**EC**	**UD**
LCC	1	$3*f(LCC)_{0,1}*f(FL)_{0,1}*f(OS)_{0,1}*f(EC)_{0,1}*f(UD)_{0,1}$	$1*f(LCC)_{0,2}*f(FL)_{0,2}*f(OS)_{0,2}*f(EC)_{0,2}*f(UD)_{0,2}$	$1*f(LCC)_{0,3}*f(FL)_{0,3}*f(OS)_{0,3}*f(EC)_{0,3}*f(UD)_{0,3}$	$1*f(LCC)_{0,3}*f(FL)_{0,3}*f(OS)_{0,3}*f(EC)_{0,3}*f(UD)_{0,3}$
FL		1	$1/3*f(LCC)_{1,2}*f(FL)_{1,2}*f(OS)_{1,2}*f(EC)_{1,2}*f(UD)_{1,2}$	$1/3*f(LCC)_{1,3}*f(FL)_{1,3}*f(OS)_{1,3}*f(EC)_{1,3}*f(UD)_{1,3}$	$1/3*f(LCC)_{1,4}*f(FL)_{1,4}*f(OS)_{1,4}*f(EC)_{1,4}*f(UD)_{1,4}$
OS			1	$1*f(LCC)_{2,3}*f(OS)_{2,3}*f(EC)_{2,3}*f(UD)_{2,3}$	$1*f(LCC)_{2,4}**f(OS)_{2,4}*f(EC)_{2,4}*f(UD)_{2,4}$
EC				1	$1*f(LCC)_{3,4}**f(OS)_{3,4}*f(EC)_{3,4}*f(UD)_{3,4}$
UD					1

Figure 7.2.1. the MPC for the proposed MADA

For example, element (0,1) represents the importance of life-cycle cost relative to facility layout. Functions of life-cycle cost ($f(LCC)_{0,1}$) and facility layout ($f(FL)_{0,1}$) are included since they are the two base attributes of the pairwise comparison in question. Operating strategy, excess capacity, and utility demands are all inter-related with life-cycle cost, so the values of these attributes may impact the importance of life-cycle cost relative to facility layout. So, functions of the values of these attributes are included to model these inter-relationships ($f(OS)_{0,1}$,$f(EC)_{0,1}$, and $f(UD)_{0,1}$). The rest of this matrix is compiled analogously.

The values of the modification functions must be determined for each of the appropriate values. The modification functions may be tabulated for the importance relationship between life-cycle cost and facility layout, element (0,1), are listed in Figure 7.2.2. These values were determined by the author after examination and compilation of the data concerning inter-dependencies mentioned in the CII Task Force's research documentation. The modification functions for the remaining elements in the MPC are given on the following pages in Figures 7.2.3 through 7.2.11.

$f(LCC)_{0,1}$ =

- 1.5 if LCC = Very Expensive
- 1.3 if LCC = Expensive
- 1 if LCC = Moderate
- 1.3 if LCC = Inexpensive
- 1.5 if LCC = Very Inexpensive

$f(FL)_{0,1}$ =

- 1 if FL = Normal
- 1.3 if FL = Compressed

$f(OS)_{0,1}$ =

- 1.5 if OS = Continuous
- 1/1.3 if OS = Non-Continuous

$f(EC)_{0,1}$ =

- 1.3 if EC = Yes
- 1/1.1 if EC = No

$f(UD)_{0,1}$ =

- 1 if UD = Normal
- 1/1.1 if UD = Minimized

Figure 7.2.2. The modification functions for the importance relationship between life-cycle cost and facility layout

The remaining modification functions may be determined and tabulated.

These are presented in Figures 7.2.3 through 7.2.11.

$f(LCC)_{0,2}$ =

- 1.5 if LCC = Very Expensive
- 1.3 if LCC = Expensive
- 1 if LCC = Moderate
- 1.3 if LCC = Inexpensive
- 1.5 if LCC = Very Inexpensive

$f(FL)_{0,2}$ =

- 1 if FL = Normal
- 1.1 if FL = Compressed

$f(OS)_{0,2}$ =

- 1/1.3 if OS = Continuous
- 1 if OS = Non-Continuous

$f(EC)_{0,2}$ =

- 1 if EC = Yes
- 1 if EC = No

$f(UD)_{0,2}$ =

- 1 if UD = Normal
- 1 if UD = Minimized

Figure 7.2.3. The modification functions for the importance relationship between life-cycle cost and operating strategy

$f(LCC)_{0,3}$ =

- 1.3 if LCC = Very Expensive
- 1.1 if LCC = Expensive
- 1 if LCC = Moderate
- 1.1 if LCC = Inexpensive
- 1.3 if LCC = Very Inexpensive

$f(FL)_{0,3}$ =

- 1 if FL = Normal
- 1/1.3 if FL = Compressed

$f(OS)_{0,3}$ =

- 1/1.3 if OS = Continuous
- 1.1 if OS = Non-Continuous

$f(EC)_{0,3}$ =

- 1/1.3 if EC = Yes
- 1 if EC = No

$f(UD)_{0,3}$ =

- 1 if UD = Normal
- 1 if UD = Minimized

Figure 7.2.4. The modification functions for the importance relationship between life-cycle cost and excess capacity

$f(LCC)_{0,4} =$
- 1.3 if LCC = Very Expensive
- 1.1 if LCC = Expensive
- 1 if LCC = Moderate
- 1.1 if LCC = Inexpensive
- 1.3 if LCC = Very Inexpensive

$f(FL)_{0,4} =$
- 1 if FL = Normal
- 1 if FL = Compressed

$f(OS)_{0,4} =$
- 1/1.3 if OS = Continuous
- 1 if OS = Non-Continuous

$f(EC)_{0,4} =$
- 1 if EC = Yes
- 1 if EC = No

$f(UD)_{0,4} =$
- 1 if UD = Normal
- 1/1.5 if UD = Minimized

Figure 7.2.5. The modification functions for the importance relationship between life-cycle cost and utility demands

$f(LCC)_{1,2} =$
- 1 if LCC = Very Expensive
- 1 if LCC = Expensive
- 1 if LCC = Moderate
- 1 if LCC = Inexpensive
- 1.3 if LCC = Very Inexpensive

$f(FL)_{1,2} =$
- 1 if FL = Normal
- 1.3 if FL = Compressed

$f(OS)_{1,2} =$
- 1.5 if OS = Continuous
- 1/1.1 if OS = Non-Continuous

$f(EC)_{1,2} =$
- 1/1.1 if EC = Yes
- 1.1 if EC = No

$f(UD)_{1,2} =$
- 1 if UD = Normal
- 1/1.3 if UD = Minimized

Figure 7.2.6. The modification functions for the importance relationship between facility layout and operating strategy

$f(LCC)_{1,3} =$
- 1/1.3 if LCC = Very Expensive
- 1 if LCC = Expensive
- 1 if LCC = Moderate
- 1 if LCC = Inexpensive
- 1 if LCC = Very Inexpensive

$f(FL)_{1,3} =$
- 1 if FL = Normal
- 1 if FL = Compressed

$f(OS)_{1,3} =$
- 1 if OS = Continuous
- 1 if OS = Non-Continuous

$f(EC)_{1,3} =$
- 1/1.5 if EC = Yes
- 1.3 if EC = No

$f(UD)_{1,3} =$
- 1 if UD = Normal
- 1 if UD = Minimized

Figure 7.2.7. The modification functions for the importance relationship between facility layout and excess capacity

$f(LCC)_{1,4} =$
- 1 if LCC = Very Expensive
- 1 if LCC = Expensive
- 1 if LCC = Moderate
- 1 if LCC = Inexpensive
- 1 if LCC = Very Inexpensive

$f(FL)_{1,4} =$
- 1 if FL = Normal
- 1.3 if FL = Compressed

$f(OS)_{1,4} =$
- 1.1 if OS = Continuous
- 1/1.1 if OS = Non-Continuous

$f(EC)_{1,4} =$
- 1/1.1 if EC = Yes
- 1.1 if EC = No

$f(UD)_{1,4} =$
- 1 if UD = Normal
- 1.5 if UD = Minimized

Figure 7.2.8. The modification functions for the importance relationship between facility layout and utility demands

$f(LCC)_{2,3}$ =
- 1/1.5 if LCC = Very Expensive
- 1/1.3 if LCC = Expensive
- 1 if LCC = Moderate
- 1 if LCC = Inexpensive
- 1 if LCC = Very Inexpensive

$f(FL)_{2,3}$ =
- N/A if FL = Normal
- N/A if FL = Compressed

$f(OS)_{2,3}$ =
- 1/1.3 if OS = Continuous
- 1.3 if OS = Non-Continuous

$f(EC)_{2,3}$ =
- 1/1.5 if EC = Yes
- 1.5 if EC = No

$f(UD)_{2,3}$ =
- 1 if UD = Normal
- 1 if UD = Minimized

Figure 7.2.9. The modification functions for the importance relationship between operating strategy and excess capacity

$f(LCC)_{2,4}$ =
- 1.3 if LCC = Very Expensive
- 1.1 if LCC = Expensive
- 1 if LCC = Moderate
- 1 if LCC = Inexpensive
- 1 if LCC = Very Inexpensive

$f(FL)_{2,4}$ =
- N/A if FL = Normal
- N/A if FL = Compressed

$f(OS)_{2,4}$ =
- 1/1.5 if OS = Continuous
- 1 if OS = Non-Continuous

$f(EC)_{2,4}$ =
- 1 if EC = Yes
- 1 if EC = No

$f(UD)_{2,4}$ =
- 1 if UD = Normal
- 1.5 if UD = Minimized

Figure 7.2.10. The modification functions for the importance relationship between operating strategy and utility demands

$f(LCC)_{3,4}$ =

- 1.3 if LCC = Very Expensive
- 1.1 if LCC = Expensive
- 1 if LCC = Moderate
- 1.1 if LCC = Inexpensive
- 1.3 if LCC = Very Inexpensive

$f(FL)_{3,4}$ =

- N/A if FL = Normal
- N/A if FL = Compressed

$f(OS)_{3,4}$ =

- 1 if OS = Continuous
- 1 if OS = Non-Continuous

$f(EC)_{3,4}$ =

- 1.1 if EC = Yes
- 1/1.1 if EC = No

$f(UD)_{3,4}$ =

- 1 if UD = Normal
- 1/1.3 if UD = Minimized

Figure 7.2.11. The modification functions for the importance relationship between excess capacity and utility demands

It should be noted that some of the modification functions are not applicable (N/A). In these cases the attribute in question is not inter-related with either of the two attributes of the pairwise comparison. For example, $f(FL)_{3,4}$ is N/A since facility layout is not inter-related with either excess capacity or utility demands.

The next step in the analysis is to identify the alternatives. These are given on the following page in Figure 7.2.12.

	Alternative 1	**Alternative 2**	**Alternative 3**
LCC	Expensive	Inexpensive	Very Expensive
FL	Compressed	Compressed	Normal
OS	Continuous	Non-Continuous	Continuous
EC	Yes	No	Yes
UD	Normal	Normal	Minimized

Figure 7.2.12. The alternatives to be used in the demonstration of the proposed MADA method

Then, for each alternative, the MPC must be calculated. These calculations are shown in Figures 7.2.13 through Figures 7.2.15.

Alternative 1:

1	3*1.5*1.3 *1.5*1.3 *1	1*1.3*1.1 *1/1.1*1 *1	1*1.1*1/1.3 *1/1.3*1/1.3 *1	1*1.1*1 *1/1.3*1 *1
	1	1/3*1*1.3 *1.5*1/1.1 *1	1/3*1*1 *1*1/1.5 *1	1/3*1*1.3 *1.1*1/1.1 *1
		1	1*1/1.3* *1/1.3*1/1.5 *1	1*1.1* *1/1.5*1 *1
			1	1*1.1* *1*1.1 *1
				1

Figure 7.2.13. The modified MPC for alternative 1

Alternative 2:

1	3*1.3*1.3 *1/1.3*1/1.1 *1/1.1	1*1.3*1.1 *1/1.3*1 *1	1*1.1*1/1.3 *1.1*1 *1	1*1.1*1 *1*1 *1
	1	1/3*1*1.3 *1/1.1*1.1 *1	1/3*1*1 *1*1.3 *1	1/3*1*1.3 *1/1.1*1.1 *1
		1	1*1* *1.3*1.5 *1	1*1* *1*1 *1
			1	1*1.1* *1*1/1.1 *1
				1

Figure 7.2.14. The modified MPC for alternative 2

Alternative 3:

1	3*1.5*1 *1.5*1.3 *1/1.1	1*1.5*1 *1/1.3*1 *1	1*1.3*1 *1/1.3*1/1.3 *1	1*1.3*1 *1/1.3*1 *1/1.5
	1	1/3*1*1 *1.5*1/1.1 *1/1.3	1/3*1/1.3*1 *1*1/1.5 *1	1/3*1*1 *1.1*1/1.1 *1.5
		1	1*1/1.5* *1/1.3*1/1.5 *1	1*1.3* *1/1.5*1 *1.5
			1	1*1.3* *1*1.1 *1/1.3
				1

Figure 7.2.15. The modified MPC for alternative 3

Now, the principal eigenvectors may be calculated, and normalized. These are tabulated, and explained in Section 7.2.1.

7.2.1 Analysis of Results

The normalized principal eigenvectors for the three alternatives, as shown in Figure 7.2.12, are presented in Figure 7.2.1.1. In addition to these three vectors, the unmodified weights are given so the that impact of the modification functions may be clearly seen.

	Unmodified	**Alternative 1**	**Alternative 2**	**Alternative 3**
LCC	.231	.274	.243	.241
FL	.077	.061	.089	.058
OS	.231	.135	.253	.174
EC	.231	.322	.199	.320
UD	.231	.208	.216	.208

Figure 7.2.1.1. A comparison of attribute weights across several alternatives using modification functions in the MPC

It can be seen by comparing these vectors that the modification functions have the capability to significantly change the principal eigenvector. These changes reflect the differences between alternatives, and the variations from the "typical" case. In a traditional AHP analysis, the attribute weights for all alternatives only reflect the "typical" case. That is, for the "typical" case, life-cycle cost (LCC), operating strategy (OS), excess capacity (EC), and utility demands (UD), are weighted equally. Upon examination of the alternatives, one would find that none of these alternatives are really "typical." For example, what is a "typical" operating strategy, or a "typical" life-cycle cost? To model different alternatives on the same scale would be, in effect, "biasing" the results. That is, the MPC for each alternative should reflect the nuances and individuality of that specific alternative. Any extraordinary strengths or weaknesses of an alternative, due to values or combinations of values, are in effect averaged out, since the MPC and the vectors of preference values are created from the perspective of the "typical" case.

For example, in Alternatives 1 and 3, the values of life-cycle cost (LCC), operating strategy (OS), and excess capacity (EC), drive the importance of operating strategy down, relative to the "typical" case. Analogously, the values of operating strategy and excess capacity drive the importance of operating strategy up in Alternative 2, relative to the "typical" case. That is, the ranking of attributes by importance is dependent on the values of those attributes, and the modification functions reflect this dependency. In the case of this demonstration, operating strategy is approximately twice as important in Alternative 2 as it is in Alternative 1. In a traditional AHP analysis the importance of operating strategy would remain constant across all alternatives, but the values of the attributes in Alternative 2 imply that operating strategy is additionally more important than it is in the “typical” case. The utilization of modification functions in the matrix of pairwise comparisons allows the model to capture how the inter-dependencies between attributes impact the cardinal ranking by importance.

7.3 A Summary of Chapter 7

Section 7.1 describes the implementation of the AHP analysis for production facilities. Tables 7.1.1.1 through 7.1.1.3 allow a user to determine desirability indices for different production facility alternatives.

Section 7.2 demonstrates the proposed multiattribute decision analysis. A matrix of pairwise comparisons was created using modification functions that account for the attribute inter-relationships, and an analysis of the results was given.

8. Conclusions and Suggestions for Future Work

8.1 Contributions and Accomplishments

Two primary objectives have been accomplished in this thesis. The first is the creation of an AHP analysis for production facilities, process plants in particular. The analysis was structured to create a design method that considers the life-cycle of production facilities, so that designs with the better balance of cost and performance were ranked higher. One of the difficulties of utilizing life-cycle engineering is the lack of accepted standardized methodologies. The use of AHP in this analysis is an attempt to overcome this difficulty by proposing the use of a rational methodology that has been used successfully in other disciplines.

The second primary objective which has been accomplished in this thesis is the development of a multiattribute decision analysis methodology that models inter-relationships between attributes. One of the major weaknesses of the AHP is it's inability to model inter-relationships. That is, the values of the attributes of a production facility have impacts on the values of other attributes. The proposed methodology acknowledges, and attempts to resolve, this weakness in an attempt to create a more objective model.

This was done with the use of modification functions. The modification functions are used in the MPC, or in the vector of value preferences, of an AHP analysis to change values depending on the attribute choices. The goal of the use of the modification functions is to more objectively model these complex entities.

8.2 Limitations of the Methodology

The limitations of the AHP have been widely discussed and published. These include problems with modeling uncertainty. Forman (Goicoechea et.al, 1992) points out that, "Pairwise comparisons can be used to derive a subjective probability distribution for the relative likelihoods of the scenarios. Alternatively, if available, probabilities from 'objective' probability distributions can be incorporated."

Rank reversal is also sometimes seen as a weakness of the AHP. That is, when a particular attribute is omitted from analysis, the ordinal ranks of unchanged alternatives may switch. That is, the ranking of alternatives can be affected by the consideration of different attributes.

8.3 Extension and Enhancement of the Modified AHP

Extension of the modified AHP would include the creation of a computer model that does all the numerical calculations, including the principal eigenvector technique. As mentioned in Chapter 5, these calculations do not require additional data or input from the user beyond that of a traditional AHP analysis, so calculations of the modified AHP my be made in parallel with calculations of the traditional AHP so that results may be compared.

In Chapter 6, several constraints of the design of production facilities were identified, such as cost of capital and product demand. Though these constraints are considered to be constant across all alternatives (and therefore would not impact a traditional AHP analysis), it is possible that the values of these constraints would have an impact on values in the modified MPC or the modified preference vectors. For example, product demand is considered to be a constraint in the design of production facilities. It remains unchanged across alternatives, therefore it is not considered to be an attribute in an AHP analysis, though it can be seen that the value of product demand would have an impact on the importance of excess capacity. That is, the importance of excess capacity would increase (as would the preference of the existence of excess capacity) if the value of product demand is high.

If follows that these pre-established objectives and constraints could be a part of the modified AHP analysis, though they would not be modeled as attributes in the traditional sense. Modification functions could be set up for attributes which are inter-related with, or driven by, the values of these pre-established objectives and constraints.

Additionally, the impact of modification functions on the consistency of MPC's should be investigated. That is, since the modification functions change the values in a MPC, the modification functions would also change the first eigenvalue, and hence the consistency ratio of that MPC.

The directionality of an inter-relationship should be investigated. That is, if two attributes have been determined to be inter-related, is there a "direction" to the inter-relationship? Or, does the value of one attribute "drive," or control, the value of one or several others. And if so, how can this be modeled. Does the value of an attribute imply a value of it's inter-related attributes? To what degree should this implication be accounted for within a model?

The degree of inter-relationship should be investigated as well. For example, if inter-relationships are only modeled if there exists a "strong" inter-relationship, how does this impact the scale of the fuzzy modeling scheme? In the proposed model, an inter-relationship is modeled with a "yes" or a "no" (refer to the IDM in Section 5.2). What if "strong," "moderate," and "weak" inter-relationships are modeled differently? This could also be related to the scale of the numerical equivalents. For example, if only the "extremely strong" inter-relationships are considered, could one scale up or down the numerical equivalents? And what impact does this have on the consistency of results?

8.4 A Summary of Chapter 8

Chapter 8 presents the conclusions and suggestions for future work of this thesis. The contributions and original accomplishments are described in Section 8.1. The limitations of the methodologies utilized are briefly discussed in Section 8.2. The suggested extensions and enhancements for the proposed multiattribute decision analysis are given in Section 8.3.

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Appendix A - Attribute Definitions

Annual/Operating Cost

The costs of running a facility over a period of time. The operating costs include: maintenance equipment, labor, and training, refurbish/replace, head count, utilities, production materials, and cost of failure. Annual costs do not include initial or deconstruction costs.

Design Standards

Design standards are generally accumulated detail specifications for routine materials of construction, sizing of common elements (like heat exchangers), and guidelines for material selection. There generally will be a basic premise that the standards are built around and which must be clearly understood to assess the impact on detailed design. Design Standards can be project, corporate or industry specific.

Excess Capacity

Excess capacity is defined as the amount of capacity that is built into the facility or scope that exceeds the current requirements or projected needs. Generally, this is the amount of capacity that is achievable beyond the stated requirements. Achieving this additional capacity would not require "de-bottlenecking" or any significant investment in time or money. The initial cost of the facility would be reduced if there is no excess capacity.

Excess Design Factor

The factor applied to ensure that a given element operates as intended. This is not redundancy. Excess Design Factor is applied after all usual design parameters are determined. For instance, given a heat transfer coefficient, temperature gradients, etc., the extra heat exchange surface added to insure against the unknown but only achieve the current or projected requirements.

Facility Design Life

The time in years of the expected business life of the facility. While the facility could physically last longer, the facility "design" life is for the business use originally intended. For example, a warehouse could be built to meet a specified need for storage for the next five years. After the five years the building could be converted to some other use. The facility design life in this example is five years. Facility design life is frequently based on projected product life.

Facility Layout

The extent to which the layout of equipment and operations is compressed within the footprint of the facility. There are usually accepted standards of space required for certain operations. A "normal" layout utilizes these accepted standards. A "compressed" layout minimizes the facility footprint and maximizes unit density (reducing normal clearances and access). The layout drives the size of a facility and the facility size drives the cost of the facility.

Infrastructure Requirements

The infrastructure (both inside and outside the plant boundaries) necessary for the successful operation of the facility. These requirements usually include additional utilities, roads, parking, cafeteria space, environmental / waste treatment, etc.

Initial Cost

All the costs associated with the preparation of a production facility for operation. These costs include: research, planning, engineering design, land and land improvements, infrastructure costs, and the cost of the equipment.

Level of Automation

The level of instrumentation and control expected to control the operation. The mix of manual and automatic tasks will be defined. The way information is gathered and stored is included in the level of automation.

Life-Cycle Cost

The total cost of ownership of a production facility during the life-cycle. This includes all costs from the planning and design stage, the construction/equipment stage, the maintenance stage, the facility operations stage, and the decommissioning stage.

Location

The location of the facility site from the perspective of the country, state, and municipal location as well as the location of the facility within the site boundary.

Maintenance Requirements

The planned or routine labor and material necessary to keep the facility or process useful and operating as intended. Included are preventive maintenance programs, spare parts, needs, etc.

Materials of Construction

The type and quantity of all materials that are included in the permanent facility.

Operating Strategy

The intended operational plan. That is, operating hours per week; semi-annual turnarounds for maintenance; overnight maintenance staffing; etc. This is the detailed plan for operating the facility. It incorporates the production demands (cyclical, uniform, seasonal) with the operational issues of maintenance, staffing, and capacity. The choices for operating strategy are continuous or non-continuous. Continuous operation is 24 hours/day, seven days/week. Non-continuous operation is anything less than seven days/week and 24 hours/day.

Redundancy

Relating to reliability, redundancy is the amount of backup provided in the design. For instance, two boilers, each of which are sized to meet the known requirements would indicate 100% redundancy.

Reliability Requirements

Equipment reliability is the capability to meet the quality and safety standards consistently over the life of the equipment and operate when needed at the plant level. It would generally be the ratio of product manufactured meeting quality standards to the design capacity.

Required Facility Availability

The time the plant is available to make a product. This does not include planned maintenance. It is generally determined by the throughput required per year divided by capacity.

Risk Exposure

All extraordinary risk exposure which the facility owner may encounter from internal facility operations and/or external conditions. Includes owner's risk exposure:

- To facility occupants and contents due to operations, such as from especially hazardous processes or materials.
- To protect persons or property from external factors such as extreme climate, acts of vandalism, terrorism, etc.
- Due to plant operations impacting the external environment (natural and human)
- Created by external conditions, such as extraordinary environmental requirements or public or political attitudes.

Schedule/Delivery Considerations

The plan and schedule by which the project is delivered. Includes aspects such as:

- The delivery strategy (Phased construction, design-build, design-bid-build).
- The contracting strategy (Guaranteed maximum, lump sum, reimbursable, etc.).
- Construction methods such as on-site and off-site fabrication, modular), etc.
- Availability of labor and construction equipment.

Utility Demands

The amount of the various utility consumption requirements. For example, heating or cooling loads, horsepower requirements, BOD and COD loading, etc.

Utility Type

Energy for the process and facility operations can be provided through various means. Examples include electricity, fuel oil natural gas, steam or water. These utilities can usually be purchased from the local municipal utility or generated (converted) within the facility. Conceptual design decisions must be made as to how the required utilities will be supplied to, or generated within, the plant. Effluent treatment should be evaluated in the same way.

Appendix B - Calculation of the Preference Values for the Cost Attributes

As mentioned in Chapter 6, a "logically consistent" matrix of pairwise comparisons was created in order to determine the preference values for the cost attributes. For all the cost attributes, the choices were: very expensive, expensive, moderate, inexpensive, and very inexpensive. "Logically consistent" means that for any alternative, an alternative with a lower cost is more preferable, if all other attributes are kept constant. So, for these five choices for cost, a MPC of preference may be created. This MPC is presented in Figure B.1.

	Very Expensive	Expensive	Moderate	Inexpensive	Very Inexpensive
Very Expensive	1	1/3	1/5	1/7	1/9
Expensive	3	1	1/3	1/5	1/7
Moderate	5	3	1	1/3	1/5
Inexpensive	7	5	3	1	1/3
Very Inexpensive	9	7	5	3	1

Figure B.1. A MPC for the preference values of the cost attributes

The normalized principal eigenvector of this matrix is presented on the following page in Figure B.2.

Very Expensive	0.033
Expensive	0.063
Moderate	0.13
Inexpensive	0.26
Very Inexpensive	0.51

Figure B.2. The normalized principal eigenvector for the MPC given in Figure B.1

The consistency ratio of the MPC in Figure B.1 is less than 6%. Therefore, the consistency ratio is well within the boundaries of what is considered acceptable (Saaty, 1980).

Appendix C - The Cost Elements and The Life-Cycle Advisor

The list of cost elements was developed as part of the CII Task Force's *Life-Cycle Advisor.* The Life-Cycle Advisor is Windows-based software that allows a user to understand the implications, with respect to cost and performance over the life-cycle of a production facility, of the specification of the attributes used in the AHP analysis.

The cost elements that the CII Task Force listed are listed in Table C.1.

Phase	**Cost Element**
Planning and Design	Research and Technology Project Planning Engineering Design
Construction/ Equipment	Land and Improvements Facility Building Process/Manufacturing Operations Infrastructure Cost
Maintenance	Equipment Labor and Training Refurbish/Replace
Facility Operations	Labor and Training Utilities and Waste Treatment Production Materials Cost of Failure
Decommissioning	Demolition/Disposal Remediation

Table C.1. The cost elements of the life-cycle for production facilities

Appendix D - Sample Raw Data

The worksheets used to collect the data for the AHP analysis are attached. It should be noted that there are two types of worksheets. The first is the MPC used to calculate the importance rankings of the attributes. The second was used to generate the preference vectors for each attribute. Since there were only a few choices for each attribute, no MPC's were used. The calculations of the preference values for the cost attributes are discussed in Appendix B.

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For each of the blank cells in the attached matrix, fill in the appropriate value:

1 = Equally as important
3 = Moderately more important
5 = Strongly more important
7 = Very strongly more important
9 = Extremely more important

where the row label precedes the column label. For example, if "**life-cycle cost**" is strongly more important than "**initial cost**", then the value of cell **A** would be 5. If "**life-cycle cost**" is moderately more important than "**annual cost**," then the value of cell **B** would be 3. If the column label is more important than the row label, simply invert the number. For example, if "**annual cost**" is moderately more important than "**initial cost**", then the value of cell **C** would be 1/3. Please consider performance over the life-cycle for a typical production facility. Refer to the driver definitions if needed.

		Life Cycle-Cost	Initial Cost	Annual Cost	Facility Layout	Facility Design Life	Location (micro)	Operating Strategy	Utility Type	Risk Exposure	Excess Capacity	Infrastructure Requirements	Schedule/ Delivery Considerations	Level of Automation	Redundancy	Maintenance Requirements	Utility Demands	Design Standards	Materials of Construction	Reliability Requirements	Required Facility Availability	Excess Design Factor
Cost Attributes	Life Cycle-Cost	1	3	3	3	5	9	1	7	5	1	3	3	5	7	3	1	5	3	5	7	7
	Initial Cost		1	1	1	3	7	1/3	5	3	1/3	1	1	3	5	1	1/3	3	1	3	5	5
	Annual Cost			1	1	3	7	1/3	5	3	1/3	1	1	3	5	1	1/3	3	1	3	5	5
Design Attributes	Facility Layout				1	3	7	1/3	5	3	1/3	1	1	3	5	1	1/3	3	1	3	5	5
	Facility Design Life					1	5	1/5	3	1	1/5	1/3	1/3	1	3	1/3	1/5	1	1/3	1	3	3
	Location (micro)						1	1/9	1/3	1/5	1/9	1/7	1/7	1/5	1/3	1/7	1/9	1/5	1/7	1/5	1/3	1/3
	Operating Strategy							1	7	5	1	3	3	5	7	3	1	5	3	5	7	7
	Utility Type								1	1/3	1/7	1/5	1/5	1/3	1	1/5	1/7	1/3	1/5	1/3	1	1
	Risk Exposure									1	1/5	1/3	1/3	1	3	1/3	1/5	1	1/3	1	3	3
	Excess Capacity										1	3	3	5	7	3	1	5	3	5	7	7
	Infrastructure Requirements											1	1	3	5	1	1/3	3	1	3	5	5
	Schedule/Delivery Considerations												1	3	5	1	1/3	3	1	3	5	5
Schematic Attributes	Level of Automation													1	3	1/3	1/5	1	1/3	1	3	3
	Redundancy														1	1/5	1/7	1/3	1/5	1/3	1	1
	Maintenance Requirements															1	1/3	3	1	3	5	5
	Utility Demands																1	3	1	3	5	5
	Design Standards																	1	1/3	1	3	3
	Materials of Construction																		1	3	5	5
	Reliability Requirements																			1	3	3
	Required Facility Availability																				1	5
	Excess Design Factor																					1

Figure D.1. The matrix of pairwise comparisons used in this analysis

AHP Knowledge Base Development Task #2

For each attribute/driver, define the performance ratio of the choices. A choice that performs better with respect to the life-cycle will have a higher score. Use the nine-point scheme, shown below, as a verbal reference. For example, for the attribute "**facility layout**", the choices are **normal** and **compressed.** If a **normal** facility layout performs "**strongly better**" than a **compressed** facility, then the preference ratio would be normal : compressed :: **5 : 1**. If a **compressed** facility performs **"moderately"** better than a **normal** facility, then the preference ratio would be normal : compressed :: **1 : 3.** Please consider performance only over the life-cycle for a typical production facility (i.e., do not consider any affects of cost). Refer to the definitions if needed.

1 = Performs as well as
3 = Performs moderately better than
5 = Performs strongly better than
7 = Performs very strongly better than
9 = Performs extremely better than

Facility Layout:
Normal : Compressed :: **3/1**

Facility Design Life:
Less than 10 years : 10 to 20 years : Greater than 20 years **::** **1/3/3**

Location (micro):
Non-Accessible : Accessible :: **1/3**

Operating Strategy:
Continuous : Non-Continuous :: **7/1**

Utility Type:
Convert : Purchase :: **3/1**

Risk Exposure:
Low : Medium : High :: **5/3/1**

Excess Capacity:
No : Yes :: **1/5**

Infrastructure Requirements:
Existing Infrastructure : Moderate Additional Infrastructure : Extensive Additional :: **5/3/1**

Schedule/Delivery Strategy:
Compressed : Normal :: **3/1**

Level of Automation:
Low : Medium : High :: **1/3/5**

Redundancy:
None : Selective : Full :: **1/3/3**

Maintenance Requirements:
Low : Normal : High :: **7/3/1**

Utility Demands:
Normal : Minimized :: **1/3**

Design Standards:
Project Specific : Corporate : Industry Standard :: **5/1/3**

Materials of Construction:
Standard Performance : High Performance :: **1/5**

Reliability Requirements:
Normal : High :: **1/5**

Required Facility Availability:
Low : Medium : High :: **1/3/5**

Excess Design Factor:
None : Usual : High :: **3/5/1**

Vita

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