6-2002

A Model for Optimizing the Selection of Project Delivery Systems Using Analytic Hierarchy Process (AHP)

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A MODEL FOR OPTIMIZING THE SELECTION OF PROJECT DELIVERY SYSTEMS USING ANALYTIC HIERARCHY PROCESS (AHP)

by

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A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science in Construction Management
Department of Construction Engineering, Materials Engineering
and Industrial Design

Western Michigan University
Kalamazoo, Michigan
June 2002

ACKNOWLEDGMENTS

Initially, I wish to acknowledge Dr. Osama Abudayyeh who has extended his valuable time and took special interest to discuss and review my work. Also, I would like to thank the members of my graduate committee, Dr. Jawahar Nesan, and Dr. Steve Butt for taking their time to review my thesis.

Special thanks is extended to experts who have providing necessary information and cooperation for the research.

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The project delivery systems applicable to the construction industry in the U.S. consist of different approaches. This study focuses on three main approaches, (1) Design-Bid-Build (DBB), (2) Design-Build (DB), and (3) Construction Management (CM). Since each construction project is unique, selecting the right project delivery system is a tough decision.

This study develops a decision making system, based on the Analytic Hierarchy Process (AHP), for selecting the best delivery system for a given construction project. AHP is a decision making mathematical model developed by Thomas L. Saaty and consists of a hierarchical structure. It analyzes several alternatives for a given problem and develops priorities in ratio scales.

This thesis highlights the different applications of AHP. It also discusses the automation of AHP decision generations, using the decision support software program, Expert Choice. Finally, the thesis discusses a model that was developed to choose the best delivery system using AHP and Expert Choice.

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BACKGROUND

Over the past years, project delivery systems played a major role in the construction industry. When considering the definition of a project delivery system, it is the contractual structure and compensation arrangement the owner uses to acquire a completed facility that meets his requirements through the design as well as the construction services (Smith, 2000). However, choosing the appropriate delivery method for a given project depends upon the specific requirements of the project. Some of the reasons behind the decision are project cost, schedule, type of owner, type and size of the project, quality, and others. Hence, the owner should select a delivery system after a careful evaluation of the process, and of his needs and capabilities, because every delivery system has its own shortcomings, benefits, and limitations.

Continuous changes in technology and the increasing sophistication in buildings require specialization of design and construction services (Konchar and Sanvido, 1998). Also, in response to owners' special requirements, urgency of schedules, enhanced quality requirements in construction, limited financial resources, the desire in less conflicts and disputes between parties, and the benefit of taking minimal legal risk, various project delivery systems evolved. Design-Bid-Build (DBB), Design-Build (DB), and Construction Manager at risk or agency Construction

Manager (CM) are the three principal delivery systems currently in use in the U.S. construction industry.

With every other key objective, owners' desire for project life cycle costing evolved in each project delivery system. Decisions made in the early stages of the project's life cycle have greater influence on a project's outcome than decisions made in later stages (Miller, Garvin, Ibbs, and Mahoney, 2000). Every dollar spent on research, design, and value engineering/ constructability studies in the preconstruction phase can save millions of dollars during a project's life (Dorsey, 1997).

Over the past few decades, federal, state, and local government have relied almost entirely on the conventional DBB delivery method (Miller, 2000), while private owners used the DB and CM methods. Also, other delivery systems exist such as Turnkey (DB by developer), Design-Build-Lease, Design-Build-Lease-To-Own, and Bridging.

When an owner wants to hire an agency to handle various phases of a project such as planning, design, and construction, while cooperating with the owner and the designer, he should consider the Construction Manager approach. This approach can be Agency Construction Manager or At-Risk Construction Manager. The following subsections discuss each delivery system in detail.

1.1 Types of Project Delivery Systems

1.1.1 Design-Bid-Build (DBB)

As the name implies, this delivery system is a linear sequence of procedures: design, bid, and build. Initially an owner hires a designer to produce preliminary and detailed drawings and specifications. Next, owner requests bids from contractors for construction services. After submitting bids to perform the work by contractors, the lowest bidder is generally selected. Nowadays, prequalification of contractors is recommended for a better ultimate product rather than depending on a strict low-cost system. In public sector, because they are dealing with taxpayers' money or public money, quality sacrificed for the lowest bidder (Dorsey, 1997). However, private owners are mostly concerned with the selection of bidders to get the required quality of the facility. Below is a list of advantages and disadvantages of this conventional approach.

Advantages of DBB

(1). It is a simple and straightforward procedure.

(2). Owner can actively be involved in the design and construction process; making sure he is getting what he has paid for (Mulvey, 1998).

(3). In a cost-driven point of view, competitive bidding will produce the most reasonable market price for a project (Dorsey, 1997).

(4). Architect/Engineer (A/E) professional responsibility enhanced in this system and also the close relationship with owner leads to a good quality product (AIACC, 1996).

(5). It is easy to understand and easy to follow the guidelines to execute the work.

(6). In the public sector, it avoids favoritism by owners because of low-bid method of selection (Dorsey, 1997).

(7). Because the architect and the contractor has no direct contractual relationship disputes and conflicts are minimized.

Disadvantages of DBB

(1). Contractor has no input during the design phase; hence an experienced contractor's knowledge of constructability, value engineering, and other issues will not be utilized (AIACC, 1996).

(2). The linear nature of the process can lead to a lengthy construction schedule.

(3). If re-bidding, value engineering, or re-design is necessary, critical project delays and additional costs can be experienced (AIACC, 1996).

(4). Due to the totally separate roles of A/E and the contractor with the owner there will be the potential for litigation resulting from disputes (AIACC, 1996).

(5). For large, complex projects, DBB usually produces heavy paper work.

1.1.2 Design-Build (DB)

This delivery system deviates from the traditional method. The main feature is its single source of responsibility for both design and construction services. This approach is gaining popularity, particularly in the private sector. Some public agencies are also increasingly using DB. Mostly, a DB agency has in-house design and construction capabilities. Otherwise, an agency may subcontract to get the desired design or construction services. Selecting suitable engineering or construction firm under this approach is based on certain key factors (Yates, 1995):

(1). Previous experience with similar projects,

(2). quality of key personnel,

(3). construction capabilities,

(4). project management capability,

(5). engineering capabilities,

(6). quality of project control.

The DB agency can be a single firm, or a joint venture for a particular project. Usually under in-house DB, they produce repetitive work while the Consultancy/subcontractor DB may be required when some specialized services are needed (Dorsey, 1997). The DB contractor selection procedure is normally based on qualification or on cost. DB also provides some advantages and disadvantages when used by a particular project.

Advantages of DB

(1). The main advantage is the involvement of a single entity. The contractor and Engineering/Construction (E/C) team work towards the same goal as one entity, hence reducing disputes and claims (Dorsey, 1997).

(2). The single point of responsibility creates another benefit by reducing the risk, responsibility, and administration tasks of the owner (AIACC, 1996).

(3). As long as the owner does not change the project objectives after awarding a contract, DB method enhances the probability of completing a project within budget and on time (Yates, 1995).

(4). Comparing to the conventional DBB method, heavy paperwork, that includes documentation of design and construction may be minimized (AIACC, 1996).

(5). Because of the integration of design and construction processes, value engineering and constructability reviews can be used more efficiently, hence producing cost effective projects (Dorsey, 1997).

Disadvantages of DB

(1). Owner's role is not a major one, hence the ultimate product may not be up to his expectations (Yates, 1995).

(2). Architect/Engineer's (A/E) professional role may be lost when compared to the traditional method. Because in this delivery method A/E is not the owner's direct representative (AIACC, 1996).

(3). If the selection of DB is based only on price, the quality will then be sacrificed (AIACC, 1996).

(4). For an inexperienced owner this approach may be complex.

There are some variations in the implementation of DB method as follows.

- **Turnkey:** This approach is ideal for an owner who does not want to invest money until the delivery of a completed facility. There exists an agreement between owner and the contractor for a prearranged price for both design and construction. This turnkey system is suited for some special category of buildings such as standard hotels and motels, warehouses, franchise restaurants or for prototype buildings. The main drawback of this approach is that the owner must purchase the finished building regardless of its condition. To reject the building means to go for critical legal procedures (Dorsey, 1997).
- **Design-Build-Lease and Design-Build-Lease to Own:** These are further variations of turnkey. These approaches are attractive to owners who do not want to handle the project financing and also like to have a tenant agreement for a period of time. At the end of the lease period, owners can have several options including accepting the completed facility, changing the transfer date, or even cancellation. For the above options, comparing total life cycle cost of leasing versus owning and considering the responsible party for the maintenance are supportive ideas (Dorsey, 1997).
- **Bridging:** By this method, the owner's requirements regarding the project can be fulfilled through an independent A/E. Hence this method provide some protection

to owners. The duties of A/E include establishing fundamental design criteria to measure the DB's design and performing inspections to verify that the owner gets the required standards (Groton and Smith, 1998). Hence, the bridging system allows an owner and A/E to control design prior to turning the project over to a DB contractor (Dorsey, 1997). The owner takes the advantages of less project duration and the single point of responsibility, while benefits from the protection of an independent A/E.

1.1.3 Construction Management (CM)

This approach has two different ways for delivering a particular project: At–Risk Construction Management or Agency Construction Management. An agency construction management firm mainly focuses on administrative duties on behalf of the owner, while an at-risk construction management firm acts more like a general contractor.

This project delivery system can be applicable to both private and public sectors. In private sector, selection of the suitable construction management firm is straightforward, while in the public sector it is a relatively complex and lengthy process similar to the traditional DBB. When CM is used for large public projects, it is almost always an agency CM (Dorsey, 1997). Under the open and objective selection criteria in the public sector, Request For Qualifications (RFQ) are first sent to all interested responsible firms. Next, the number of candidates is reduced by the selection criteria of the owner. Then, Request For Proposals (RFP) are sent to the selected firms. Based on the interviews and also considering the criteria that may include past performance, current workload, availability of key personnel or expertise, relationship with the public owner, capability on similar projects, the public owner enters an agreement with the most suitable construction management firm. Unlike the public sector however, private sector adapts a quicker method of selection mainly based on qualifications and previous relationships. While at-risk CM is predominately present in private sector, the agency CM is an attractive approach to both private and public agencies.

There are several types of organizations that can provide CM services either at-risk or agency (Dorsey, 1997). CM firm can be a construction firm, that accomplished with new technology experience, or CM firm can be a design firm with a greater knowledge of owners perspectives such as quality and legal contract documents. Otherwise, a firm, which is accustomed to the idea of market conditions, funding sources, and newest management techniques, can exist as a management organization to provide the particular CM services.

The above mentioned firms have their own capabilities. Hence, the owner's selection should be a rational and a methodical one, which satisfies his needs and priorities. Generally, a design firm or a management firm is best suited for delivering an agency CM approach, while construction firm is more suited for the at-risk CM approach.

Advantages of CM

(1). In owner's point of view, CM plays a major role by providing a better service through recommendations, monitoring, and coordinating of project key objectives such as quality, cost, schedule, and safety.

(2). Usually, this approach can significantly reduce the project duration by fast tracking (or phased construction) which means overlapping design and construction services.

(3). Cost savings are also possible if fast track is successful.

(4). Bringing together all players at an early stage tends to cause less disputes, claims, and delays (Dorsey, 1997).

Disadvantages of CM

(1). There is no early guaranteed cost (Dorsey, 1997). Due to the phased construction, most of the work starts prior to completion of documents. Hence, change orders tend to severely affect the fee arrangement, especially, if it is Guaranteed Maximum Price (GMP).

(2). Under agency CM, who acts as an administrator for the construction phase, the agency has no authority to control subcontractors (Dorsey, 1997).

(3). In public projects, the owner and the construction manager have to deal with heavy paperwork due to CM selection criteria.

(4). If selection is based on the lowest fee, it may lead to weak administration. (Dorsey, 1997). Construction manager may not be able to provide skilled and enough personnel for execution of the project.

(5). Conflicts can arise between the construction manager and the designer over certain recommendations. Hence, owner should be knowledgeable in selecting the best recommendation.

1.2 Payment Methods in Project Delivery Systems

When delivering a project under a specific project delivery approach the method of payment or fee arrangement has a significant effect on the execution of the project. This pricing scheme consists of two main types:

(1). Lump sum (or firm price or fixed price), and

(2). Cost plus a fee with or without Guaranteed Maximum price (GMP).

Generally lump sum means the payment of a single, stipulated sum or a series of usually monthly progress payments by the owner to the contractor in addition to a prearranged lump sum at the end of the project (Dorsey, 1997). Under lump sum contracts, a selection of fixed price is requested early in the design stage. So the scope should be a well defined one to avoid cost overruns. Agreed upon fixed price for unknown elements such as site investigations or new technology requires a higher amount of contingency (Willoughby, 1995). When working under a lump sum contract with tight budget and schedule, alternatives for cost reduction should be minimized. Otherwise, quality will be questionable.

Under the cost-plus a fee approach, when an owner is unable to provide the fully completed design and is expecting many potential changes, awarding the contract can be done on a negotiated basis for actual cost plus a fixed fee or percentage fee (Dorsey, 1997). If the scope is considerably well defined and contractors commitment to a guaranteed maximum cost is reasonable, cost-plus a fixed fee which together equal the GMP will be appropriate (Gorton and Smith, 1998). But if the final cost is higher than the GMP, the contractor should be responsible for the excess. On the other hand, if the cost is lower than GMP, the savings may be shared between the owner and the contractor. However, a responsible contractor should avoid the cost saving methods that affect the quality.

Generally, conventional DBB uses the lump sum contract type, whether it is negotiated or competitive. Typically, the public sector uses competitive lump sum method. In the DB system, contract type can vary from competitive lump sum to negotiated cost plus to guaranteed maximum price with or without a shared savings clause (Dorsey, 1997). In the CM approach, it is usually a cost plus a fee arrangement. The fee can be a fixed fee or a percentage fee. Reimbursable cost can be generally the site office and personnel expenses for the agency CM while for at-risk CM it expands to labor, material, equipment and temporary facilities. If guaranteed maximum price is included in the agreement in the at-risk type, reimbursable costs are included in the GMP.

1.3 Risk Allocation in Project Delivery Systems

Risk distribution among parties, who are involved in a particular project, may depend on the type of the delivery system adopted and the method of payment. Risk is distributed among the major players of the project: the owner, the designer, and the constructor. Following discussion will describe the risk distribution in each delivery system briefly.

A contractor in the DBB delivery method, due to the lump sum contracting approach, assumes great risk. Also the prime contractor assumes the risk of scheduling, co-ordination, and administrating of work done by subcontractors and suppliers (Rubin and Wordes, 1998). Additionally, contractors and subcontractors assume other risks such as price escalation or limitations in materials or labor. The contractor is also responsible for the safety of the entire work crew on the job site.

When considering an owner's potential risks, he assumes a major risk of the final product, particularly if it does not meet his expectations. Due to the lengthy process of DBB, owner's lack of performance leads to significant delays in project schedule. Because an experienced contractor's early input is not possible in the design stage, in some cases, a designer takes a great risk when the design is not practical or cannot be build as designed. Also, another type of risk occurs due to the conflicts between contractor and a designer especially when quality is under debate.

When considering the DB approach, although the single point responsibility for both the design and construction tends to have benefits over other delivery methods, the greatest risk is also caused by that phenomenon (Dorsey, 1997). This is due to the fact that the contractor has the expanded responsibility for the design and construction of a project.

In the Turnkey and Design-Build-Lease approaches, the contractor absorbs the financial risks as well (Dorsey, 1997). Generally, contractor risks include:

(1). Fulfilling the scope of work,

(2). Meeting the project budget,

(3). Meeting the project schedule,

(4). Assuring the safety of everybody on the job site,

(5). Guaranteeing the required quality of the work,

Now consider the owners' point of view. Under DB, the owner bears a great risk for the aspects of the design because he has no direct contact with the designer. But this risk can be overcome by the "bridging" method through appointment of the separate owner's A/E.

When considering risk allocation in CM, it is better to judge the specified role of CM in either system: at –risk or agency.

Under agency CM, the firm has responsibilities such as (Dorsey, 1997):

(1). An adviser for contractor and subcontractor selection,

(2). An adviser to resolve disputes between owner and trade contractors,

(3). A coordinator and monitor of cost, time, quality, and safety, with no responsibility for these tasks.

Whereas, in the at-risk CM approach the CM holds more risks, such as (Dorsey, 1997):

(1). Generally liable for construction means and methods of delivering the finished facility,

(2). Selection of direct contractor and subcontractors,

(3). Guarantee of quality and performance,

(4). Liable for safety on the project,

(5). Responsible for payment to subcontractors.

Overall, successful risk allocation minimizes the total cost of that risk (Rubin and Wordes, 1998). As a rule of thumb, the best approach to risk management is to allocate the risk to the party who can best handle it and bear its cost (Dorsey, 1997).

The summarization of the three main project delivery systems are as given in the following Table 1.

Table 1. Summary of Project Delivery Approaches

Type of Delivery System	**Features/Best for**	**Advantages**	**Disadvantages**
DBB (Design-Bid-Build)	Owner's maximum control Public owners Large organizations High quality in design Longer duration Less experienced owners Less complex projects	Simple and straightforward process Disputes and conflicts are minimized Competitive bidding produces most reliable market price Owner's get what they have paid for	Lengthy process Experienced contractors has no input in the initial stage For large projects produces heavy paperwork
DB (Design-Build)	Well defined project scopes Private owners Tight schedules Owner's least involvement Experienced owners	Single point of responsibility Shorter duration Possibility of cost-effective Integration of expert knowledge at the beginning	Owner's involvement is minimized Sometimes quality will be questionable For an inexperienced owner this is a complex one
CM (Construction Management)	Owner's maximum control Both private & public owners High quality Shorter duration Large, complex projects Less experienced owners	Less disputes and claims Possible cost savings Reduced project duration by fast tracking	No early guaranteed cost Additional staffing cost for CM

CHAPTER 2

CONCEPTS AND APPLICATIONS OF ANALYTIC HIERARCHY PROCESS (AHP)

2.1 General Concept Behind AHP

The Analytic Hierarchy Process (AHP) is a mathematical model developed by Thomas L. Saaty to use as a decision-aiding tool in a multi-criteria decision environment (Saaty, 1980). Generally, the construction industry is a risky business and results in complex judgments on a daily basis. Making a sound decision based on past experience and knowledge may lead to a successful end product. This powerful tool, AHP is simplifying a given problem by (Gass, 1985):

(1). Identifying possible causes;

(2). Developing alternatives;

(3). Selecting among alternatives;

(4). Implementing the chosen alternative.

A typical structure of a decision hierarchy is shown in Figure 1. As seen in this figure, a particular problem can be broken down into different levels. But structuring of the hierarchy depends on the decision-maker. It can be constructed from knowledge and judgment of an individual or from several brainstorming sessions of a group of experts. Usually, the ultimate goal need to be kept at the top of the hierarchy in level 1 followed by criteria in level 2. Each criterion should be compared with respect to the goal. If more clarification is required in each criterion, sub-criterion can be added in level 3. Finally, at the lowest level, the alternatives can be compared with respect to the each criterion or each sub-criterion.

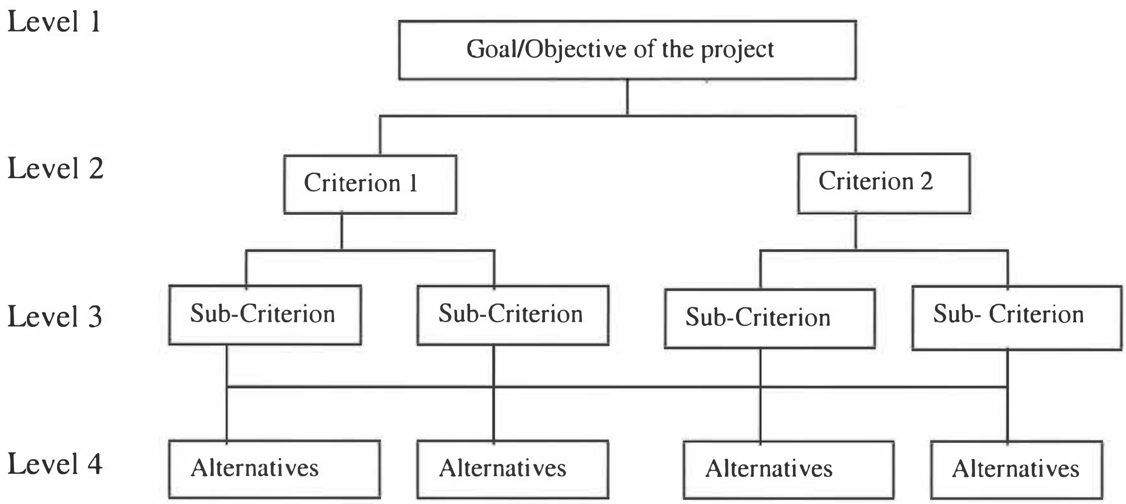


Figure 1. A Typical AHP Hierarchical Structure

The formation of criteria, and sub-criteria are normally based on the experience, knowledge and preference of the decision-maker. The AHP, helps decision-makers to find the "best" answer, not the "right" answer (Forman and Selly, 2000).

The AHP consists of following basic steps developed by Saaty (Saaty, 1980). For easy reference, it is illustrated as a flow chart in Figure 2. Each necessary step is described in detail with a simple example.

The detailed description of each of the steps is documented below.

(1). Construct the AHP decision tree by reducing complex decisions to a set of simple solutions.

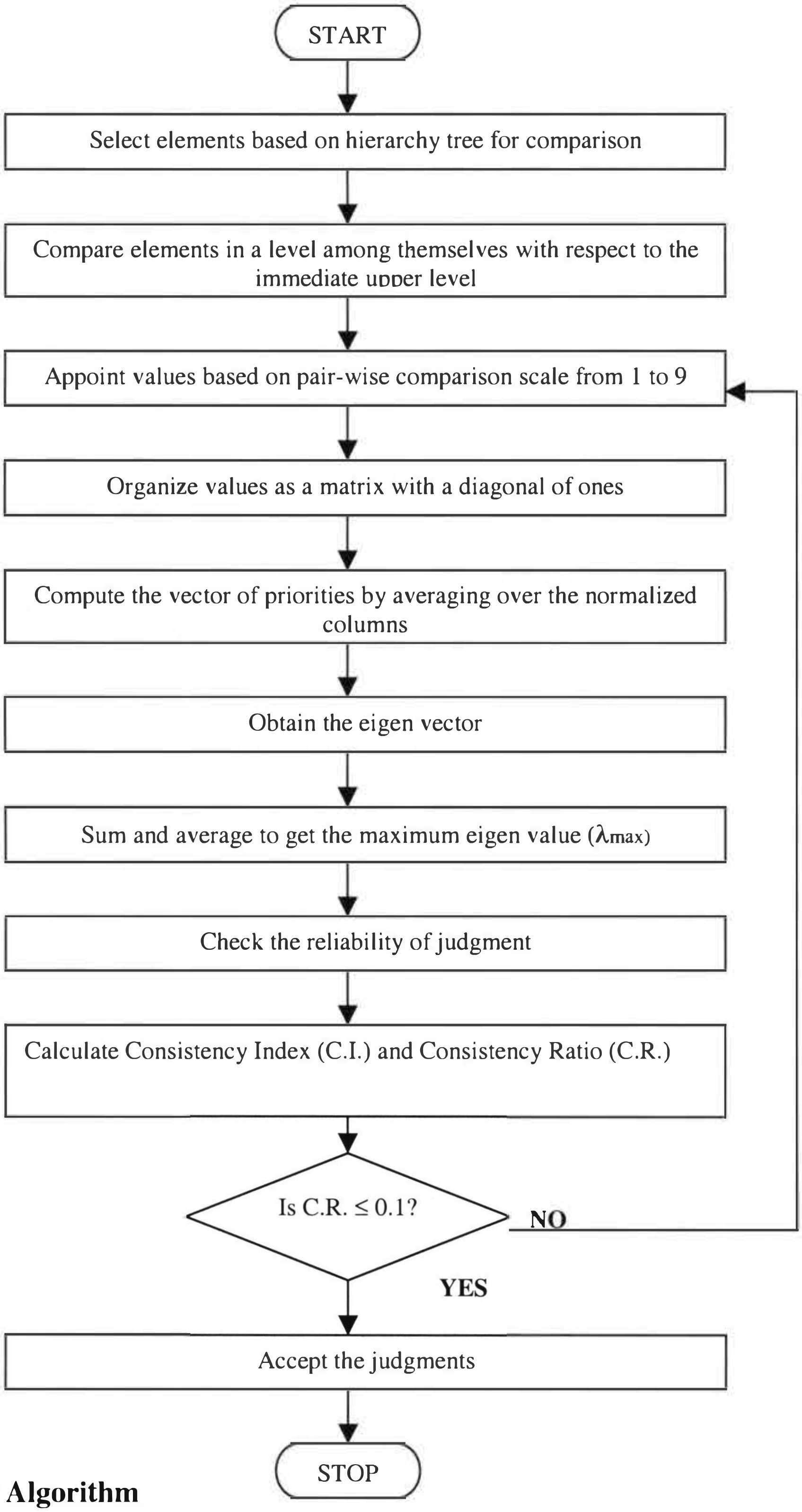


Figure 2. The AHP Algorithm

2). Once the hierarchical tree is developed, a process of pair-wise comparisons is applied. This process assigns weights of importance to each criterion or sub-criterion (Alhazmi and McCaffer, 2000). For this procedure, Saaty developed a ratio scale or predetermined scale of relative importance as in Table 2. (Mclntyre, Kirschenman and Seltveit, 1999).

Table 2. The Pair-wise Comparison Scale

Degree of Importance	Definition
1	Equally important
3	Moderately important
5	Strongly important
7	Very strongly important
9	Extremely important
2,4,6,8	Intermediate values

The process is performed by giving a value from the range 1 to 9 to each element (such as the criteria, the sub-criteria and the alternatives). Elements in each level are compared to themselves with respect to the immediate upper level. As an example, when giving the priority it is normally based on how the criterion affects the goal or the relative importance assigned to the criteria by the decision-maker. Preferences will be given when comparing alternatives with respect to a criterion. When there is a need to enter the reverse comparisons, the reciprocal values are automatically entered in the appropriate places to give the opposite judgments (Saaty, 1982). A simple example for a pairwise comparison is illustrated in Table 3 with a 2 level hierarchy.

Consider A, B, and C as the 3 choices for some particular criterion. When assigning priority values to the choices comparing with respect to the criterion it can be shown as in Table 3.

Table 3. An Example for Pair-wise Comparison

criteria	A	B	C
A	1	4	3
B	1/4	1	2
C	1/3	1/2	1

As the first step of the pairwise comparison process, element A must be compared to A, B, and C with respect to the criterion. Same procedure should follow for elements B and, C. The elements appearing in the left-hand column should always be compared with the elements in the top row (Saaty, 1982). If this comparison is a more favorable one, then the value in the matrix is an integer. Otherwise it is a fraction. This is going to be further clarified in following discussion.

When considering the verbal judgments of the above matrix,

- There are nine spaces in the matrix. The spaces (A, A), (B, B), and (C, C) have the value 1, because an element is equally important when compared to itself (Saaty, 1980).
- When entering the value 4 for the space (A, B), it is considered that A is moderately to strongly more important than B. For the vice versa, to give the opposite judgment, the space (B, A), is filled with ¼ . Hence the reciprocal values are automatically formed.
- When considering the meaning of (C, B) value ½ , C is equally to moderately less important than B.
- The value (A, C), 3 is formed as A is moderately more important than C.
- Finally, for a 3x3 matrix such as the earlier example, although there are nine spaces to be filled, we need to know only 3 values. The main diagonal is always filled with the value 1 and half of the matrix is filled with the reciprocal values.

(3). After conducting the pair-wise comparisons for the particular criterion, the values are organized in the form of a matrix as follows.

$$\begin{pmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{pmatrix}$$

(4). After summarizing the pairwise comparisons as a matrix with the principal diagonal is filled with one, the eigen vector is determined. As the first step, the vector of priorities is computed.

The pair-wise comparison matrix can be normalized by dividing each element of the matrix by its column total (Al-Harbi, 2001). In other words, for this approximation method of vector calculation, a process of averaging the normalized columns is going to be used (Saaty, 1980). For the above example the normalized matrix is as follows.

$$\begin{bmatrix} .632 & .727 & .50 \\ .158 & .181 & .333 \\ .211 & .091 & .167 \end{bmatrix}$$

(5). Then averaging across the rows gives the following priority vector with respect to the particular criterion or it is the relative importance of the elements.

$$\begin{bmatrix} .619 \\ .224 \\ .156 \end{bmatrix}$$

(6). Next, in order to measures the reliability of judgment through pairwise comparisons, a Consistency Index (C.I.) should be taken into consideration as follows. C.I. is the representation of deviation from consistency.

$$\text{C.I.} = (\lambda_{\max} - n)/(n\text{-}1) \qquad (1)$$

where, $\lambda_{\max}$ = maximum eigen vector element

n = size of the matrix

Saaty developed a ratio called Consistency Ratio (C.R.) to compare the C.I. of a particular matrix with a similar size matrix. If C.R. is less than 0.1 the judgments are accepted. If C.R. is greater than 0.1 the judgments should be reassessed (Chavis, Lin and Ko, 2001). Hence, the relationship between C.I. and C.R. is as follows.

$$\text{C.R.} = \text{C.I.} / \text{R.I.} \qquad (2)$$

where, C.R. = Consistency Ratio

C.I. = Consistency Index

R.I. = Random Index

Random Index (R.I.) is an average consistency index of a randomly generated reciprocal matrix and it is a known value for a known order of matrix.

For the above current example approximate consistency calculations should proceed as follows. We have to multiply the original matrix with the column vector obtained from step (4) as illustrated below to get the second column vector.

$$\begin{bmatrix} 1 & 4 & 3 \\ 1/4 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix} \begin{bmatrix} .62 \\ .22 \\ .16 \end{bmatrix} = \begin{bmatrix} 1.98 \\ 0.69 \\ 0.48 \end{bmatrix}$$

In the next step, we have to divide the corresponding values of this second column vector by the corresponding values of the first column vector that is obtained in step (4) and obtain the following eigen vector.

$$\begin{bmatrix} 3.19 \\ 3.14 \\ 3.00 \end{bmatrix}$$

Summing all these values and taking the average gives the value $\lambda_{max} = 3.11$.

Then, C.I. = 3.11-3 / (3-1) = 0.06

Corresponding R.I. for order of 3 matrix is 0.58

Hence, C.R. = 0.06/0.58 = 0.103

The calculated C.R. value is very close to the required value of 0.1. Otherwise the above steps should be repeated for new pair-wise comparison values.

If there are more than two levels, then the above steps should be repeated for every level in the hierarchy. Finally, by combining the priority vectors of criteria and the priority vectors of alternatives the composite priority vector can be obtained. In the case of selecting among alternatives, the highest priority can be chosen (Saaty, 1980).

However, the above mathematical approach is time consuming and complex to implement manually. Fortunately, the AHP procedure has been automated. A number of commercial software packages exist. In this thesis, Expert Choice, professional commercial software will be used to solve the AHP model. Such decision support software packages simplify the generation of alternate solutions.

2.2 Applications of AHP

2.2.1 Pre-Qualification of Contractors

AHP has been used as a method to select the best-qualified contractor to perform a project (Al-Harbi, 2001). In this project, the AHP problem was formulated as follows.

Goal: Choosing the best-qualified contractor

Criteria: (a). Experience, (b). Financial stability, (c). Quality performance, (d). Manpower resources, (e). Equipment resources, and (f). Current workload

Alternatives: Contractor A, Contractor B, Contractor C, Contractor D, and Contractor E

The author use the manual AHP procedure described in the section 2.1 to select the most-qualified contractor to perform the project.

2.2.2 Personnel Selection

The Construction Management and Engineering Division at North Dakota State University used the AHP and Expert Choice software program to assist with the decision of selecting a division director (Mclntyre, Kirschenman and Seltveit, 1999).

For selecting the suitable candidate, they decomposed the decision problem as follows.

Goal: Selecting the most suitable candidate

Criteria: (1). Administrative experience, (2). Teaching experience, (3). Experience in Research, (4). Experience in services, including advising, and membership in professional bodies, and (5). Any past experience in construction industry

Alternatives: candidate A, candidate B, candidate C, candidate D, candidate E, candidate F, candidate G and candidate H

The selection committee evaluated and ranked each candidate through pair-wise comparisons for each criterion. Then the decision was made using AHP assisted by the Expert Choice software program. Out of the eight candidates, they have selected three candidates for further consideration.

2.2.3 Cost Effective Approach to Waste Water Treatment in China

AHP was used as a cost-effective approach to waste water treatment for the Pearl River in a city in China (Tao and Hills, 1999). The hierarchy system was developed as three levels.

Goal: A cost-effective wastewater treatment approach

Criteria: (1). Construction period, (2). Management, (3). Urban sewer system requirement, (4). Environmental pressure, (5). Construction investment, (6). Unit treatment cost of sewage, (7). Land requirement for removing each unit of pollutant from sewage, and (8). Removed amount of pollutant per unit sewage

Alternatives: (1). One municipal wastewater treatment plant, (2). One medium-scale centralized sewage treatment plant, (3). A small-scale centralized sewage treatment plant, (4). Decentralized wastewater treatment operated by industries, (5). Facilities operated by joint venture or foreign–owners, and (6). Facilities operated by small and middle scale hotels and restaurants

After carrying out the pair-wise comparisons for the above eight criteria, overall ranking for the six alternatives were obtained. For the existing immediate pollution problem, the small and medium scale centralized sewage plants were ranked at the top rather than large-scale treatment plants.

CHAPTER 3

THE AHP MODEL FOR PROJECT DELIVERY SYSTEMS

The first step in developing a hierarchy is to decompose the problem into three major levels: the goal, the criteria and the alternatives as discussed in chapter two. In order to develop the hierarchy for the selection of best project delivery system, based on the requirements of the owner, the following specific criteria can be identified: (a) Tight schedule, (b) Limited budget, (c) High quality, (d) Clear scope, (e) Complex project, (f) Less risk, (g) Better owner's control, and (h) Less conflicts.

The feasible choices available to reach the ultimate goal successfully can exist as alternatives. The three principal delivery systems are selected as alternatives to create the AHP model. These delivery systems are (a). Design/Bid/Build (DBB), (b). Design/Build (DB), and (c). Construction Management (CM).

Below is a discussion of each criterion.

1. Tight schedule can be explained as time available for the entire project, including design and construction, is very short. This is a major issue for selection especially in selecting the Design/Bid/Build delivery system because of its linear process (Konchar and Sanvido, 1998).

2. Project budget is a main concern for public and private owners alike. A facility under construction is a liability to the owner. Hence, turning the liability to an asset at the end of the project should be gained through a properly selected delivery

system and the cooperation of all parties (Dorsey, 1997). Therefore, project budget is also a major criterion in selecting the best delivery system.

3. The next key criterion is the quality of both design and construction. However, the term “quality” depends on the owner’s expectations. Also degree of quality varies with the type of project delivery system (Konchar and Sanvido, 1998). In Design/Bid/Build, standards of quality normally have driven by the designers, whereas in Design/Build, it is usually contractor-driven. Anyway, the owner is the one who decides if the ultimate quality is acceptable or not.

4. Project scope is another important criterion, which includes the owner’s objectives regarding the project, expected quality standards, and the ultimate performance of the finished facility (Miller, Garvin, Ibbs and Mahoney, 2000). Each major party should be knowledgeable with the project scope especially designers. This scope is a very important issue in the Construction Management approach. At the beginning of the project the owner and the Construction manager should be clear with respect to the role and the responsibilities. If GMP is used, clear scope becomes critical since it affects the GMP automatically.

5. When delivering a complex project with new innovations under Design/Bid/Build linear process, time taken for the design phase may be lengthy, with an additional period for the construction phase. Hence, when selecting a delivery system, the complexity of the project is also a key factor (Mulvey, 1998).

6. When considering the less risk criterion, risk distribution among key personnel in the project may depend on the type of the delivery system adopted (Rubin and Wordes, 1998).

7. Another criterion to be considered is the owner's control over the entire project. This plays a major role in traditional Design/Bid/Build (DBB) unlike in the integrated Design/Build (DB). So, if an owner is really interested in participating in the design and construction phases, he has to select the delivery system appropriately (Dorsey, 1997).

8. The last criterion is conflicts between the parties involved. Sometimes if more parties are involved, more disputes and conflicts arise, hence less productivity. So this is another criterion that owner should consider (Mulvey, 1998).

To get a better feed back from the experts in the field, a questionnaire form was developed (See appendix A) and completed by experts from state agencies and consultants who have experience with at least one of the three-project delivery systems. The summary of the averaged data is produced as in the Table 4.

The data provided by the experts gave guidance in evaluating the preference for the alternatives with respect to each selected criterion. Additional information is added where appropriate from the literature. Finally, by analyzing all the relevant literature and data gathered for the model, six criteria were selected as the most appropriate out of the eight criteria in the questionnaire. The criteria chosen are: (a) tight schedule, (b) limited budget, (c) high quality, (d) clear scope, (e) complex project, and (f) less risk.

Table 4. Summary of Averaged Data

	Tight schedule	Limited budget	High quality	Clear scope	Better owner's control	Complex project	Less risk	Less conflicts
DBB	4	4	7	7	8	4	5	4
DB	6	4	6	5	4	6	5	4
CM	6	7	5	4	5	7	3	4

An AHP model for the project delivery system is shown in Figure 3.

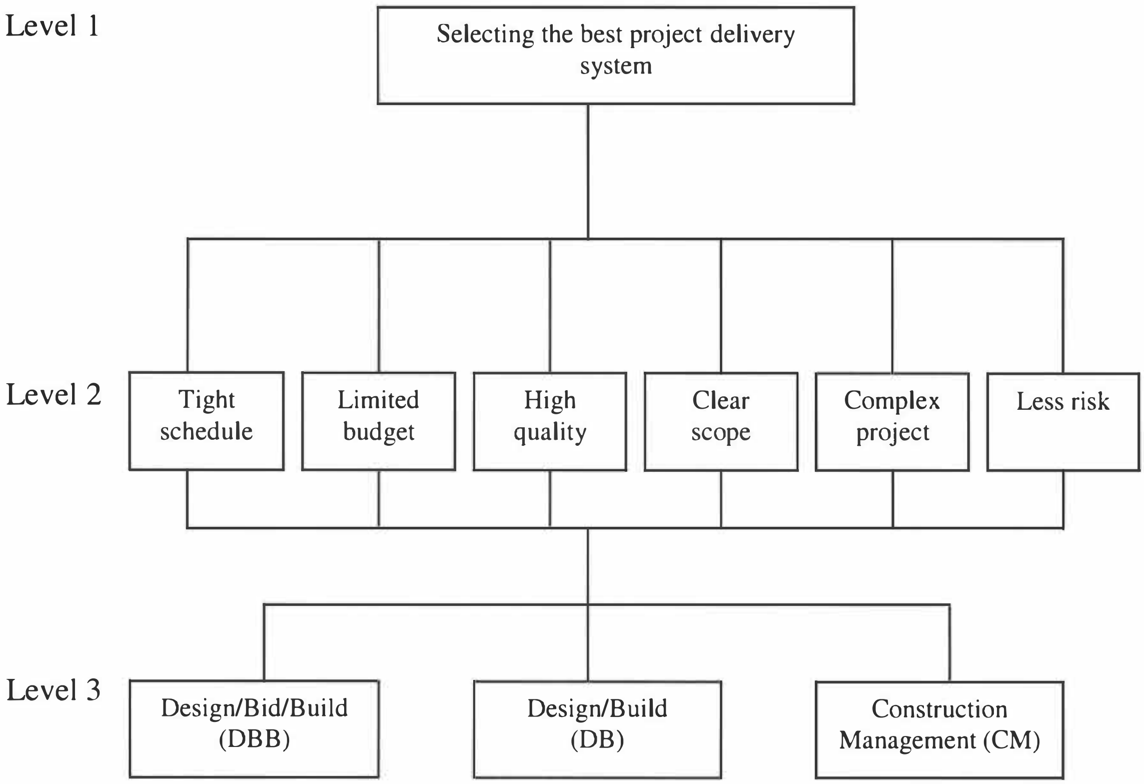


Figure 3. The Project Delivery AHP Model

In the Figure 3, Level 1 or the top level describes the goal of selecting the right delivery system. The six decision criteria identify the level 2 of the hierarchy. At the last, level 3 lists the three alternatives.

Once the decision hierarchy has been established, decision-makers have to indicate the preference or priority for each alternative. Since we know more about the alternatives than the criteria, the "bottom-up" approach is selected to give the preference. That means, evaluating the preference for the alternatives with respect to the criteria before evaluating the importance of the criteria with respect to the goal (Forman and Selly, 2000).

Preference evaluation of the three alternatives with respect to each of the six criteria should proceed as follows. When considering the first criterion " tight schedule" judgment can be made about the preference for the alternatives DBB, DB and CM. The pair-wise comparison scale 1 to 9 should be used as the guide as was discussed in chapter 2. Next, the priorities for the alternatives, with respect to the remaining five criteria is obtained in a similar manner.

The importance of each criterion with respect to the goal of selecting the best project delivery system should be evaluated as follows. As an example, the criterion "tight schedule" should be compared to the "limited budget" with respect to the goal of choosing the best project delivery system. Then the tight schedule should be compared to the remaining four criteria in similar way. Next, the same procedure is repeated with the remaining criteria by comparing themselves with respect to the goal.

CHAPTER 4

IMPLEMENTATION OF AHP MODEL: CASE STUDIES

To check the validation of the developed AHP model, several case studies from the literature were identified. Expert Choice 2000 software was used to facilitate the computations. As discussed in chapter 3, the " bottom-up" approach was selected to give the preference for alternatives with respect to each criterion. The judgment of preferences for alternatives with respect to the each criterion will be same for the each case study. As the next step, judgment of importance was recorded with respect to the goal, selecting the best project delivery system for each case study separately. Then the Expert Choice software gives the final outcome, which is the best project delivery system. Finally, sensitivity graphs were used to do the analysis. Each case study is presented as a subsection below.

4.1 Case Study for Design/Bid/Build (DBB)- Construction of a Fire Station (Dorsey, 1997)

4.1.1 Background

DBB delivery system was chosen to construct a four-bay fire station with budgeted cost of $ 1 million in Elk-Valley Township, which is close to a major city. Due to budgetary problem public bonds had to be sold. The state law required separate prime contracts for electrical and mechanical work. Project duration was six months without any liquidated damages.

4.1.2 Analysis

When applying the data relevant to the above case study to the AHP model, the governing criteria were selected as (a) limited budget, (b) tight schedule, and (c) clear scope. The other three criteria high quality, complex project, and less risk were considered secondary.

As the first step, relative preferences for alternatives, DBB, DB and CM are compared with respect to the criterion tight schedule. (See appendix B). The inconsistency value is recorded as 0.01. After all judgments are made, priority values can be summarized as in Table 5 for the criterion tight schedule.

Table 5. Priority Values for the Criterion Tight Schedule

Project Delivery System	Rank
DB	.592
CM	.333
DBB	.075

The highest priority for the tight schedule results as 0.592 for the DB. Similarly, the priorities can be seen for rest of the five criteria. Judgment of preference for alternatives with respect to each criterion is same for all case studies. Summary of ranked values of priorities for all six criteria is shown in Table 6.

Table 6. Summary of Ranked Preferences for Six Criteria

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
DBB	.075	.625	.196	.429	.084	.558
DB	.592	.136	.493	.143	.444	.122
CM	.333	.238	.311	.429	.472	.320

Next the judgment of importance should be done for each criterion with respect to the goal. For the Elk-valley fire station, the judgments of importance can be recorded according to the decision makers input values (See appendix B). It can be reproduced as a matrix in Table 7 for easy reference.

When considering the verbal judgments of some of the values in the matrix as explained in the chapter 2 and the Expert Choice 2000, it can be summarized as follows:

1. The value ½ in the first row means that for this particular case study, limited budget is equal to moderately prefer to tight schedule.
2. The value 4 in the second row means that limited budget is moderate to strongly prefer to clear scope.
3. The main diagonal is always filled with the value 1 and below half is filled with reciprocal values.

Table 7. Verbal Judgment of Importance as a Matrix

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
Tight schedule	1	1/2	5	2	5	5
Limited budget	2	1	6	4	6	5
High quality	1/5	1/6	1	1/3	2	2
Clear scope	1/2	1/4	3	1	4	3
Complex project	1/5	1/6	1/2	1/4	1	1/2
Less risk	1/5	1/5	1/2	1/3	2	1

4.1.3 Results and Discussion

Finally, Table 8 illustrates the ultimate judgments for the case study as DBB with highest priority 0.383.

Table 8. Decision Solution for the Elk-Valley Fire Station

Project Delivery System	Rank
DBB	.383
CM	.322
DBB	.295

This is matched with the original delivery system. CM and DB ranked as second and third respectively. Here, inconsistency is 0.03.

In every figure the inconsistency value should be less than 0.1 for the acceptable results. Then the sensitivity analysis is conducted by the performance sensitivity graph, which is a comprehensive graph that consists of weights of criteria and rankings of alternatives (See appendix B).

4.2 Case Study for Design/Build (DB)-Expansion of Utah's Interstate - 15 (ENR, 2000)

4.2.1 Background

Design-Build has been incorporated in a mega project in Salt Lake City's Interstate-15, which connects North and South Salt Lake City Valley. Utah Department of Transportation has been concerned about the repair of this highway because of Winter Olympics in 2002 with huge budget of $ 1.59 billion and huge amount of work such as reconstructing 130 bridges, expansion of lanes, repairing urban interchanges and improving interstate junctions. The Centennial Highway Endowment Fund was created to fund this huge project. State officials looked for a relative speedy solution to the reconstruction of this highway, which was located in highly, traveled area. They selected the Design-Build delivery approach by modifying the Utah State law as selecting the bidder by the best value not the least cost.

4.2.2 Analysis

To check the accuracy of the developed AHP model, the pairwise comparison for the judgment of importance has been done in a similar fashion as in the earlier case study. The paramount criterion selected for this case study was the tight schedule. Project budget and quality were considered secondary.

The importance of judgment for criteria with respect to the goal can be seen with decision–makers input pair-wise comparison values (See appendix B). As in previous case study, it will be a matrix. It is shown in the Table 9.

Table 9. Verbal Judgment of Importance as a Matrix

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
Tight schedule	1	7	5	5	5	5
Limited budget	1/7	1	1/2	1/2	2	2
High quality	1/5	2	1	4	3	3
Clear scope	1/5	2	1/4	1	3	3
Complex project	1/5	1/2	1/3	1/3	1	2
Less risk	1/5	1/2	1/3	1/3	2	1

4.2.3 Results and Discussion

After performing the pair-wise comparisons, the decision solution was given as shown in Table 10, DB with 0.439 in the highest position.

Table 10. Decision Solution for the Utah's Interstate-15

Project Delivery System	Rank
DB	.439
CM	.345
DBB	.216

Inconsistency is 0.08. Hence the model matches the actual selected project delivery system.

4.3 Case Study for Design/Build (DB)- Hospital Expansion (ENR, 2000)

4.3.1 Background

Design/Build was successfully used in the expansion of the Rose Cancer Center in Royal Oak, Michigan. With existing two levels, the new project consisted of four more additional levels. Total project cost is $ 17 million. The major concern was maintaining the patients' comfort while doing the construction at the same location. Hence, speedy delivery was an essential criterion. Quality and budget are also important criteria.

4.3.2 Analysis

When considering the major criterion for the AHP model, tight schedule is the governing one. Quality and cost are also taking major roles. Judgment of importance is carried out as in the same way (See appendix B). Relevant matrix is shown in Table 11.

Table 11. Verbal Judgment of Importance as a Matrix

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
Tight schedule	1	3	2	5	4	4
Limited budget	1/3	1	1/2	3	3	4
High quality	1/2	2	1	4	3	2
Clear scope	1/5	1/3	1/4	1	2	1
Complex project	1/4	1/3	1/3	1/2	1	1/2
Less risk	1/4	1/4	1/2	1	2	1

4.3.3 Results and Discussion

The output of this case study is shown in Table 12 after performing the pair-wise comparisons. DB was ranked as the highest value of .402. Inconsistency is recorded as 0.04. CM and DBB were ranked as second and third respectively. The original adapted delivery system for the Hospital expansion was DB. Hence, the AHP model has given an acceptable results for this case study too. Sensitivity analysis was carried out as earlier (See appendix B).

Table 12. Decision Solution for the Hospital Expansion

Project Delivery System	Rank
DB	.402
CM	.330
DBB	.268

4.4 Case Study for Construction Management (CM)- Construction of an Office Building (Dorsey, 1997)

4.4.1 Background

An Insurance company, an experienced owner with several project delivery methods other than Construction Management, has selected CM at risk with GMP for constructing a major office building in their home city. With a budget in 1972 of $ 22 million, the particular building was incorporating distinguished architectural features with twenty-four stories. Due to the twenty-three months of project schedule, fast tracking was needed. There was an incentive per day for the construction manager, but no penalty for any delays. Several concerns were present due to the adjacent government buildings, a post office and a courthouse. Special expensive foundation was required to avoid any possible effect on the adjacent buildings.

4.4.2 Analysis

To check the validation of the developed AHP model the pair-wise comparison was done as in previous cases. High quality and complex project were selected as paramount criteria (See appendix B). The reproduced matrix is as shown in the Table 13 for the values which are input to the model.

Table 13. Verbal Judgment of Importance as a Matrix

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
Tight schedule	1	3	3	2	1	2
Limited budget	1/3	1	1	2	1/2	2
High quality	1/3	1	1	2	1	2
Clear scope	1/2	1/2	1/2	1	1	2
Complex project	1	2	1	1	1	2
Less risk	1/2	1/2	1/2	1/2	1/2	1

4.4.3 Results and Discussion

Pair-wise comparison judgment was made for the importance of each criterion and finally achieved the priority values as in Table 14. Inconsistency is recorded as 0.05 for this case study.

Table 14. Decision Solution for the Office Building

Project Delivery System	Rank
DB	.381
CM	.361
DBB	.258

In this case study DB ranks as the highest of 0.381 and CM as 0.361. This is different than the original selected project delivery system CM. Sensitivity analysis for this case study is also done and explaining in brief (See appendix B).

In this case study final results show a different delivery system than the implemented CM. But both DB and CM have very closed prioritized values. Because ranked values basically depends on the decision-makers perspective on each criterion these values may be different for another decision-maker. If the decision-maker wants to select the CM instead of DB there would not be any major effects.

4.5 Case Study for Construction Management (CM)- Performing Arts Center (Dorsey, 1997)

4.5.1 Background

A $75 million cost performing arts center was proposed to build in Cincinnati, Ohio under public money. The governing criteria were maximizing the quality of the facility, complexity, achieve early completion, and clear scope of the project. Because of the high cost of the project and hence the risk involved, owner needs an assistance in a timely manner. They selected agency CM as the project delivery system.

4.5.2 Analysis

For the AHP model, cost, quality, complexity and scope criteria are, taken into consideration in different degree of importance to the selection of the project delivery system. Judgments of importance are recorded (See appendix B) as earlier. The relevant matrix is shown in the Table 15.

4.5.3 Results and Discussion

The results for the final judgment are shown in the Table 16. In this case study, the highest priority is DB and followed by CM. Delivery system derived from the model is different than the implemented CM approach. But the priority values of the two approaches are very close. Hence, if the decision-maker prefers the CM approach instead of DB, there would not be any major effects when implementation. As in the previous case study this might result in a different approach from a different perspective. The sensitivity analysis for this case study is illustrated and explained in the appendix (See appendix B). Inconsistency is recorded as 0.06.

Table 15. Verbal Judgment of Importance as a Matrix

	Tight schedule	Limited budget	High quality	Clear scope	Complex project	Less risk
Tight schedule	1	1/3	1/4	1/2	1/3	2
Limited budget	3	1	1	3	1/2	2
High quality	4	1	1	5	3	4
Clear scope	2	1/3	1/5	1	1/3	2
Complex project	3	2	1/3	3	1	4
Less risk	1/2	1/2	1/4	1/2	1/4	1

Table 16. Decision Solution for the Performing Arts Center

Project Delivery System	Rank
DB	.371
CM	.354
DBB	.275

4.6 Discussion of Case Studies

Finally, for easy reference the summary of the output of all the case studies is shown in the Table 17.

Table 17. Summary of the Output of Case Studies

Case study	Project Delivery System	
	Implemented	AHP model
1. Elk-Valley Fire Station	DBB	DBB
2. Utah's Interstate-15	DB	DB
3. Hospital Expansion in MI	DB	DB
4. Office Building	CM	DB
5. Performing Arts Center	CM	DB

It can be seen that from the table, results for case studies 1, 2, and 3 are acceptable. Case studies 4 and 5 were delivered initially under Construction Management approach, but for the model DB ranked with the highest priority and CM was the second. But, the priorities resulted for both approaches are closer values. Hence, CM approach can also be taken as the final selection to deliver the project. Because, different individuals have the different perspectives for the same problem, this might be given a different solution for another decision-maker.

CHAPTER 5

CONCLUSION

This thesis has focused on the selection of the best project delivery system from the owner's point of view. This model mainly depends on the owner's appraisal method, which includes evaluation criteria and relative importance of each criterion. This AHP model provides a systematic approach to assist the owner in making a sound decision under multi-criteria environment.

A set of major criteria was developed based on the requirements of the selection process. Tight schedule, high quality, and limited budget are considered as the major criteria. Scope, complexity, and risk are also taken into consideration. Importance of these six criteria depends on the owners' perspectives. Although time, cost and quality are the major criteria, sometimes quality can be sacrificed to overcome the schedule problems. For another owner, budget may be the prime concern.

The owner can use his experience, values, and knowledge to breakdown the problem into hierarchy and then can easily follow the implementation steps of the model. The model can be modified to suit the respective parties understanding of the problem and also can be altered to cover all the important issues. It is worth noting that providing judgments solely depends on the decision-maker's requirements and preferences as well as the characteristics of each alternative. Especially in a group session, different individuals with various knowledge and experience levels will have different perceptions on giving preferences and importance. Also, there can be situations when two people establish their preference in the same direction but different degrees.

In constructing the Project Delivery Systems (PDS) decision model with multiple criteria, the owner must select the most important factors to assist his decision. When making judgments, he can alter the values wisely if the consistency ratio or inconsistency shows a value greater than 0.1. This provides a feed back to the decision-maker regarding his judgment. However, as real life problems are full of inconsistencies, it is not practical to achieve a consistency ratio of exactly 0.0. However, it is important to mention that, to achieve the best decision means not to minimize the consistency ratio. Usually, consistent judgments through pair-wise comparisons will lead to good decisions, but the reverse is not always true. The developed AHP model can easily be updated. But further alterations of the hierarchy by adding more criteria or sub-criteria will lead to more complex decisions and also more inconsistency.

Using this AHP model with Expert Choice 2000 software on a number of case studies produced acceptable results. The model can incorporate real world inconsistencies. The quality of the input data depends entirely on the experience and knowledge of the decision-maker. This AHP technique has proved a powerful decision making tool that enhances the understanding of a complex problem and provides a measure of consistency of the decision-maker at the same time.

Finally, it is worth noting that different conclusions can be made by different decision-makers, and different outcomes may be achieved depending on the specific needs and interests of each decision-maker.

However, there is no right view or answer as a particular problem can be illustrated in several ways and must exert some creativity. Every construction project is unique and has unforeseen outcomes. The developed AHP PDS model can assist in selecting the best delivery system given a set of criteria.

Future research directions in the area of project delivery systems and AHP methodology may include the efficiency and accuracy of the technique, ease of modeling, standardization of the criteria, and acquiring more information from experts through a national survey. Providing the case study details to a number of experts may be given a more accurate feedback regarding the pair-wise comparison values. Perhaps, this model will provide a basis for future studies, and for eventual adaptation of the AHP model to the project delivery selection problem.

Appendix A

Questionnaire Form and Raw Data

Title (optional): ____

Organization (optional): ______________________________________

Questionnaire for selecting a delivery system in different criteria

1. Type of your organization: (please select one)
   City ___ County___ State ___
   Consulting___ Contractors ____

2. Types of work: (check all relevant)
   Industrial _____ Highways/Bridges________
   Commercial/Building_____ Others ________

3. What percentage of work (approximately) is completed under these project delivery methods?
   Design/Bid/Build (DBB) ____
   Design/Build (DB) ______
   Construction Management (CM) _____

4. Please indicate (approximately) number of employees in your organization
   Top management ____ Project Engineers ____
   Design Engineers ____ Project Managers ____
   Other technical staff ___

5. Please rank the importance of criteria shown across the table in the selection of the project delivery system. Please use a scale from 1 to 8 with 1 being least important and 8 being most important.

	Tight schedule	Limited budget	High quality	Clear scope	Better owners control	Complex project	Less risk	Less conflicts
Design/Bid/Build (DBB)								
Design/Build (D/B)								
Construction Management (CM)								

Table A.1 Summary of Gathered Raw Data

	Tight schedule	Limited budget	High quality	Clear scope	Better owner's control	Complex project	Less risk	Less conflicts
DBB	4 2 2 6	5 2 5 5	8 6 6 7	8 8 3 7	8 8 8 8	5 5 1 6	3 6 7 2	3 4 4 6
DB	8 1 8 8	3 1 6 7	8 6 5 3	6 8 3 3	2 7 4 2	7 5 7 4	4 6 2 7	6 6 1 3
CM	8 5 5	8 8 5	6 4 4	5 3 4	6 6 3	8 7 7	6 1 3	8 2 1

Appendix B

Case Study Results

Case Study 1- Elk-Valley Fire Station

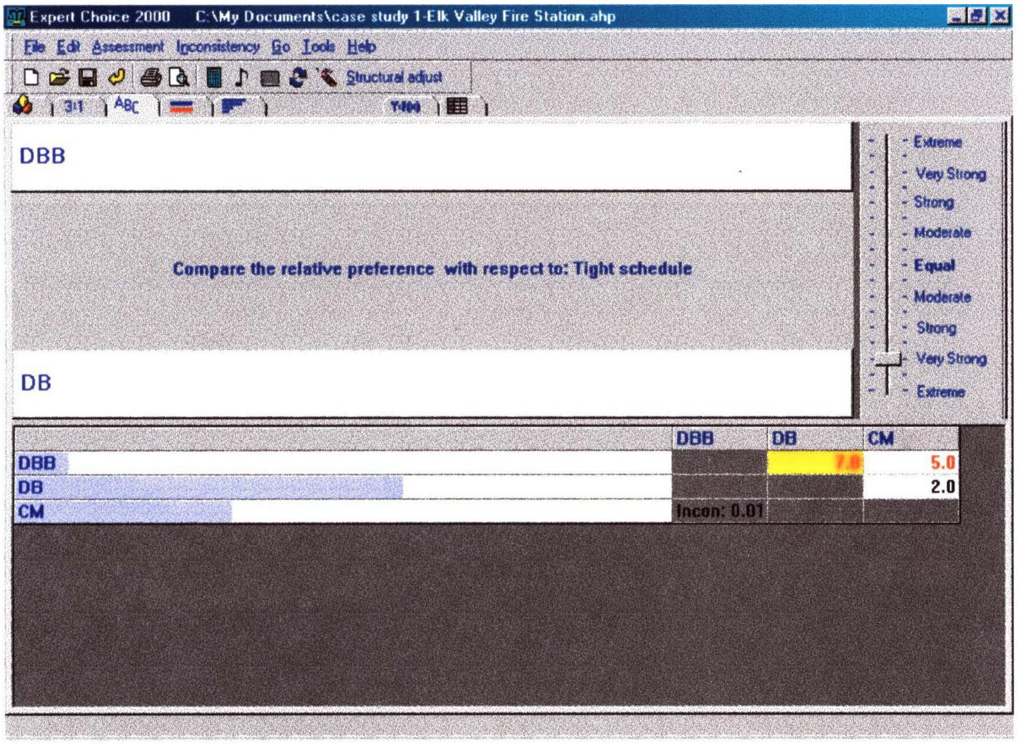


Figure B.1 Relative Preference to the Criterion Tight Schedule

To select the judgment for preference the verbal scale can be used in either up or down as shown in the Figure B.1. As an example, the red number 7.0 indicate that DB is very strongly preferred to DBB with respect to the tight schedule. Also, the black number 2.0 indicate that DB is equal to moderately prefer to CM with respect to the criterion tight schedule. Note the inconsistency value is recorded as 0.01.

For judgment of importance for criteria with respect to the goal, input values can be seen as in the Figure B.2. When considering the 2.0 value in red in first row that means for this particular case study, limited budget is equal to moderately prefer to tight schedule with respect to the goal, selecting the best project delivery system.

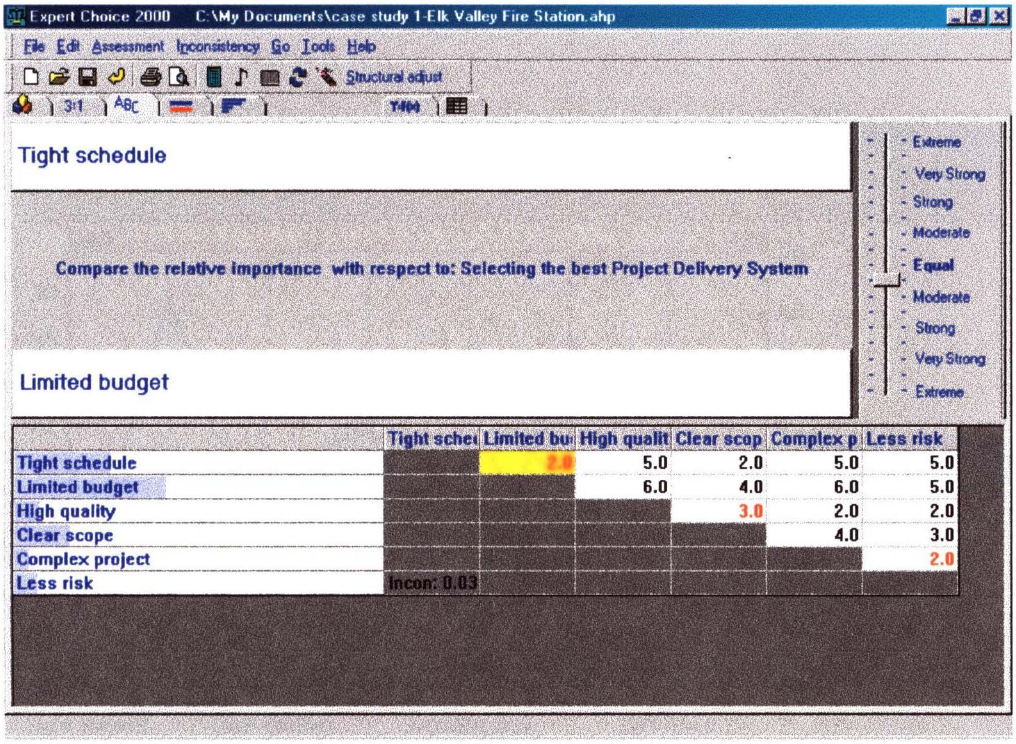


Figure B.2 Judgment of Importance for Elk-Valley Fire Station

Inconsistency is recorded as 0.03. Next step is the conducting the performance sensitivity analysis as in the Figure B.3. The relative preference for each alternative with respect to each criterion shows the intersection points where the alternatives' curves meet the vertical criterion line. It can be read from the right-y axis. The overall priority for the project delivery systems for the Elk-Valley fire station is shown at the right Y-axis. The rectangular bars show the relative importance of the each of the criterion. It can be read at the left Y-axis. So the DBB can be selected as the delivery system for the Elk-valley fire station. Clicking the criterion bars one at a time and adjusting the weights attributed to each of them performs sensitivity analysis. All the other criteria will be changing automatically according to that change.

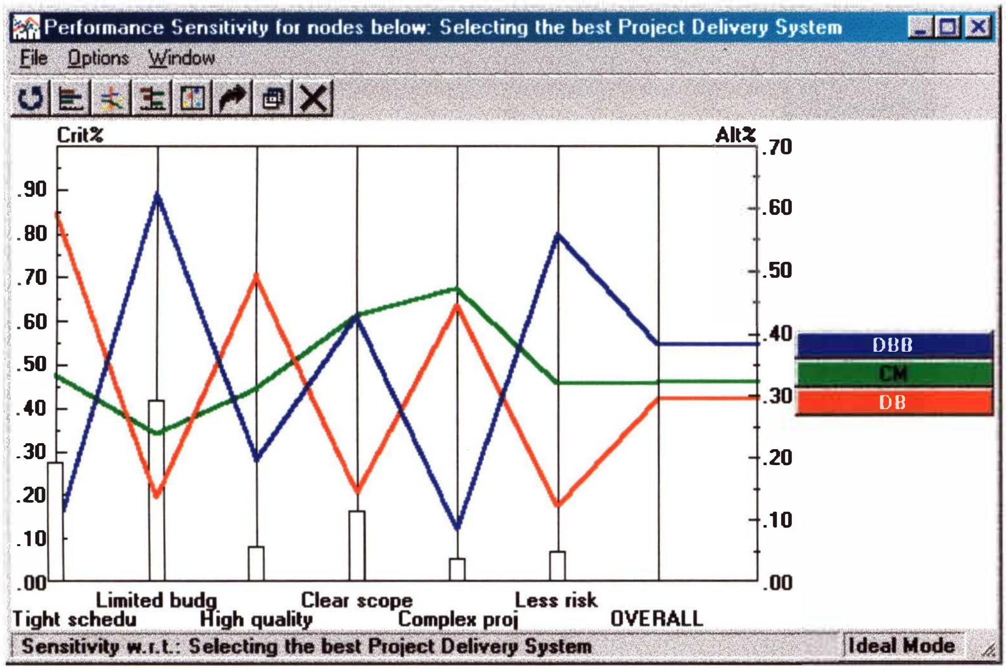


Figure B.3 Sensitivity Analysis for the Elk-Valley Fire Station

Case Study 2- Expansion of Utah's Interstate-15

The judgment of importance for this case study is shown in the Figure B.4. The input values depend on the decision-makers perspectives. The inconsistency is recorded as 0.08. Sensitivity analysis graph is shown in Figure B.5. DB is ranked at the highest position.

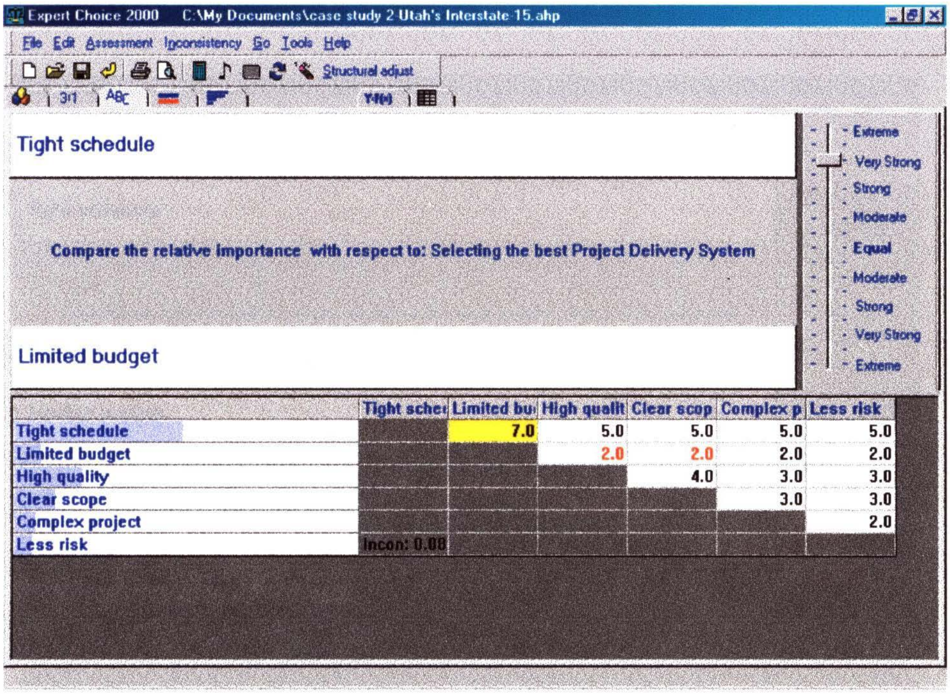


Figure B.4 Judgment of Importance for Utah's Interstate-15

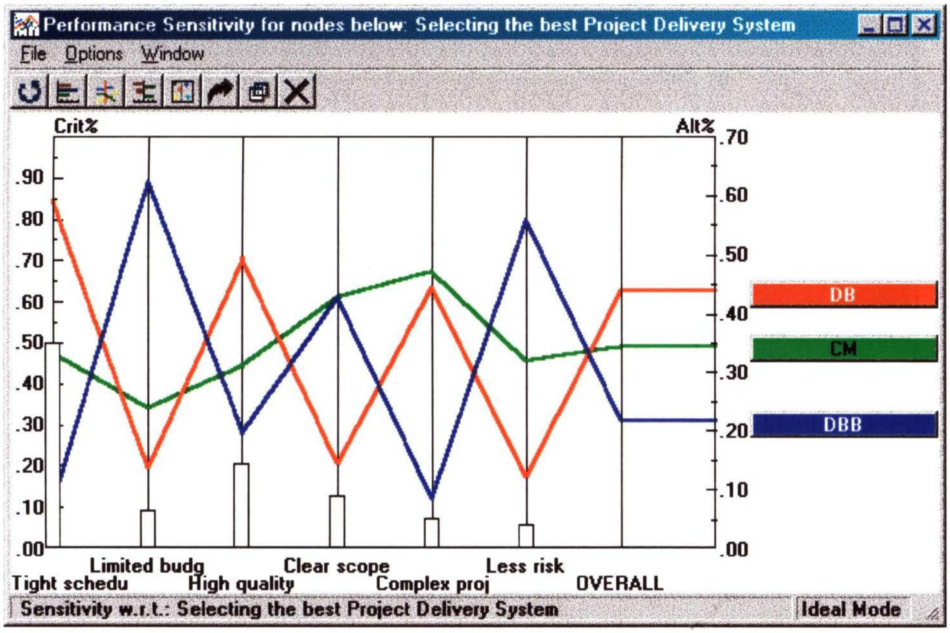


Figure B.5 Sensitivity Analysis for Utah's Interstate-15

Case Study 3- Hospital Expansion

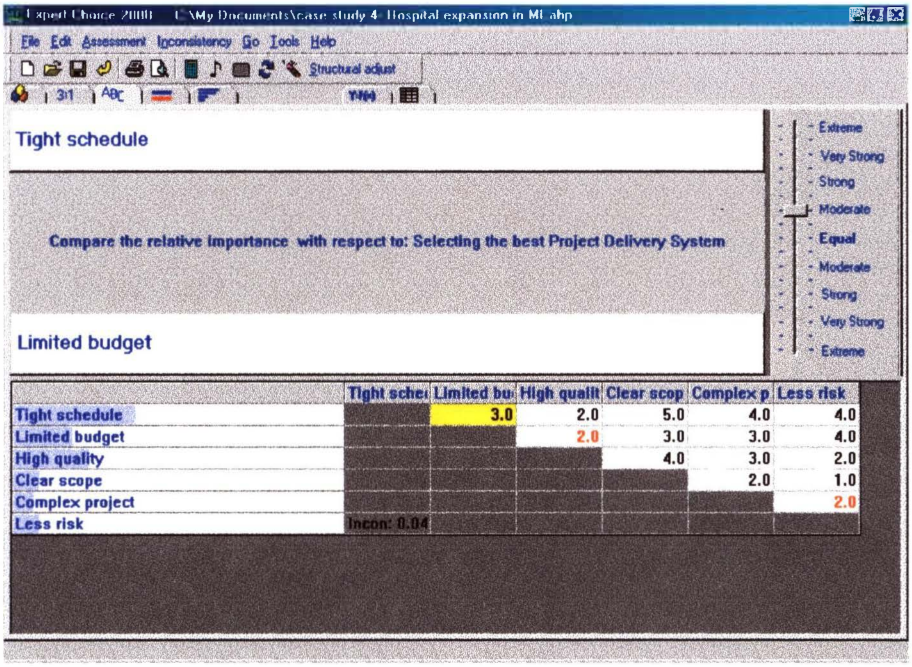


Figure B.6 Judgment of Importance for the Hospital Expansion

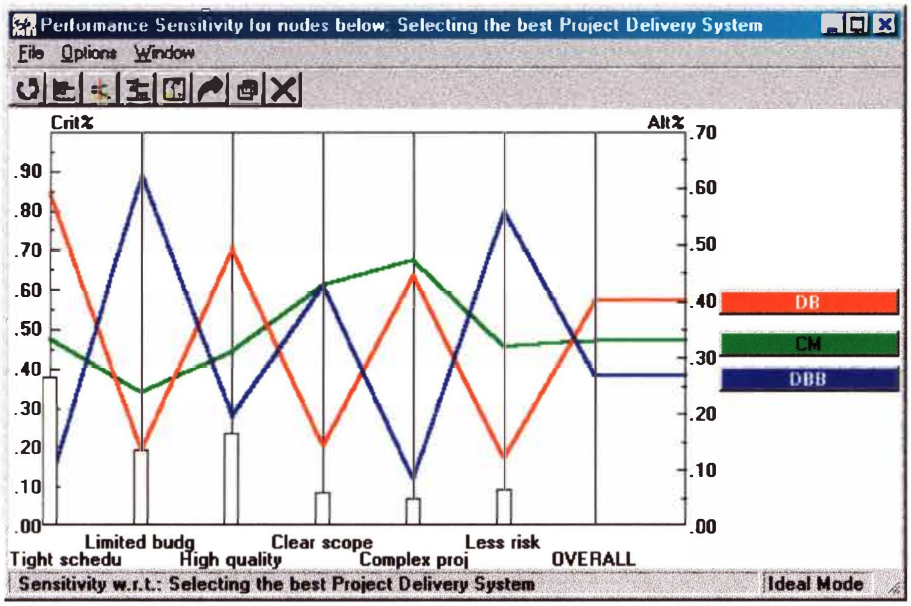


Figure B.7 Sensitivity Analysis for the Hospital Expansion

Case Study 4- Construction of an Office Building

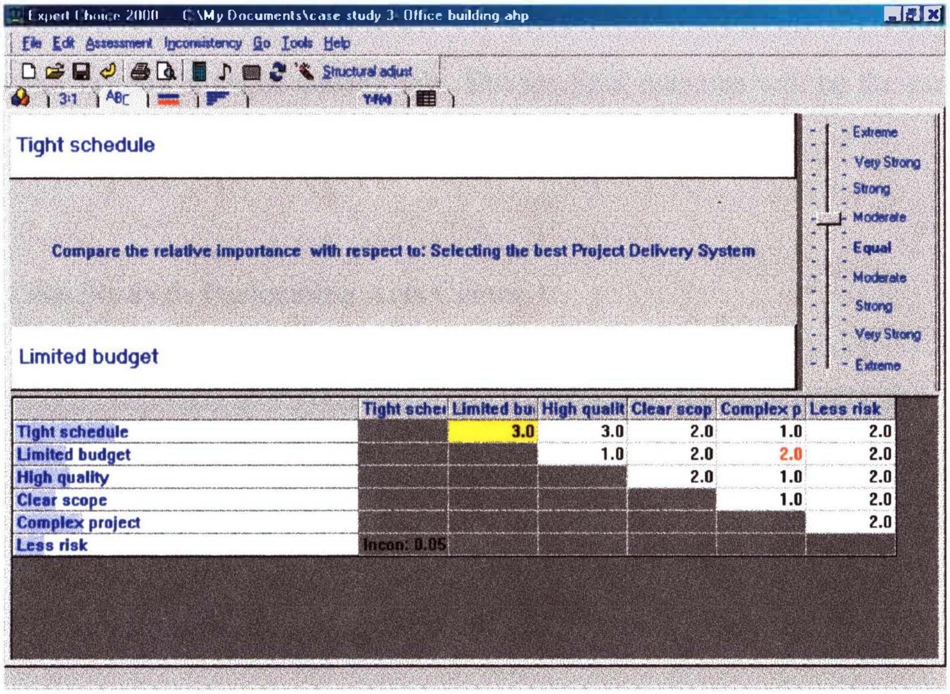


Figure B.8 Judgment of Importance for the Office Building

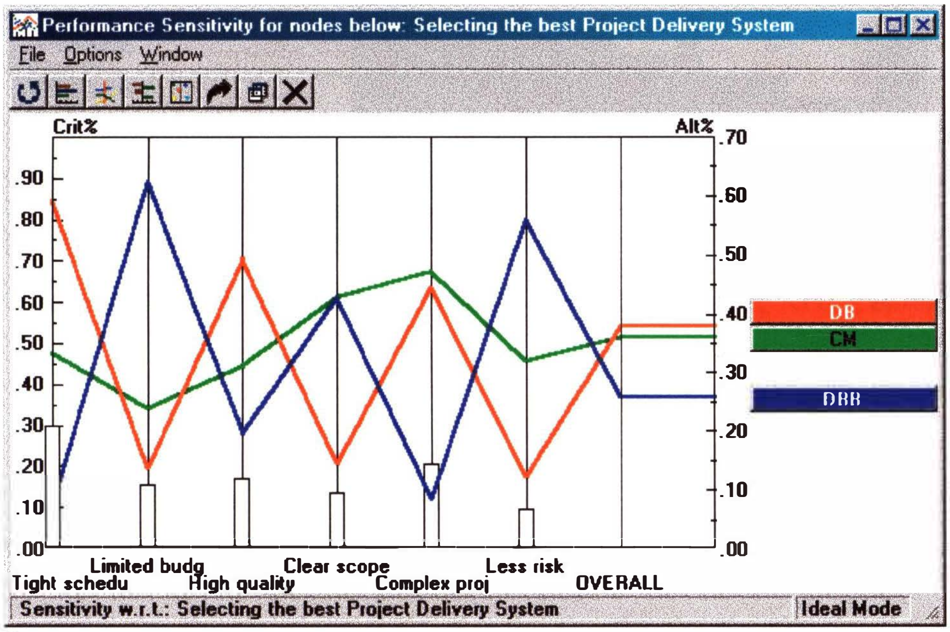
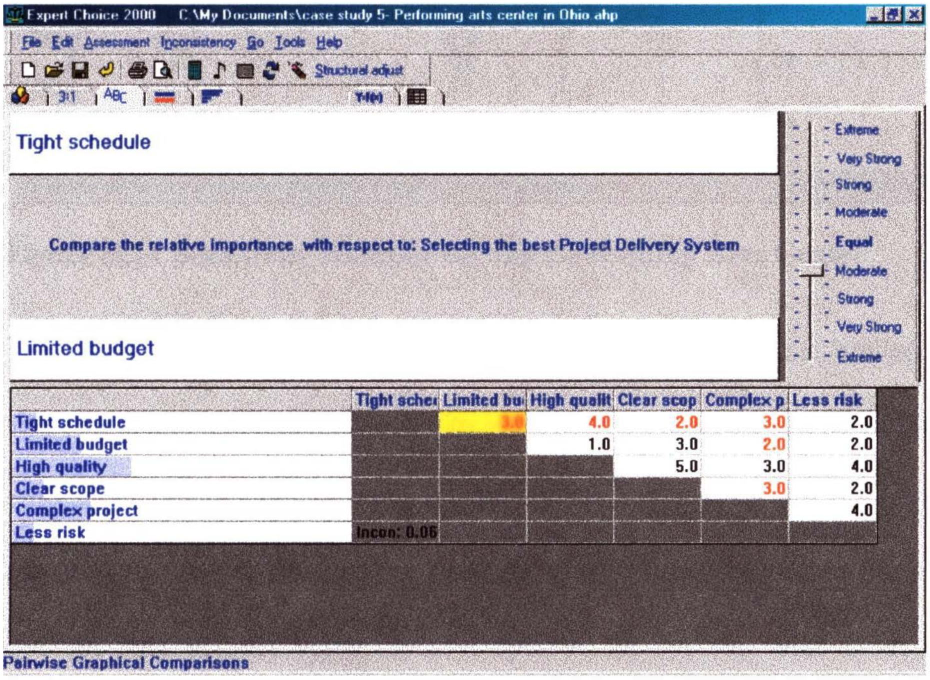


Figure B.9 Sensitivity Analysis for the Office Building

When try to adjust the weights attributed to each major criterion by clicking the relevant criterion bar (high quality and complex project) the weights attributed to other criteria changed accordingly. But the final outcome will be the same as DB in the highest position and CM as second.

Case Study 5- Performing Arts Center



	Tight sche	Limited bu	High qualit	Clear scop	Complex p	Less risk
Tight schedule		3.0	4.0	2.0	3.0	2.0
Limited budget			1.0	3.0	2.0	2.0
High quality				5.0	3.0	4.0
Clear scope					3.0	2.0
Complex project						4.0
Less risk	Incon: 0.06					

Figure B.10 Judgment of Importance for the Performing Arts Center

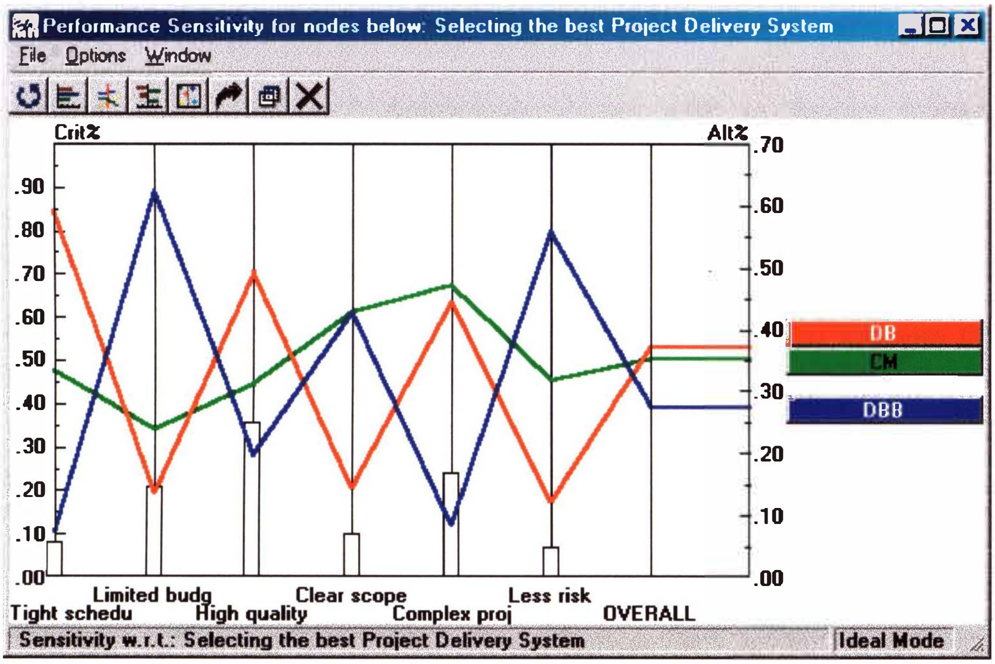


Figure B.11 Sensitivity Analysis for the Performing Arts Center

In this case study, high quality, complex project and limited budget were taken as major criteria. When try to adjust the weights attributed to those values by clicking the each relevant criterion bar DB and CM were got the highest priorities respectively. But when clicking only the limited budget criterion bar although DBB gets the least priority value out of 3 options, the ranking value is very close one to other 2 ranking values of DB and CM.

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