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FUNCTION ANALYSIS RELATING TO DECISION MAKING

IN VALUE ENGINEERING

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ABSTRACT

This paper attempts to analyze the interrelationship of FAST, CPM, and the cause-effect analysis techniques in VE study. The study process is conducted by deriving one diagram from the other. It has been found that FAST, CPM, and the cause-effect diagrams can represent each other. The study process follows the VE job plan.

In addition, this paper discovered four mathematical methods through five case studies in selecting functions for development. Respectively, Matrix analysis provides an efficient method in selecting functions. The AHP methodology determined the priorities selection of the functions through the calculation methods recommended by Saaty. The accuracy of the result is ensured by logical consistency checking. The Payoff matrix is a set of simplified methods in decision making. In applying Bayes' theorem, both "a priori" and "a posteriori" analyses are experienced. A posteriori probabilities provide a reversed probability when the subsequent information is known. The four methods are used together to comprehensively arrive at a final decision for developing functions during a VE study. The final decision is thus scientific and reliable. The methodology so developed contributes to the VE literature as a new technique that can be applied in the field.

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CHAPTER 1. INTRODUCTION

1.1. Background

1.1.1. History of Value Engineering

Value engineering technique emerged during World War II. When World War II broke out, material shortages began occurring, and electrical components that once were plentiful were committed to strategic applications. General Electric, concerned with the difficulty of obtaining critical materials to produce war equipment, assigned electrical engineer Mr. Lawrence D. Miles to the purchasing department. His mission was to find adequate material and component substitutes to manufacture the designs of needed war equipment. During these war years, Miles found that many of the substitutes used provided equal or better performance at less cost by understanding and addressing the intended function of the product. Miles separated function from activity and defined function as "What it must do." and "How it does it." Therefore, "Value" can be improved by relating function to cost. The relationship he provided is expressed below as (Parker, 1977):

$$Value = \frac{Function}{Cost} \qquad \text{(i)}$$

Miles named this discipline "Value Analysis".

When the Navy adopted Miles' techniques, they called the program "Value engineering". This name is commonly used and accepted since the chartering of the Society of American Value Engineers (SAVE), now named SAVE international.

Mr. Lawrence D. Miles, who developed the system of techniques known as value engineering, is now universally known as the "father of value engineering".

1.1.2. The basic concept in VE study

1. Classifying functions

The functions of broken-down activities of a project are classified into basic functions and second functions. Those performance features that must be attained if the total item is to be desired are basic functions. Those performance features other than those that must be accomplished are secondary functions. Hence, the secondary function is desired to have, but is not needed. It is necessary only because of the method used to accomplish a basic function.

2. Function language

The function language is the heart of the VE methodology. It uses quantifiable verbs and nouns with measurable parameters to describe the function. It answers the questions, such as:

What is the product/component?

What does the product/component do?

What must the product/component do?

The verb indicates what the item does, and the noun indicates what the subject is. The verb defines the item's required action. The noun must be measurable or at least understood in measurable terms. For instance, instead of 'provide sound', 'amplify sound' would be better.

3. <u>The relationship of function, cost and worth</u>

The function is the specific purpose of use intended for an item. For instance, for the following items, the appropriate function definitions are as under:

	Item	Verb-noun function definition
1	screwdriver	transmits torque
2	light	creates contrast
3	can opener	cuts metal

Functions include all kinds of purpose, including the sell functions and aesthetic functions.

Economic value is a VE concern, not a moral, political or social value. There are different types of economic values: esteem value, exchange value or use value. Worth is the least cost to perform a required function. Worth is just a technique of value index, not an absolute value and it is based upon the personal evaluator's judgment and experience. It is used only as a tool to identify the value index relationship of functions. The formula of the relationship of value, worth, and cost can be stated in the following:

$$Value = \frac{Worth}{Cost} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

This formula of Eqn. (ii) follows from Eqn. (i), wherein "function" is considered equivalent to "worth". In analyzing Eqn. (ii), we conceive as follows:

- When worth = cost = value, this can be seen as fairness.
- When worth > cost = bargain, this can be seen as a bargain.
- When worth < cost = poor value, this can be seen as poor value.

Hence, a product/components needs development when worth < cost.

1.1.3. Value Engineering Job plan (King, 2000)

Value engineering is the systematic application of recognized techniques which identify the function of a product or service, establish a monetary value for that function, and provide the necessary function reliably at the lowest overall cost. This is the definition of Value engineering stated by the Society of American Value Engineers.

SAVE international established a methodology for the performance of Value engineering studies. The methodology is broken down into a series of steps, introduced as a job plan. It systematically displays all facts and ideas necessary for an effective analysis, therefore, to improve the decision making process. The beginning of value engineering study is the project selection. Once the project is selected, the value engineering study, that is the job plan, is ready to be performed. Job plan steps are described in the following paragraph and illustrated in Figure 1-1.

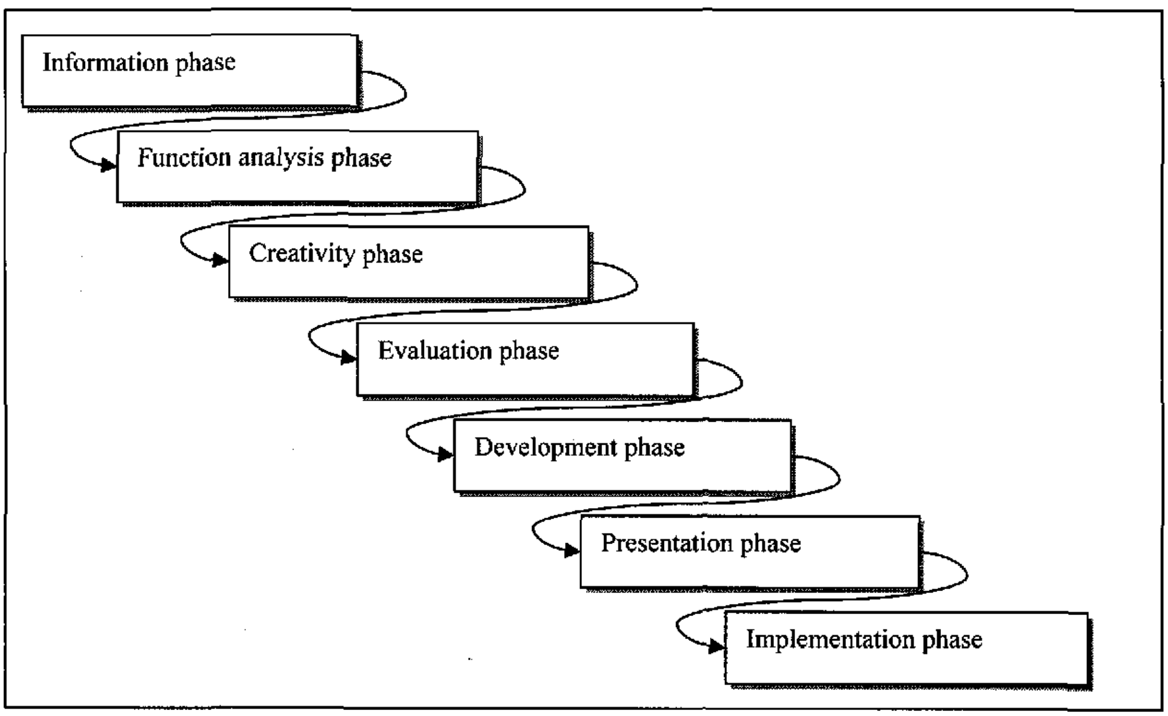


Figure 1-1 VE Job Plan

1. Information phase

The information gathering can be the most underrated phase in the VE job plan. The information received from the project must be objective and factual to ensure that it is not influenced by opinion or assumption. In addition, the indirect information can also be very useful in a VE study. For instance, for the construction of the concrete column, the information of the project will answer the following questions: what needs to be constructed? How to work on it? Why does a certain activity have to be done? What are the specifications and criteria? Who will take the work? Where will the work be done? Seeking all the useful facts that related to the project is the critical task of this phase.

2. Functional analysis phase

The function analysis approach to problem solving can not be over emphasized in value analysis. It is a remarkable system technique that was experienced throughout the history of value engineering. The technique requires converting the function into verb and noun statements. Therefore, the function of any product or process, procedure or project, is translated into a structure of words. A FAST (Function Analysis System Technique) diagram plays an important part during the function analysis phase by structuring the functions of the project into a visible and logical network. In this paper, two other techniques will be examined on the basis of the concept and purpose of function analysis.

3. Creativity phase

The task of the creativity phase is to generate ideas to perform the functions by brainstorming. It takes creativity to discover alternate designs, methods, ideas, processes that will accomplish the functions that need to be performed. The creativity approach is an idea-producing process intended to generate a large quantity of ideas for problem solving. There are many attitudes or influences that block the creative process based on the background of each individual. Therefore, it is critical to realize the mental blocks and counteract them. Brainstorming is one of the most effective techniques during the creativity phase.

4. Evaluation phase

The preceding creativity phase generates a large quantity of alternatives. Now it is time to analyze the ideas, cull out the impractical, and select those valuable ideas for further analysis. The first step is to develop a set of evaluation criteria by which to judge the ideas. Next, the most feasible alternatives will be selected. Several techniques can be applied for evaluating an idea or solution to a problem, such as numerical technique, feasibility ranking, paired comparison, weighted evaluation, and evaluation matrix. In this report, several methods will be used for evaluation purpose, including Bayes' theorem, Payoff matrix, AHP and the matrix analysis technique.

5. Development phase

The development phase is to formulate ideas from the creativity phase. Those ideas will be fully integrated into practical project solutions. The project cost is forecasted, and people affected by the changes are identified. The aim is to clarify what to expect from them to achieve the VE proposal. Adequate planning is necessary in this phase to ensure the completion of the proposal. Worksheets are designed to help in preparing the recommendation documents.

6. Presentation phase

Key points for presentation include the following: name of the project, present cost, quantity, proposed cost, sketches – both present and proposed, advantage and disadvantage, breakeven chart, summary cost breakdown, and recommendation. The VE proposal report for recommended changes is made in written form.

A presentation contains sufficient discussion. Potential savings are based on a valid cost analysis with break-even and return on investment.

7. Implementation phase

The implementation phase is to ensure that approved VE recommendations are converted into actions. People have fear and roadblocks to accept new ideas. Therefore, an important strategy in selling an idea is the preparation of a fully developed implementation plan which includes many aspects of the effort such as persuasion and negotiation. It is always necessary for a VE idea to be presented in written form. Apparently, those ideas will be turned into reality by achieving the implementation phase, and that makes the value engineering exercise meaningful.

1.2. Literature Survey

1.2.1. The function analysis phase

In 1967, Charles W. Bytheway laid the foundation for a logical function analysis method. He developed a Function Analysis System Technique (FAST) diagram by describing a how-why question technique. It provides a double check on answers to the how, why, when questions. The FAST diagram has been an important technique in VE studies during the past decades since then (Snodgrass & Kasi, 1986).

During this thesis study, other similar diagrams were consulted. One of them is the critical path method (CPM) diagram. The CPM was developed specifically for the scheduling system of construction. This approach remains essentially unchanged from its earliest formulation. The network techniques of the CPM are empirical, logical, and well-established.

The other one is the cause-effect diagram which was developed by Professor Kaoru Ishikawa of the University of Tokyo. Cause-effect diagram is a quality control method that originated and later came into wide use throughout Japanese industry. However, it can be applied to the solution of any problem (Ishikawa, 1976).

1.2.2. The evaluation phase

In this phase, alternates are examined which have been generated during the preceding phase in order to evaluate the ideas. As a numerical evaluation technique, Matrix analysis-- or paired comparisons-- was widely adopted in earlier VE research. Recently, the Analytic Hierarchy Process (AHP) technique has been applied to VE studies (Kulshrestha & Deshpande, 2002). The AHP technique offers a logical method to set priorities and to make the decisions in a complex environment (Saaty, 1982).

Nevertheless, the more effectively a technical theory is used in solving a problem, the better a decision can be made. In this research, the AHP technique will be further discussed and other mathematical approaches will also be discussed in an effort to look for a new way for the VE study.

Knowledge which is directly concerned with the problem of decision making will also be discussed in this research. That includes two aspects: Payoff Matrix and Bayes' theorem.

1.3. Objective

Through the process of researching the interrelationship among the three Function Analysis techniques: FAST diagram, CPM methodology and Cause-effect diagram, it will be established that direct interrelationships and meanings exist between the three techniques. Therefore, when the VE studies take place, CPM and Cause-effect diagrams can also be established to analyze the functions the same as the FAST.

The process of function analysis creates a set of measurable functional data. It can be used to decide the functions that should be developed. Hitherto, VE practitioners have believed that FAST, CPM and Cause-effect techniques are distinct and different. However, this research seeks to prove that each of them can be directly derived from the other, thus creating an interdependent function analysis system for use in value engineering.

It is the objective in this research, to discover the different types of decisions yielded by using Matrix analysis, AHP, Payoff matrix, and Bayes' theorem. Each of these methods produces different results for the type of functions that are good candidates for development. However, by taking a comprehensive approach to decision analysis, a more meaningful result can be found.

1.4. Purpose

The purpose of this paper is to discover the interrelationships between the FAST diagram, CPM, and cause-effect diagram and to use them in the function analysis phase of a VE study. Another purpose is to prove that mathematical approaches such as Matrix analysis method, AHP method, Payoff matrix, and Bayes' theorem can be applied with useful effect in a VE study when used in conjunction.

The combined application of the mathematical approaches helps to save time and resources by selecting suitable functions for development. This is especially helpful when a large number of functions exist as candidates for development.

1.5. Scope

The scope of the work is limited to analyzing five cases that interweave FAST, CPM and Cause-effect diagram. It is focused on researching the interrelationship among the FAST diagram, CPM and Cause-effect diagram techniques. The purpose is limited to analyzing the three diagrams to represent each other. CPM diagram is based on its original application area that is in the construction planning process.

The next point is to focus on the mathematical methods. The scope of the work is limited to applying Matrix analysis, Payoff Matrix, and AHP, and Bayes' theorem to analyze functions in VE study. The Payoff Matrix method determines the maximum of the maximum payoff value, the minimum of the maximum regret, the expected monetary value, and the expected opportunity loss. The AHP method evaluates the weights to be assigned for the priorities of functions; subsequently, a consistency index check is conducted to determine whether the assignment of weights is acceptable. In Bayes' theorem, a priori and a posteriori analysis are conducted.

The examples used in the paper are limited to the construction area. The final aim of this research is to facilitate decision making during the functional analysis and evaluation stages of the value engineering job plan.

1.6. Research methodology

The study outline follows the VE job plan, in the order below:

1. Analyze the FAST diagram, CPM, and Cause-effect diagram. The purpose of this process is to interpret each diagram from the other.
2. Derive six diagrams as explained in Figure 1-2, as follows:
    1) Derive CPM & cause-effect diagram from FAST
    2) Derive FAST & cause-effect diagram from CPM
    3) Derive CPM & FAST diagram from cause-effect diagram.

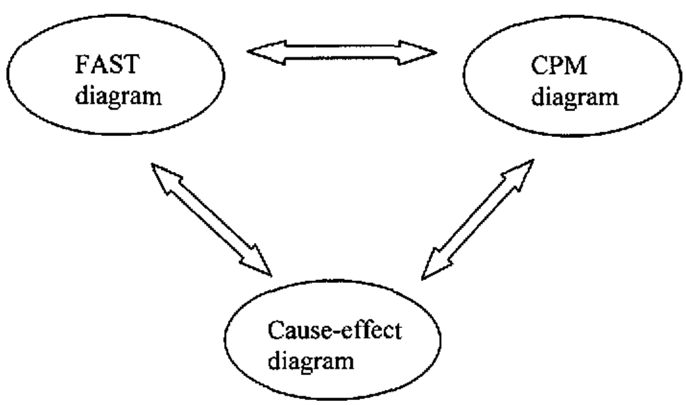


Figure 1-2 Interrelationship among FAST, CPM and Cause-effect diagrams

3. Mathematical methods are applied through five case studies. The methods include Matrix analysis, AHP, Payoff matrix, and Bayes' theorem. Results from these methods help in ranking the priorities of functions to be developed.

1.7. Number of cases studied

Part I and Part II have five case studies each. Five is considered a minimum sample size for conducting a representative observation study (Oglesby, Parker, & Howell, 1959).

1.8. Thesis layout

The thesis is in two parts: Part I and Part II. Part I deals with the intra-derivations of FAST, CPM, and Cause-effect techniques. Part I is in Chapters 2, 3, and 4. Part II deals with Matrix analysis, AHP, Payoff matrix, and Bayes' theorem. Part II is in Chapters 5, 6, 7, and 8. The results and findings are given in Chapters 9 and 10.

PART I

CHAPTER 2. DERIVATION OF CPM DIAGRAM AND CAUSE-EFFECT DIAGRAM FROM FAST DIAGRAM

2.1. FAST Diagram

2.1.1. The explanation of FAST diagram

Function is defined as "an intent or purpose that a product or service is expected to perform" (Kaufman, 1998). FAST creates a graphical mode to display functions in a logic sequence. It provides a model for all kinds of works, such as accounting, research, development, engineering and so on, as the interdisciplinary team resolves multi-faced problems.

In the FAST model, the relationships of the functions with respect to each other are determined by establishing how and why the function is performed. Regarding this principle, establishing a FAST diagram could start anywhere by taking one function and asking why and how questions about that function. When asking "how", the answer is the method to perform that function. When asking "why", the answer is the purpose of that function. The "when" direction is not part of the logic process. But it supplements intuitive thinking. The "when" direction is not time-oriented; it expresses cause and effect or the same time function. The two scope lines contain everything that the selected project does (Kaufman, 1998).

2.1.2. Case study - Construct concrete column

This section discusses a case study that utilized the FAST diagram in the construction of concrete columns in a high-rise building. In a contractor's view, a FAST diagram was established as shown in Figure 2-1 (Snodgrass & Muthiah, 1986). The higher order function in this case is *Construct Column*. The diagram assures the proper relationship of functions of the project and provides a good basis for classifying them by How/Why logic.

The FAST diagram clarifies the meaning and verb/noun descriptions of functions. The functions shown horizontally across the diagram must meet a time sequence requirement. Earlier time functions appear in a relative time sequence, later time functions will found further to the left. The "When" functions do not have a time sequence relationship, so they should be shown below or in some cases above.

2.2. Derivation of CPM diagram from FAST diagram

Regarding the FAST diagram Figure 2-1, the data of the activities of the work were collected as shown on Table 2-1 . The duration of the accomplishment of each activity of the project was designed for preparing the CPM diagram. From the data collected, all the activities in the critical path in the FAST diagram are on the list. The work needed to be done from activity 1 to activity 9 is to reach the purpose - construct concrete column.

According to the activities collected from the FAST diagram, the first activity is to fabricate the panels. Next, the panels are erected and stabilized. The side is set and reinforced after that. Then the form is constructed to encase the concrete. Once the form is ready, the concrete should be poured and cured. The description of the work activities is illustrated in the diagram and the decisions regarding the sequencing of the work constitute planning for the project. A CPM diagram was built by following the procedure of the CPM diagram as shown in Figure 2-2.

The duration of the project is shown in the CPM diagram and it is 17.5 days to have the work done.

Table 2-1 Activities of construction of concrete column

Activity	Title	Duration (hours)
1	Fabricate Panels	7
2	Erect Panels	1
3	Join Panels	2
4	Set Side	2
5	Reinforce Side	3
6	Reinforce Corner	1
7	Inspect Form	4
8	Cast Concrete	0.5
9	Cure Concrete	1
End	Construct concrete-column	

2.3. Derivation of Cause-effect diagram from FAST diagram

Similarly, the data of the activities of the work were collected as shown on Table 2-1 . The quality characteristic is the *Construct concrete- column* when the cause-effect diagram is considered. What are the causes to affect the quality of the construct column? The major possible causal factors of the construct column were gathered and they are the *construct form* and *cast concrete.*

The logic for developing cause-effect diagram is analyzed in the following:

1) What affects the quality of the construct column? They are construct form and cast concrete.
2) What causes to construct form? The panels are erected and joined; and the sides and the corners are reinforced.

3) What causes the panel to be erected? Because the finish fabricating panels make it possible. What causes to reinforce the side? Because the side is set and needs to be reinforced.

The cause-effect diagram is added until it includes all the activities from the FAST diagram in this way. The cause-effect diagram was built by following the principle of the cause-effect technique as shown in Figure 2-3.

2.4. Discussion of interconnectivity and logic of the derivation

2.4.1. In CPM diagram

At first, all the activities listed in Table 2-1 originated from the FAST diagram by following the how/why logic. They are also described in the CPM diagram by following the sequence of the work. The purpose of both diagrams illustrates the organization of the work and provides the relationship among the various aspects of the work that contribute to the breakdown of the project into activities. The logic of the CPM diagram reflects the logic of the original FAST diagram and achieves the purpose of the FAST diagram as well. Therefore, the derivative process is reasonable and logical.

Moreover, the tasks of the construction of the columns as illustrated by the FAST diagram can be executed by the CPM diagram as well. Even without consulting the original FAST diagram, the work activities are introduced clearly and logically by only the CPM diagram.

2.4.2. In Cause-effect diagram

All the activities, which originated from the FAST diagram by following how/why logic, are described in the cause-effect diagram according to the cause-effect relationships of the activities. The cause-effect diagram also illustrates the organization of the work and provides the information of the project to be analyzed. The logic of the cause-effect diagram reflects the logic of the original FAST diagram and achieves the purpose of the FAST diagram as well. In a word, the derivative process is possible and logical.

2.4.3. Integration of results

Nevertheless, it is possible to derive a CPM or a cause-effect diagram from the FAST diagram according to the procedure discussed above. The procedure is reasonable and logical for each activity. The relationship of the activities established by the CPM diagram or cause-effect diagram is described as well as when it is on the FAST diagram. The overall sequence of the project provided by the CPM diagram or cause-effect diagram is introduced as well as on the FAST diagram. Therefore, the procedure of deriving the CPM diagram or cause-effect diagram from the FAST diagram creates a new dimension in the Function analysis phase of the VE studies. The CPM diagram or cause-effect diagram may execute the same duty which is achieved originally by the FAST diagram. That allows different insights into the intricacies of the problem. This helps immensely during the creativity and brainstorming stages of the value analysis job plan.

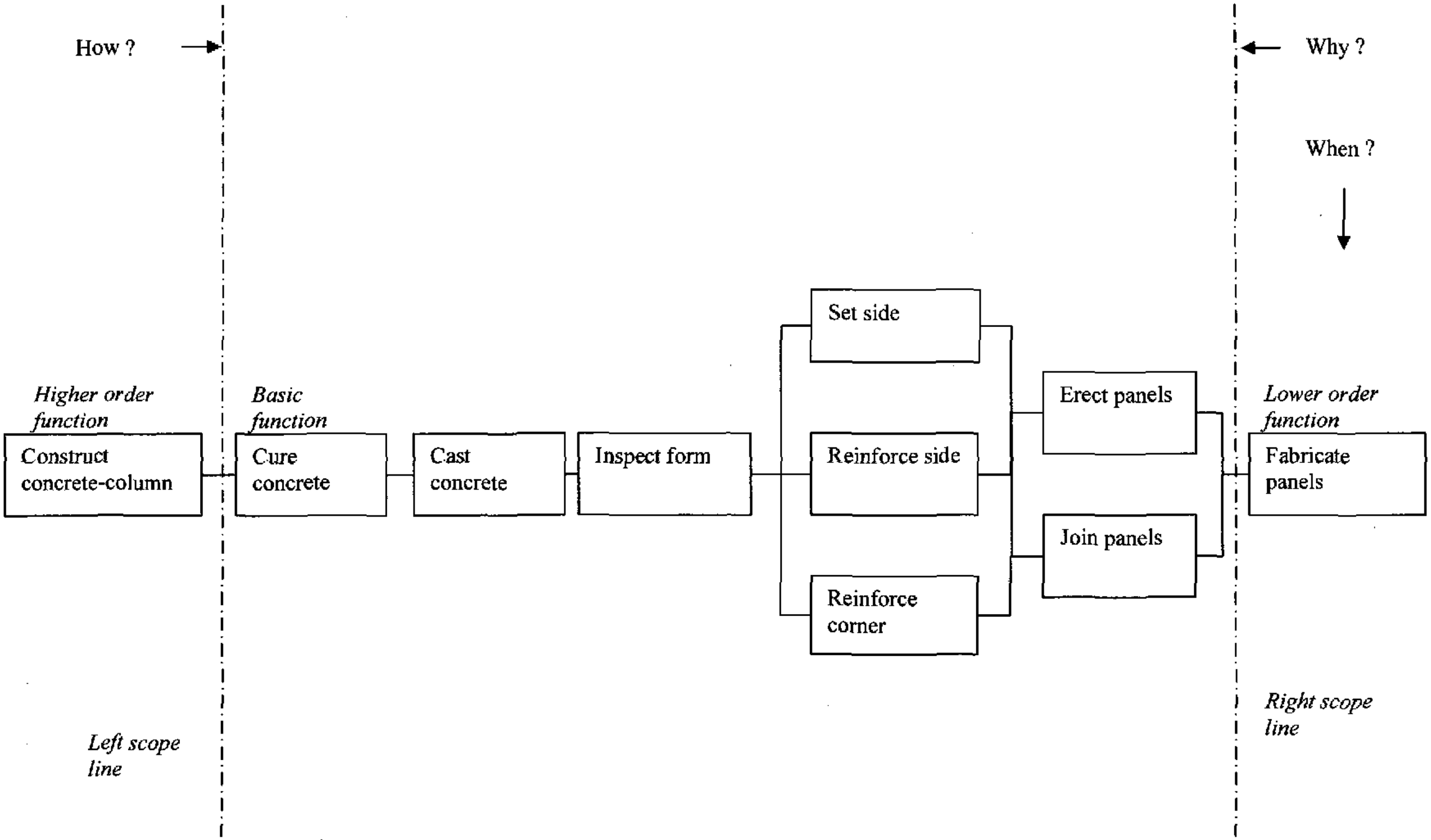


Figure 2-1 FAST Diagram of the Construction of Concrete Column (Snodgrass & Muthiah, 1986)

[redacted]

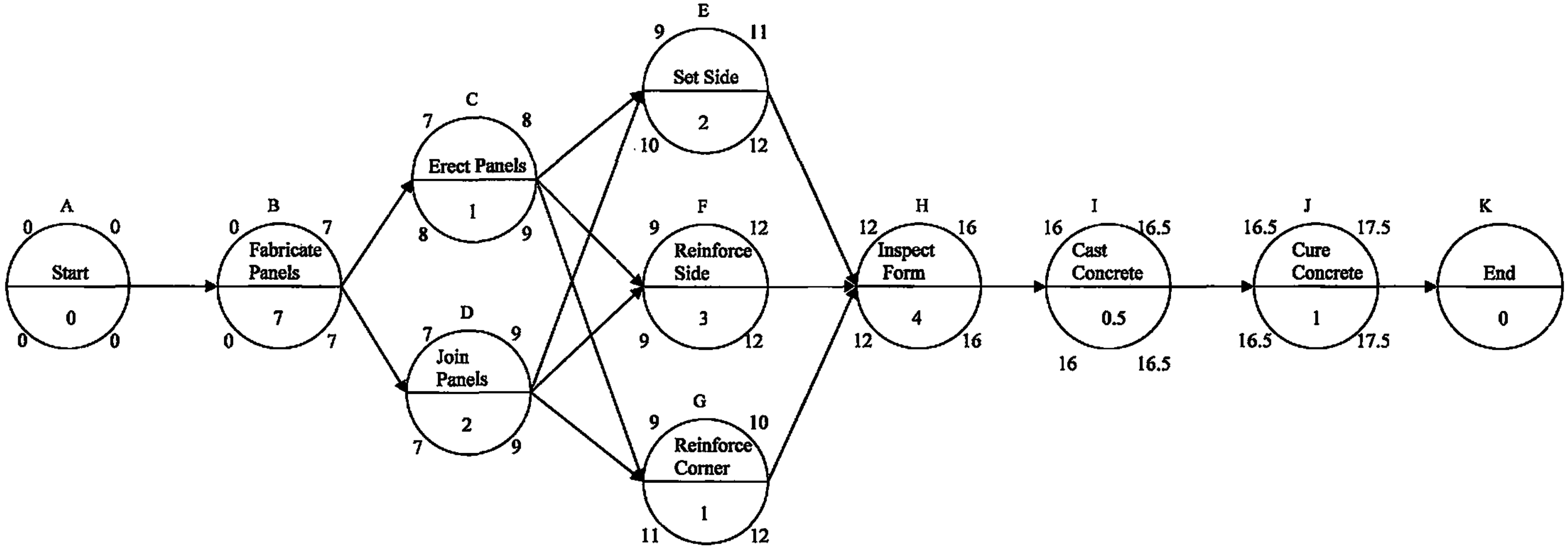


Figure 2-2 CPM for Construction for construction concrete column

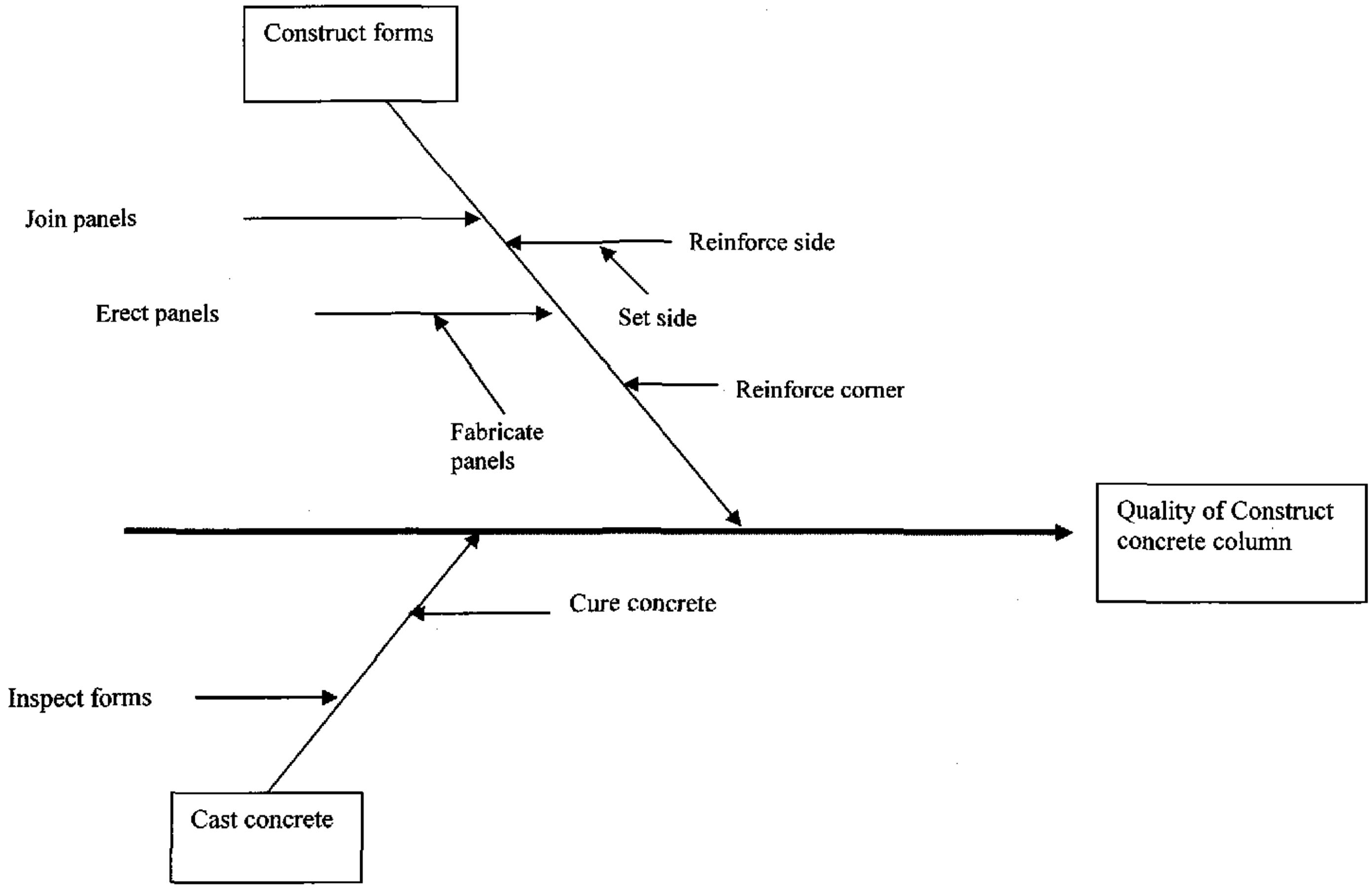


Figure 2-3 Cause-Effect Diagram for Construction of Concrete Column

CHAPTER 3. DERIVATION OF FAST DIAGRAM AND CAUSE-EFFECT DIAGRAM FROM CPM DIAGRAM

3.1. CPM Diagram

3.1.1. The explanation of CPM Diagram

The critical path method, or CPM, approach to represent logical planning factors is based on describing the project as a network of activities. In the planning process, the physical layout of the network reflects the logic and organized planning system. An example of this sequence is shown in Figure 3-1 (O'Brien, 1993).

Once the activities are placed on the nodes, the definition of the variables is required for the use of the activities. For each activity, five variables are of interest. These are:

ES: early start time of the activity

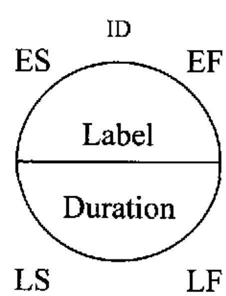
EF: early finish time of the activity

LS: late start time of the activity

LF: late finish time of the activity

ID: activity ID

The forward and backward passes can be performed by using these values. The legend of the nodes is illustrated in the following:



CPM, being inanimate, cannot make decisions; however, the use of CPM encourages decisions because the user must make decisions in order to draw the arrow diagram. Therefore, CPM is often referred to as a "decision maker" (O'Brien, 1993).

3.1.2. Case study - Small gas station

As shown in Figure 3-1 (O'Brien, 1993), CPM assembles all the information available of the project. The logic of CPM is the most important feature of the CPM method. In this case, the logic is to follow the scheduling of the construction of a small gas station.

At first, the overall sequence of work must be considered. For instance, one activity is to mobilize the site. Next the site must be prepared and the excavation must be undertaken. Following that, the footers are to be poured. Then the building structure is erected, and so on.

Regarding the CPM diagram, the duration of the project is calculated and the critical path of the project is determined. The CPM diagram provides the adequate means of planning and scheduling.

3.2. Derivation of FAST diagram from CPM diagram

According to the CPM diagram in Figure 3-1, the activities of the work were collected as shown on Table 3-1. Since it is required to use verb-noun discipline to express functions in the FAST diagram, the description of each activity is defined as Verb/noun discipline and listed in the table.

The activities are reorganized in an effort to draw the FAST diagram by following the how/why logic. Certainly, the FAST diagram can be constructed differently. It might depend on the particular individual's understanding about the work. However, the message delivered is the same: *how well does the diagram represent the relationship of breakdown activities of the project in VE study*?

A FAST diagram is established by following the how/why logic:

- How to demobilize the site? As known, the project has to be inspected then the demobilization can be executed.
- How to inspect the project? Apparently, the project has to be finished first. For instance, one of the jobs, landscaping, has to be done before finish.
- How to perform landscaping? It only can be performed after constructing exterior brick facade and exterior fascia panels.
- And so on ...

To test intuitive logic, the function of the diagram is read in the reverse "why" direction:

- Why mobilize the site? It is to perform site-work.
- Why perform site-work? It is to start excavations and install exterior utilities.
- Why excavate basin, excavate footers, etc., and install exterior utilities? It is to pour footers.
- And so on ...

The diagram is constructed in Figure 3-2 by following this procedure.

Table 3-1 Activities of small gas station

Activity	Verb/noun description	Duration (Days)
1	Mobilize site	10
2	Obtain permits	15
3	Perform site-work	8
4	Install exter.-utilities	12
5	Excavate catch-basin	2
6	Excavate footers	5
7	Excavate foundation piers	6
8	Pour footers	8
9	Erect bldg. frame	10
10	Construct exter.-brick-facade	14
11	Construct exter.- fascia-panels	4
12	Construct roof	15
13	Perform landscaping	12
14	Pour inter-slabs	10
15	Install glazing and doors	6
16	Construct interior walls	10
17	Install Elec.& mech.	25
18	Install shelves	3
19	Cover floor	6
20	Finish interior	8
21	Inspection project	1
22	Demobilize site	3

3.3. Derivation of Cause-effect diagram from CPM diagram

Similarly, the activities of Table 3-1 are collected for the cause-effect diagram. The quality of construction of the small gas station is the purpose of the analysis. The major category effect factors of the quality of the construction are drawn by over viewing the activities of the project. They can be site work, earth work, concrete work, exterior work, etc.

The logic for developing the cause-effect diagram is stated in the following:

- What are the effect factors of the quality of the construction? The activities of site work, earth work, concrete work, etc., affect the quality of the construction.
- What are the effect factors of the concrete work? The activities of construct roof, pour footers, pour interior slabs, erect building frame are the effect factors.
- And so on ...

In this way, the cause-effect diagram is added until it fully includes all the activities from CPM diagram. The diagram is completed as shown in Figure 3-3. All the activities from the CPM diagram appear on the cause-effect diagram. All the activities are related to each other by cause-effect logic. There are various methods for making cause-effect diagram depending on how the activities are organized and arranged.

3.4. Discussion of interconnectivity and logic of the derivation

3.4.1. In FAST diagram

The relationships of the activities on the CPM diagram show the sequence of the work. From the small gas station case study, it was found that when those activities are organized on a FAST diagram, this sequence is illustrated as well. The purpose of establishing the FAST diagram reflects the same idea as the CPM diagram represents. In other words, the FAST diagram can be used in an effort to describe the scheduling of the project in lieu of the CPM diagram.

3.4.2. In cause-effect diagram

Through the process of the derivation, the activities from the CPM diagram are rearranged for the cause-effect diagram. The cause-effect diagram describes the organization of the activities of the job as well as the CPM diagram. The derivation process follows the principle of the cause-effect logic and is reasonable and logical. It also provides another method to represent the CPM diagram with the cause-effect diagram in illustrating the relationships of the activities.

Furthermore, the major factors of the problems can be emphasized in the cause-effect diagram by the major category factors. Hence, it is possible that a cause-effect diagram can be an alternative of a CPM diagram when it is needed.

3.4.3. Integration of results

All three methods are interchangeable. It is possible to derive a FAST or a cause-effect diagram from the CPM diagram from the process discussed previously. Essentially, the FAST diagram can be an alternate to the CPM diagram to represent the relationships of the activities. The procedure is reasonable and logical. The cause-effect diagram reorganizes the activities from the CPM diagram. It shows the level of functions in the process by sequentially listing the analysis steps.

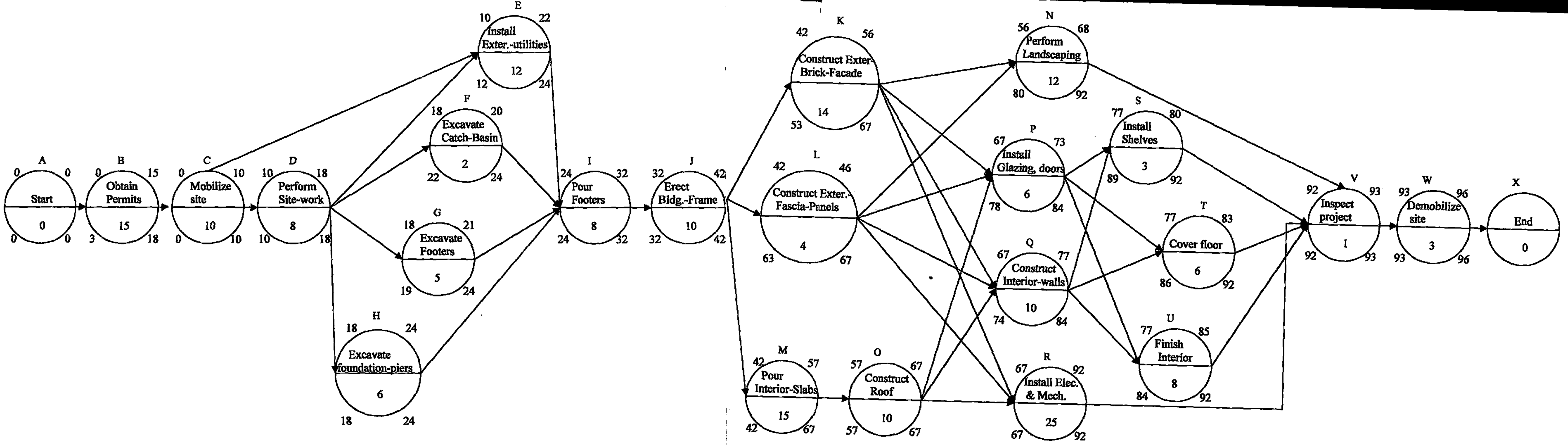


Figure 3-1 CPM for construction of Small Gas Station (O'Brien, 1993)

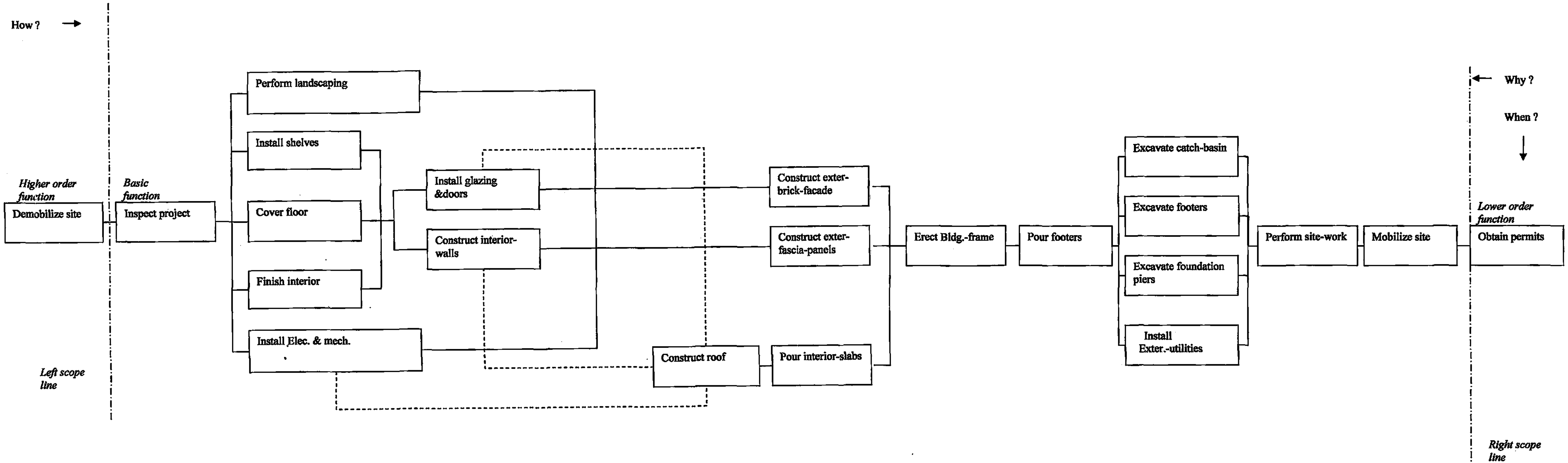


Figure 3-2 Fast Diagram for construction of Small Gas Station

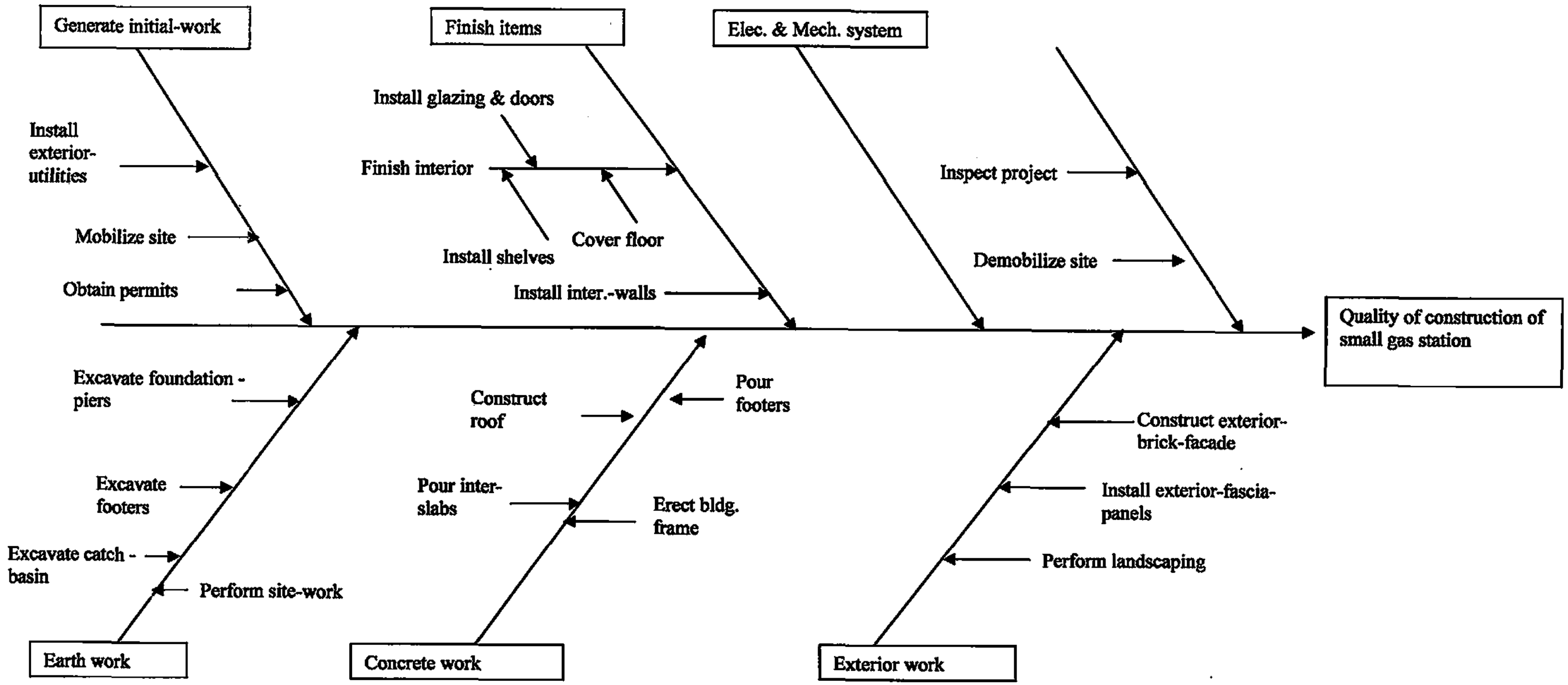


Figure 3-3 Cause-Effect Diagram for construction of Small Gas Station

3.5. Case study – Construct concrete foundation

Another set of samples of the FAST, CPM, cause-effect diagrams for construction of concrete foundation is exhibited in this section. The activities of the work are listed in Table 3-2. And the CPM diagram is built as shown in Figure 3-4; the FAST diagram is shown in Figure 3-5; the cause-effect diagram is constructed as shown in Figure 3-6.

Table 3-2 Activities of construction concrete foundation

Activity	Title	Duration (Days)
A1	Layout building	1
A2	Excavate warehouse	10
A3	Pour cap-piles	6
A4	Pour beams	5
A5	Backfill earth	10
A6	Install plumbing	3
A7	Install conduit	5
A8	Pour railroad-dock	5
A9	Pour truck- loading -dock	5
A10	Pour slabs	5
A11	Finish foundation	

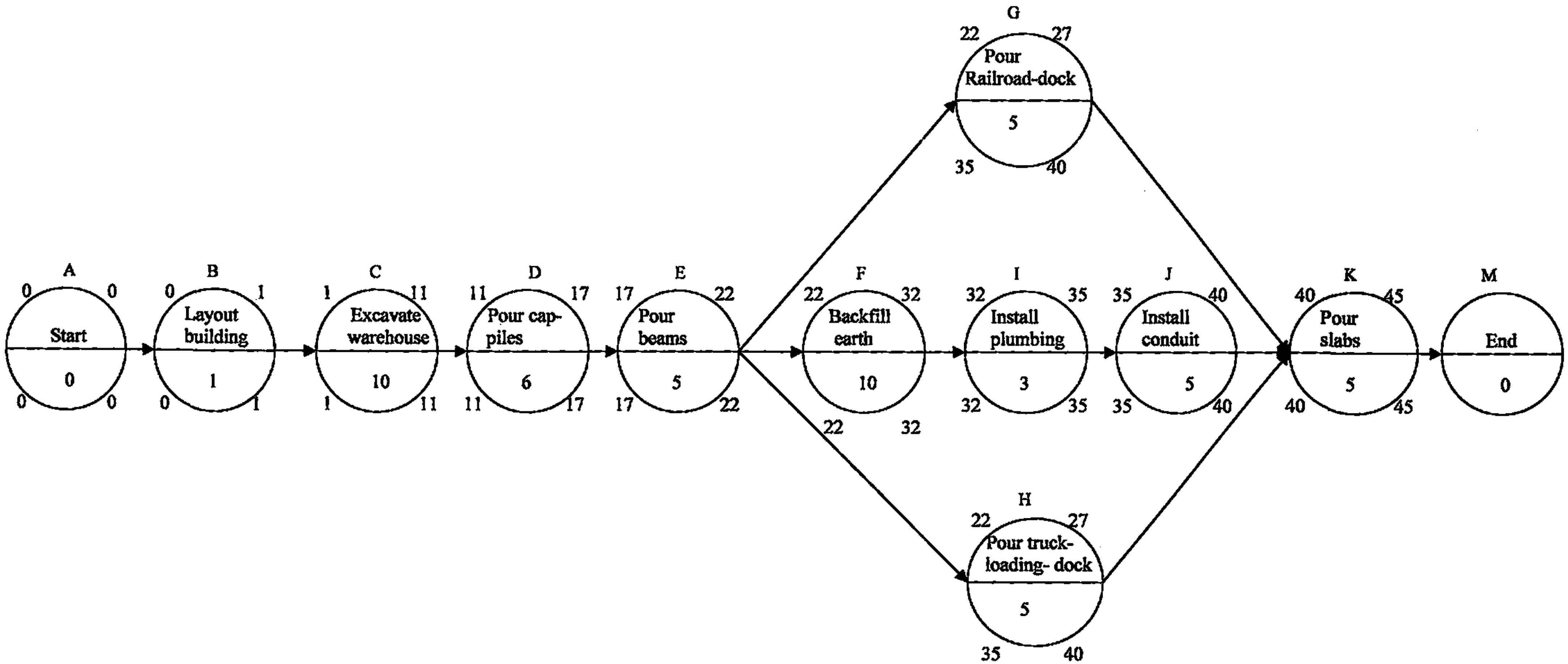


Figure 3-4 CPM Network for construction concrete foundation

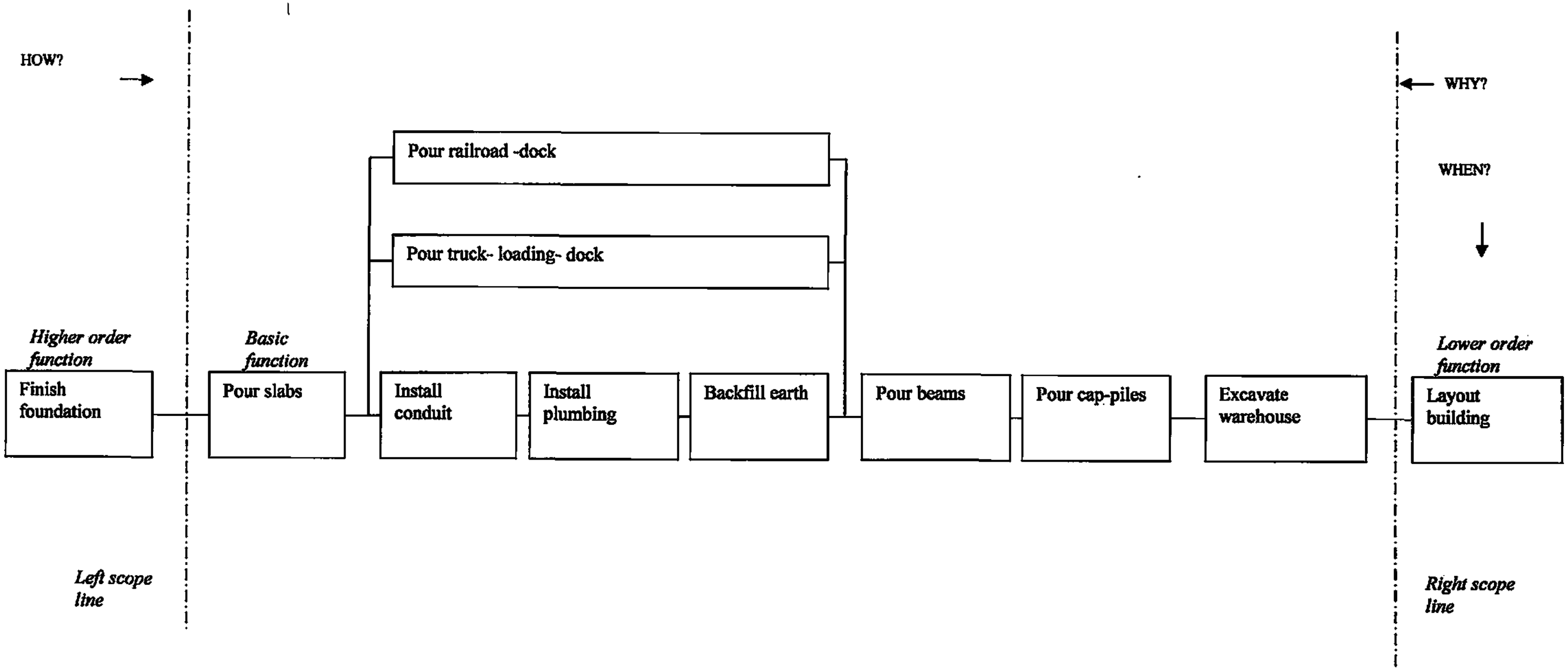


Figure 3-5 FAST Diagram for construction concrete foundation

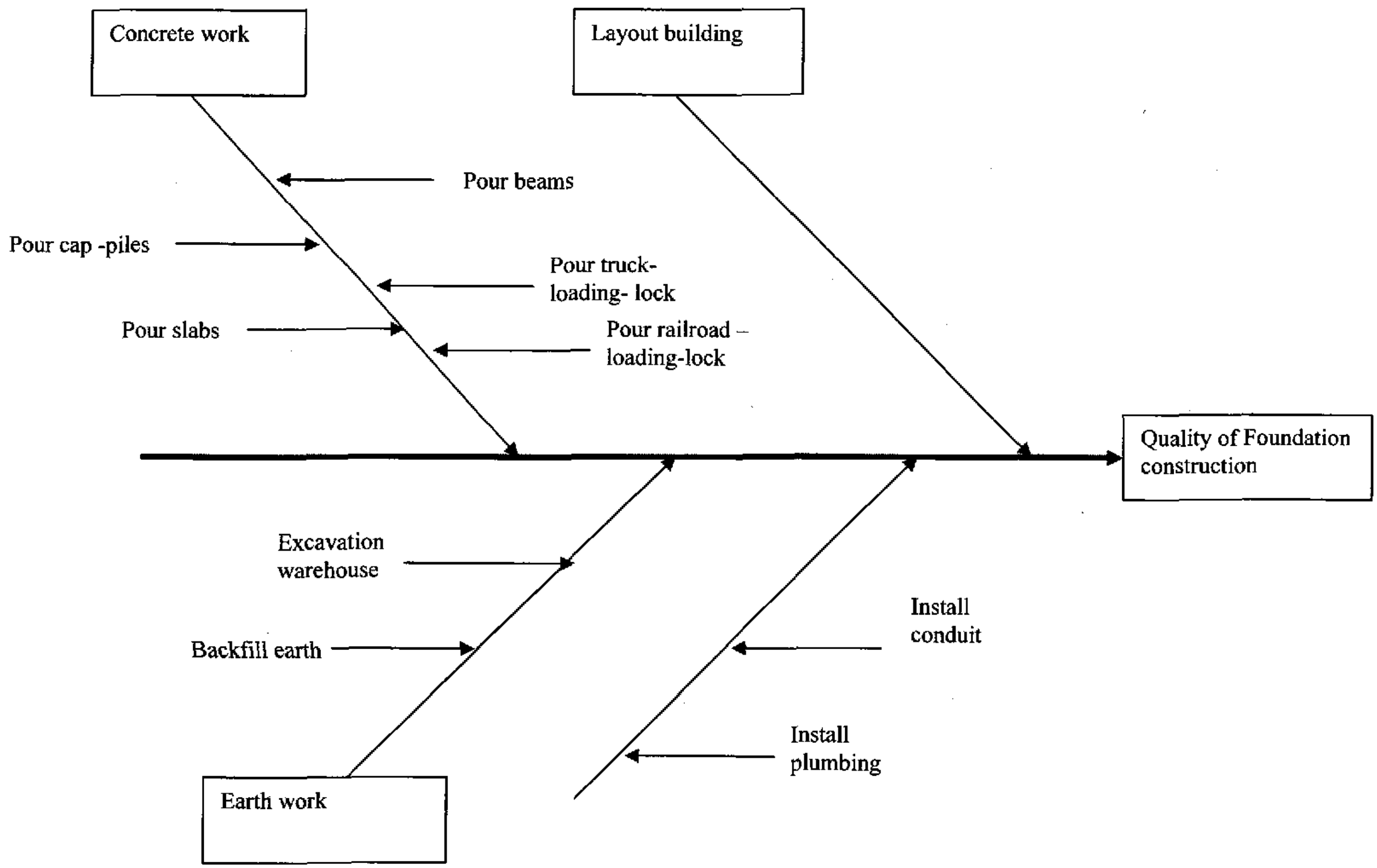


Figure 3-6 Cause-Effect Diagram for construction concrete foundation

CHAPTER 4. DERIVATION OF FAST DIAGRAM AND CPM DIAGRAM FROM CAUSE-EFFECT DIAGRAM

4.1. Cause-Effect Diagram

4.1.1. The explanation of Cause-effect Diagram

The cause & effect diagram represents the relationship between the "effect" and the "cause".

The effect is the quality characteristics and the cause is the factors. For every effect there are likely to be several major categories of causes. The cause & effect diagram illustrates the various causes of a process by sorting out the causes of the events then establishing a "cause" and "effect" relationship. A well-detailed cause & effect diagram takes on the shape of fish bones and hence the alternate name *Fishbone Diagram*. The logical question throughout the diagram is "why does this event happen?" This is a similar question to that which is asked in the FAST diagram. Therefore, it is logical to conclude that there is a relationship between FAST and cause-effect diagram. There are various methods for establishing a cause-effect diagram based on how they are organized. The possible causes of the event are clearly arranged in the diagram; therefore, all the relationships are noticeable. An example of the cause-effect diagram is shown in Figure 4-3 (Ishikawa, 1976).

4.1.2. Case study - Pipe making process

The project is one of pipe making in the manufacturing industry. The flow chart of the pipe making process is shown in Figure 4-1. Steel scars might occur during the pipe making process. So the purpose of this case study is to analyze what causes the steel scars to occur. By following the cause-effect diagram as shown in Figure 4-3, various reasons can be found. For instance, what causes the steel scars to occur? The procedures of "make pipe, remove beads, test pressure, and inspect pipe" cause the scars to occur. What are the effect factors of the pipe inspection? The surface painting, how the pipe is carried, etc. affects the inspection results. By following this logic, the cause-effect diagram is added until it fully shows the causes.

The diagram shows the level of analysis, the level of functions in the process, and how far the discussion has advanced. The diagram also sequentially lists all the steps in the process of how scarring occurs during the pipe making process. The relationships among all the activities of this process are clarified.

4.2. Derivation of FAST diagram from cause-effect diagram

All the activities of this process are collected in Table 4-1 from the cause-effect diagram Figure 4-3. The description of each activity is explained as the verb/noun discipline to be used in a FAST diagram. The higher order function is designed as finding scars. The lower order function is to prepare material.

Following the "how" path leads to a more detailed analysis and a lower level of abstraction:

- How to find scars? By inspecting the pipe.
- How to inspect the pipe? The position of the pipe has to be adjusted first.
- How to adjust the position? By rolling the bench.
- How does the rolling bench happen? Only after the pipe is carried on the bench.
- And so on …

Similarly, the "why" questions are answered:

- Why to prepare the material? It is to test roll, impurity, flare.
- Why to test roll, impurity, flare? It is to make the pipe.
- Why to make pipe? It is to correct the pipe.
- And so on …

Thus, a FAST diagram of "pipe making process" was derived from the cause-effect diagram by following the how/why logic as shown in Figure 4-2.

Table 4-1 Activities of pipe making process

ID	Verb/noun description	Duration (Hours)
1	Prepare material	5
2	Test Flare	2
3	Test Roll	1
4	Test Impurity	3
5	Make pipe	16
6	Correct pipe	3
7	Polish pipe	8
8	Bunch pipe	3
9	Move bench	1
10	Roll bench	2
11	Plan test	4
12	Drop pipe	1
13	Convey pipe	2
14	Test pressure	4
15	Adust position	2
16	Resove bunch	3
17	Remove beads	5
18	Paint surface	8
19	Carry pipe	8
20	Roll bench	2
21	Adust position	2
22	Inspect pipe	2

4.3. Derivation of CPM diagram from cause-effect diagram

The activities from cause-effect diagram are shown in Table 4-1. The duration of the activity is designed to structure the CPM network. By following the sequence of the work, the material is prepared first; then the flare, roll, impurity attributes are tested; after that, the pipe is ready to be made; the correction of the pipe comes after; and so on ... The CPM diagram indicates the sequential order in which these activities will be performed. Hence, the CPM diagram is established as shown in Figure 4-4.

The logic of the activities which appear on the cause-effect diagram is introduced as the sequence of the work in the CPM diagram. The breakdown activities of the work are illustrated logically in the CPM diagram in an effort to schedule and plan the job.

4.4. Discussion of interconnectivity and logic of the derivation

4.4.1. In FAST diagram

While comparing the FAST diagram with cause-effect diagram, to explain the "pipe making process", the purpose of the cause-effect diagram indicates all the factors that cause the scars to occur. Those factors from the cause-effect diagram are expressed as functions on the FAST diagram, as is required. Regarding the FAST diagram, the relationship of activities could be studied for better quality of the work. The derivation process is successful and acceptable. The experimental information provides a possibility: the FAST diagram can be an alternative technique of the cause-effect diagram to be used in analyzing the problems.

4.4.2. In CPM diagram

The purpose of the cause-effect diagram is to represent the relationships of the activities of the work and provides the information of the activities for the analysis of the pipe making process. This information is also delivered by the CPM diagram. Therefore, the developed CPM diagram achieves the analysis purpose of the cause-effect diagram. The derivation process is possible and acceptable. The logical analysis process can be explained completely by the CPM diagram when the cause-effect diagram is omitted.

4.4.3. Integration of results

As a result, the process of developing the FAST diagram from the cause-effect diagram shows that the FAST diagram can also be used in lieu of the cause-effect analysis. In other words, the FAST diagram contributes a technique in analyzing cause-effect logic, and it may represent the cause-effect technique in the quality control area.

The process of making the CPM diagram according to the cause-effect diagram further describes the relationship between the two techniques. Although the CPM diagram is drawn by following the scheduling of the job rather than by following the cause-effect logic, the CPM diagram describes the relationships of the activities from the cause-effect diagram reasonably and logically.

Nevertheless, the experiments of deriving the FAST diagram and CPM diagram from the cause-effect diagram provide widely possible choices when applying the function analysis techniques in VE studies.

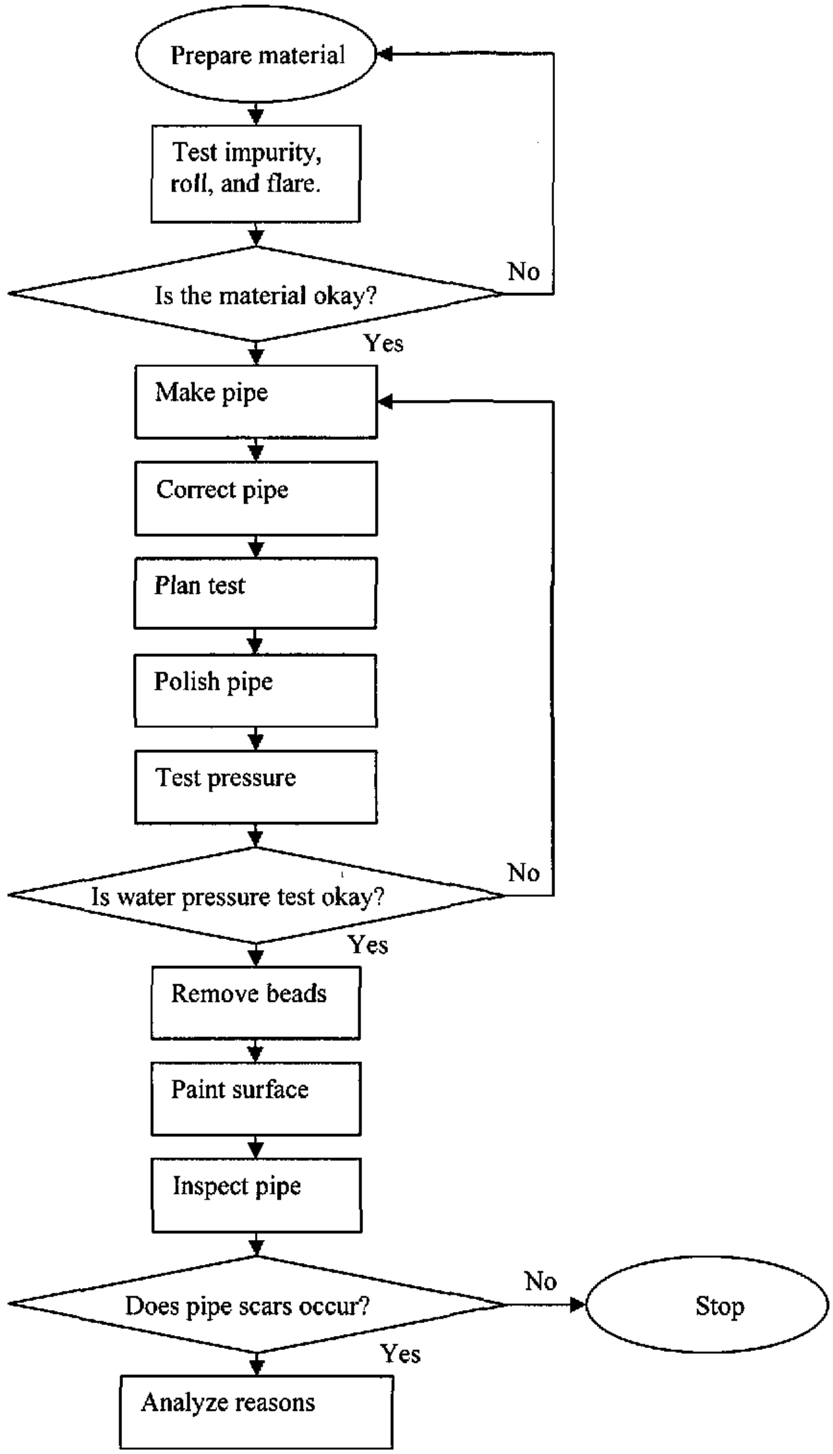


Figure 4-1 Flow chart of pipe making process

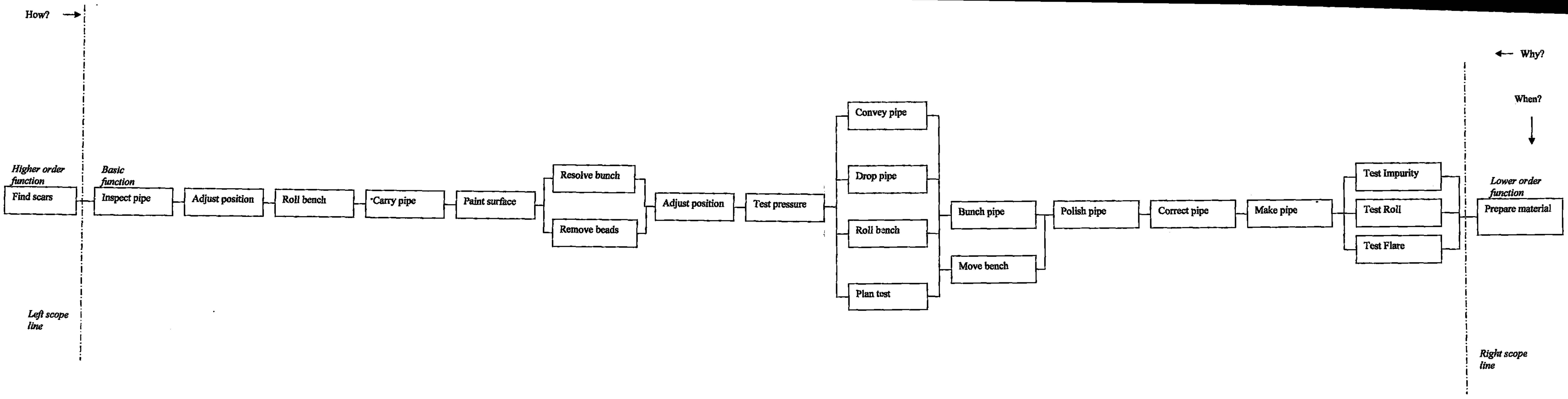


Figure 4-2 FAST Diagram of - Pipe making process

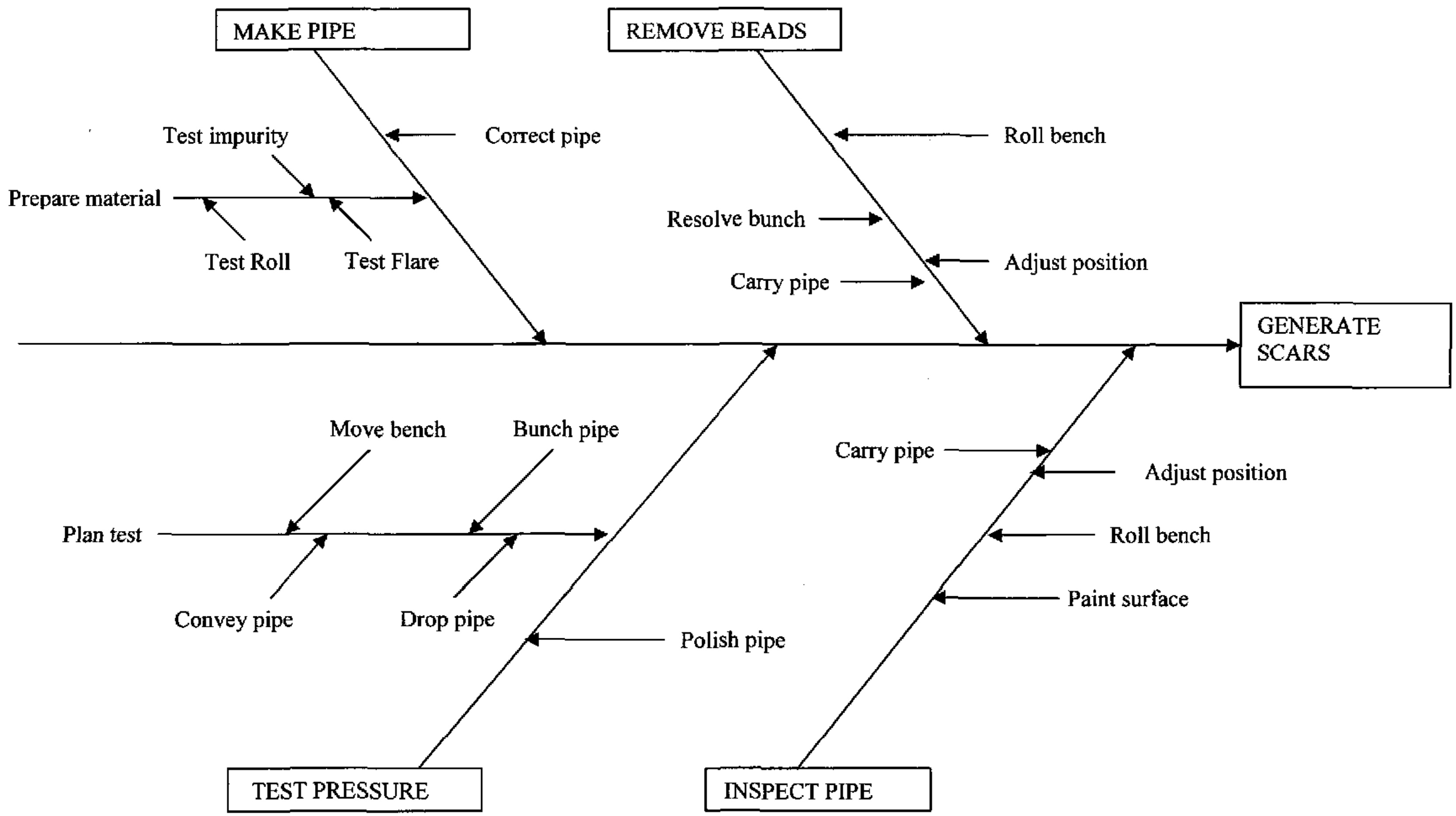


Figure 4-3 Cause-effect diagram for - Pipe making process (Ishikawa, 1976)

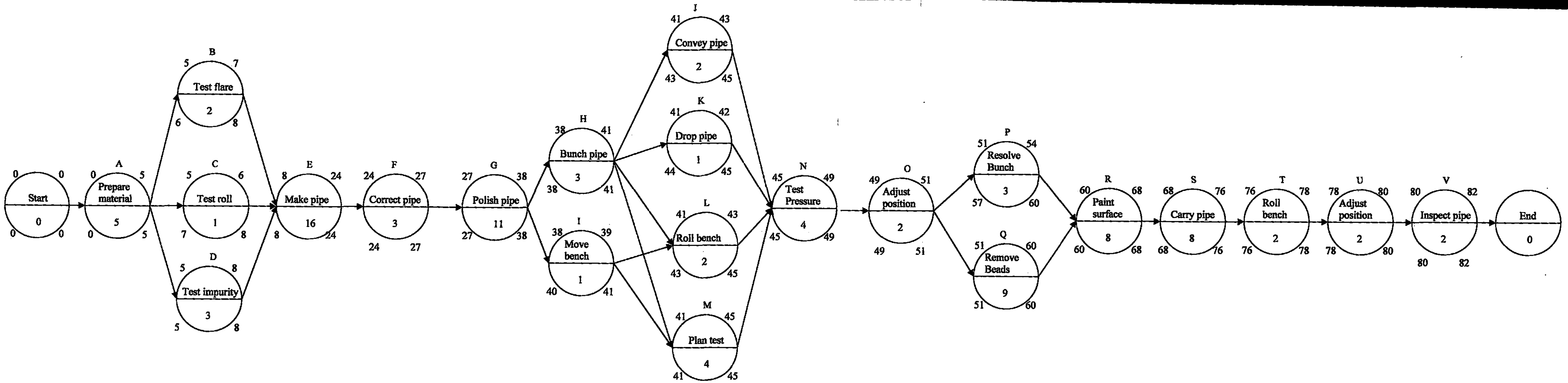


Figure 4-4 CPM diagram of - Pipe making process

4.5. Case study-site preparation

Another set of samples of the FAST, CPM, cause-effect diagrams for construction of site preparation is exhibited in this section. At first, the activities for preparing site are collected as shown in Table 4-2. Then the FAST diagram is established in Figure 4-5; the CPM diagram is shown in Figure 4-6; the cause-effect diagram is shown in Figure 4-7.

Table 4-2 Activities for site preparation

Activity	Title	Duration (days)
1	Clear site	3
2	Survey site	1
3	Layout building	1
4	Grade site	2
5	Excavate trench	11
6	Install sewer	4
7	Backfill earth	1
8	Set overhead-line	6
9	Install manholes	5
10	Install duct-bank	3

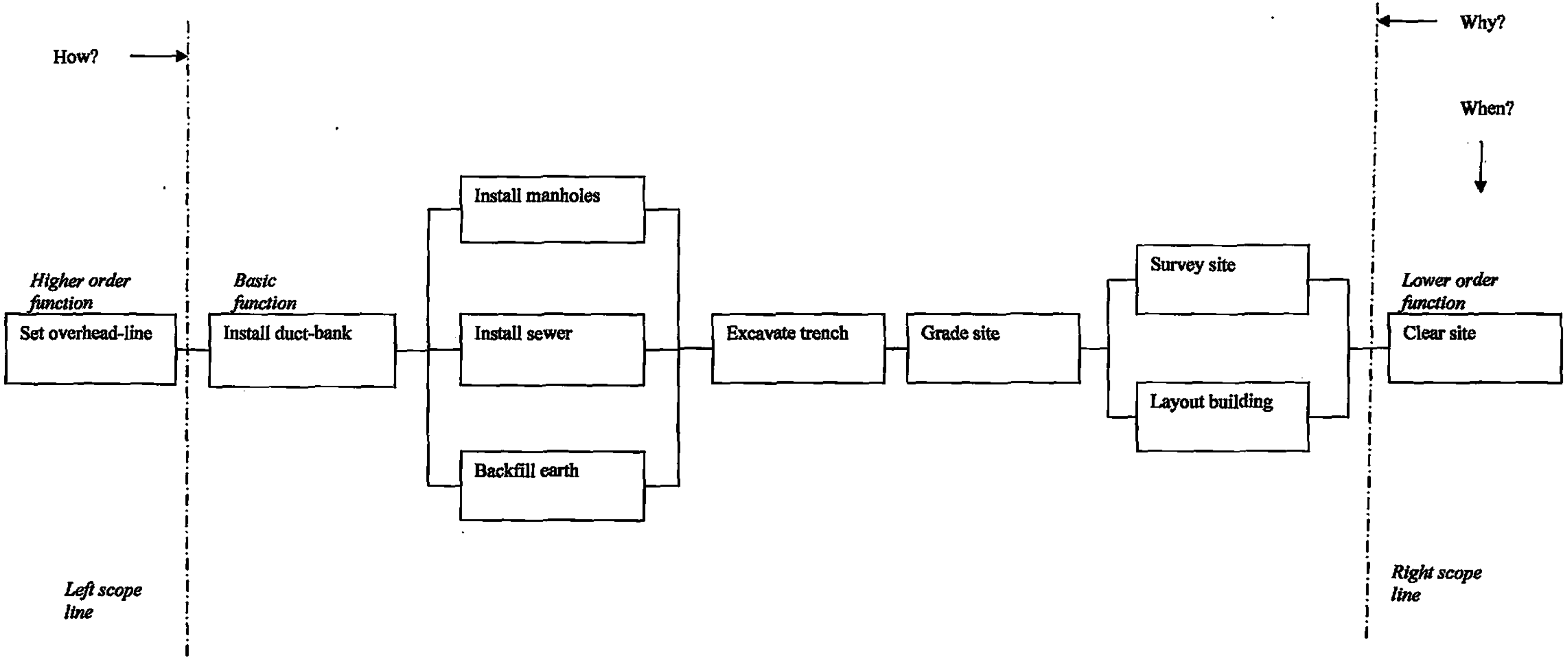


Figure 4-5 FAST Diagram for site preparation

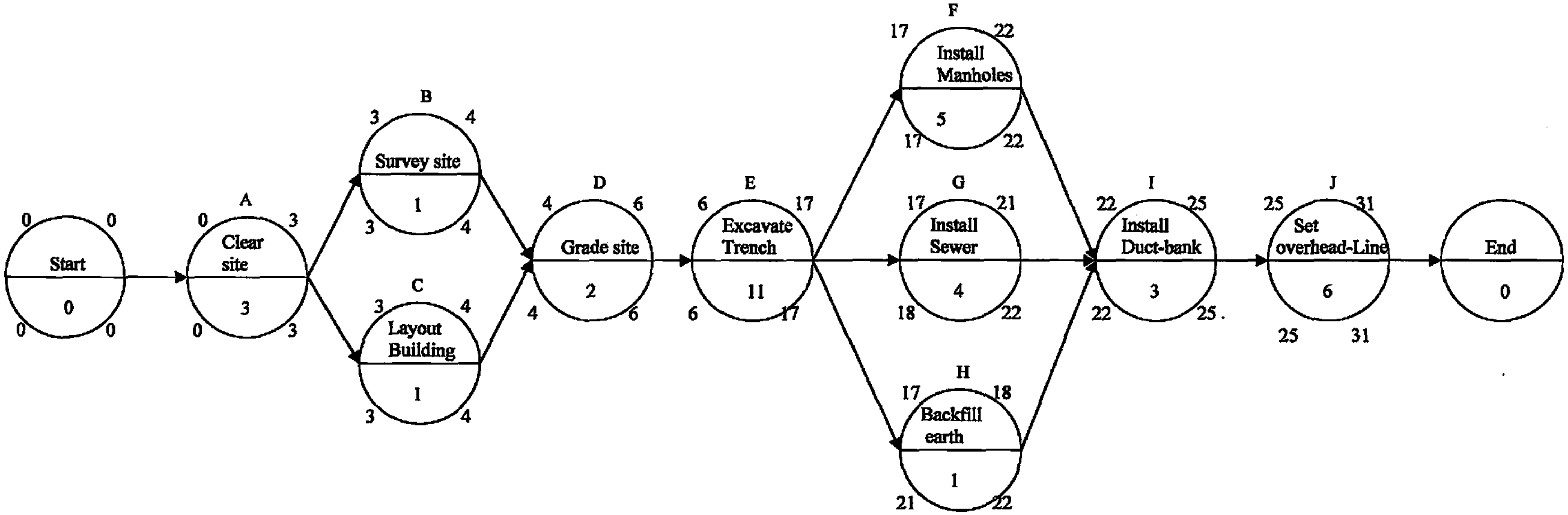


Figure 4-6 CPM for site preparation

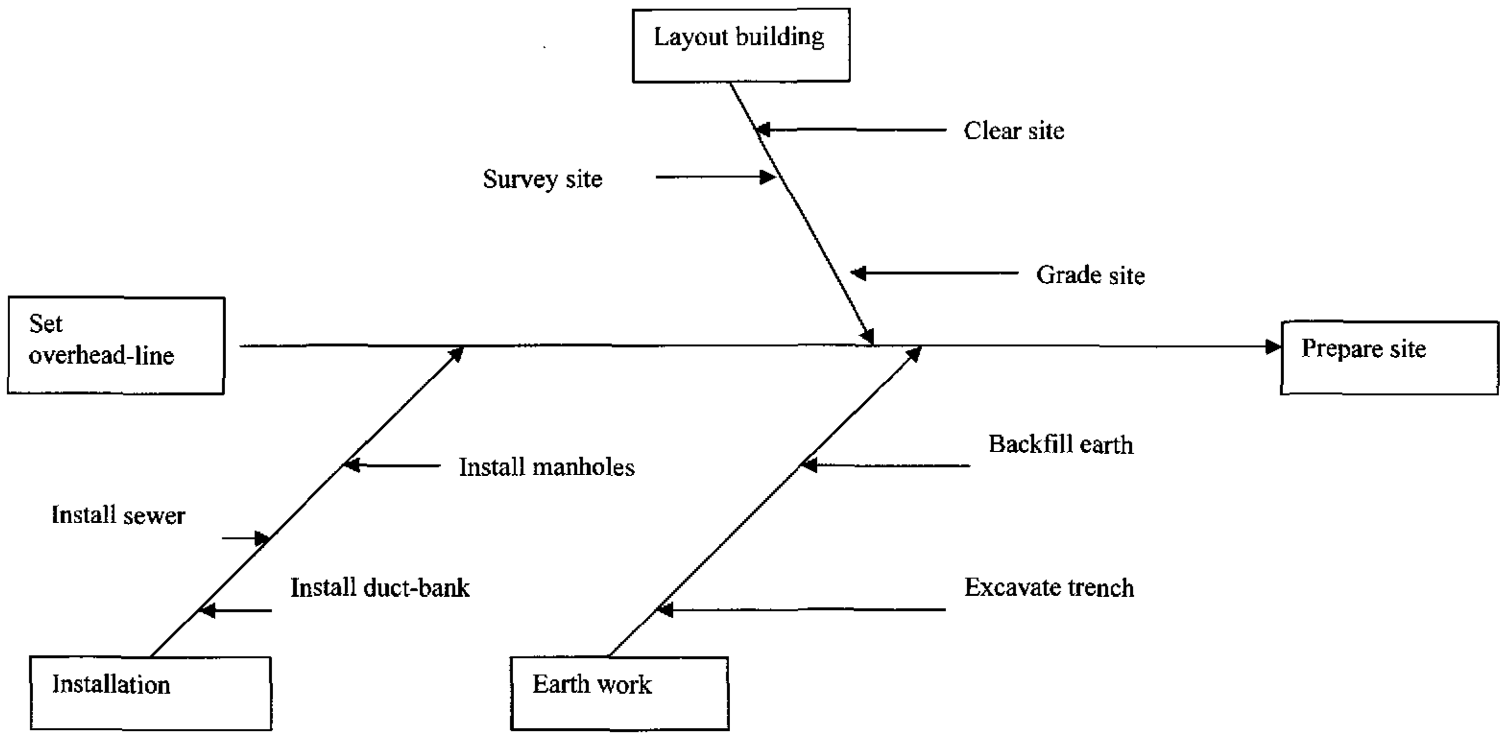


Figure 4-7 Cause-effect diagram for site preparation

PART II

CHAPTER 5. MATRIX ANALYSIS – PAIR WISE COMPARISONS & SATISFACTION FACTORS

5.1. In general

A few matrix system methods had been developed in the past. Lawrence Miles (1972) presented the Function Rating method in evaluating the importance of various functions to be performed. Mudge (1971) developed a technique called Numerical evaluation for making paired comparisons of multiple items.

In this chapter, an alternate technique will be introduced. The matrix analysis system method is divided into two steps, the weighting process and the matrix analysis. The importance of criteria, goals, objectives or attributes is evaluated as well as functions. As an application, the case study which had been used in Chapter 3 will be discussed.

5.2. Weighted evaluation process

Case 1. Construction concrete foundation

For instance, in the construction of a foundation contract, the task is to find out what function should be developed for value analysis and implementation. The FAST diagram of the project is established and the activities are identified as shown in Table 3-2. There are 11 functions collected in this case and only a few of them are valuable for further analysis.

At first, the criteria of the nature of selecting the functions are defined and discussed.

For construction projects, the importance of attributes in determining the value of functions is recognized as shown on Table 5-1. The criteria might be in conflict and that means the full satisfaction of one criterion will result in impairing or precluding the full satisfaction of the other criteria. For example, if the initial cost increases, it might cause the profit to decrease (Dell'isola, 1982).

Weighted evaluation is a process for selecting the valuable functions or ideas in areas involving multiple choices. The criteria are assigned weight values differently upon their potential impact on a project. The system adopts the paired comparison in determining the weights of the criteria.

Important functions and criteria were picked for analysis. For this case, five functions and five criteria were considered important. Importance can be gauged from cost of item or need of owner.

In Table 5-2, we judge how important each criteria is for each function. This is done by assigning a simple score for this importance. This score is applied for determining weights in Figure 5-1. All the functions should be evaluated against these criteria.

Table 5-1 Conflicting criteria in construction

C1	Low initial cost
C2	High profit
C3	High reliability
C4	High maintainability
C5	Effective Safety
C6	Good functional performance
C7	High Quality
C8	Pleasant aesthetics and environment

Table 5-2 Weight matrix for selecting the functions - Construction of foundation contract

ID	Functions		Criteria		
		C1	C2	C3	C4
		Initial cost	Profit in return	Reliability	Maintainability
A1	Layout building	4	1	7	0.1
A2	Pour piles	5	2	6	3
A3	Excavate warehouse	6	1	4	0
A4	Pour caps	3	4	8	5
A5	Pour beams	7	6	9	0.1
	Sum	25	14	34	8.2

In addition, the importance of each of the criteria is weighted by comparing one against another. The criteria are listed on the weighting format in Figure 5-1. Five criteria were compared in this case.

A sample calculation for comparison is given as below:

1. Compare A and B: if A is a medium preference, then 2 is assigned to A as stated in the lower form *A2*.
2. Compare A and C: if C is a minor preference, then 1 is assigned to C as stated in the lower form C1.
3. And so on for other comparisons.
4. Add all the scores for A. In this case, the score for A is 2 + 3 = 5. Then write the score into the upper form.
5. Assign the weights according to the scores.

The more the elements of the criteria are compared to each other, the better the result will be. As shown in the format, the elements for comparison could be any attribute, such as functions, features, goals, ideas…This may lead to weighting the functions, alternate ideas in VE studies depending on individual needs. For the purpose of this experiment, matrix analysis will be used to continue the evaluation process.

Study title: Construction of concrete foundation		**Determining weights for evaluation**	
Goals, desired criteria, functions, features…		Raw score	Assigned weight
A	Initial cost	5	3
B	Profit in return	1	1
C	Reliability	7	4
D	Maintainability	1	1
E	Safety	3	2
	Sum	17	10

	B	C	D	E
A	*A2*	*C1*	*A3*	*E1*
	B	*C2*	*D1*	*B1*
		C	*C3*	*C1*
			D	*E2*
				E

Importance Scale

3-Major preference

2-Medium preference

1-Minor preference

Figure 5-1 Pair-wise comparison for determining weights - Construction of concrete foundation (Kaufman, 1998)

5.3. Evaluation Matrix

Once the weights of criteria have been determined, the next step is to evaluate how well the various functions of the project satisfy the criteria. For ranking the satisfaction of each of the alternatives against each of the criteria, the scoring system used here is to assign 1 to 5 points on a scale of poor to excellent in the following:

1 – Poor

2 – Fair

3 – Good

4 – Very good

5 – Excellent

The analysis process is shown in Figure 5-2. Based on judgments of the VE team, satisfaction factors are entered in the matrix. The calculation results are determined by multiplying $\phi * S$ of each alternative and adding together. For instance, the scale "2-fair" is assigned to A1- layout building to represent the extent to which it satisfies the criterion – initial cost. Thus, the total score of A1 is:

$$2x3+1x1+4x4+3x1+2x2 = 30$$

The other results are determined in the same way. The alternative with the highest total points is the best selection for the decision. Thus, A5 – pour beams, should be selected with the highest score at 41. A4 - pour caps, would be the second choice.

		Initial cost	Profit in return	Reliability	Maintanbility	Safety		
		Assigned weight						
	ϕ	3	1	4	1	2		
ID	Functions	Satisfaction factor (s)					$\sum \phi \cdot s$	Ranking
A1	Layout building	2	1	4	3	2	30	3
A2	Pour piles	3	4	3	2	1	29	4
A3	Excavate warehouse	2	1	2	1	4	24	5
A4	Pour caps	5	2	4	2	1	37	2
A5	Pour beams	3	4	5	2	3	41	1

Figure 5-2 Evaluation matrix with satisfaction factors - Construct concrete foundation

Case 2. Construct concrete column

In this case, the Construct concrete column project is studied. The analysis diagrams were established in Chapter 2. The calculation followed the same steps as discussed previously. The importance of functions in fulfilling criteria is shown in Table 5-3. The weight evaluation calculation is shown in Figure 5-3; matrix analysis is shown in Figure 5-4. As a result, A4 should be selected for its highest score.

Table 5-3 Weight matrix for selecting the functions - Construct concrete column

		C1	C2	C3
		Initial cost	**Safety**	**Reliability**
A1	**Fabricate panels**	7	1	4
A2	**Erect panels**	1	2	7
A3	**Construct forms**	3	4	8
A4	**Cast concrete**	9	2	8
	Sum	20	9	27

Study title: Construction of concrete column		**Determining weights for evaluation**	
Goals, desired criteria, functions, features...		Raw score	Assigned weight
A	Initial cost	6	4
B	Safety	2	1
C	Reliability	6	4
D	Maintainability	0	0
E			
	Sum	14	10

	B	C	D
A	*A3*	*C1*	*A3*
	B	*C3*	*B2*
		C	*C2*
			D

Importance Scale

3-Major preference

2-Medium preference

1-Minor preference

Figure 5-3 Pair-wise comparison for determining weights - Construct concrete column

		Initial cost	*Safety*	*Reliability*	*Maintanbility*		
		Assigned weight					
	ø	4	1	4	0		
ID	Functions	Satisfaction factor (s)				$\sum \phi \cdot S$	Ranking
A1	Fabricate panels	7	1	4	3	45	3
A2	Erect panels	1	2	7	0	34	4
A3	Construct forms	3	4	8	0	48	2
A4	Cast concrete	9	2	8	9	70	1

Figure 5-4 Evaluation matrix with satisfaction factors - Construct concrete column

Case 3. Small gas station

In this case, the small gas station project is studied. The analysis diagrams were established in Chapter 3. The calculation followed the same steps as discussed previously. The importance of functions in fulfilling criteria is shown in Table 5-4. The weight evaluation calculation is shown in Figure 5-5; matrix analysis is shown in Figure 5-6. As a result, A5 should be selected with the highest score.

Table 5-4 Weight matrix for selecting functions - Small gas station

ID	Functions	Criteria		
		C2	C3	C4
		Safety	Quality	Environment
A1	Obtain permits	1	1	1
A2	Excavate footers	3	5	2
A3	Pour slabs	7	7	4
A4	Install doors	6	10	7
A5	Construct roof	10	9	7
	Sum	27	32	21

Study title: Construction of Small gas station		**Determining weights for evaluation**	
Goals, desired criteria, functions, features…		Raw score	Assigned weight
A	Safety	3	3
B	Quality	7	6
C	Environment	0	0
D	Maintainability	1	1
E			
	Sum	11	10

	B	C	D
A	*B2*	*A1*	*A2*
	B	*B3*	*B2*
		C	*D1*
			D

Importance Scale

3-Major preference

2-Medium preference

1-Minor preference

Figure 5-5 Pair-wise comparison for determining weights - Small gas station

		Initial cost	Safety	Reliability	Maintanbility		
		Assigned weight					
	Ø	3	6	0	1		
ID	Functions	Satisfaction factor (s)				$\sum \phi \cdot S$	Ranking
A1	Obtain permits	1	1	1	1	10	5
A2	Excavate footers	3	5	2	5	44	4
A3	Pour slabs	7	7	4	6	69	3
A4	Install doors	6	10	7	3	81	2
A5	Construct roof	10	9	7	6	90	1

Figure 5-6 Evaluation matrix with satisfaction factors - Small gas station

Case 4. Pipe making process

In this case, the pipe making process project is studied. The analysis diagrams were established in Chapter 4. The calculation followed the same steps as discussed previously. The importance of functions in fulfilling criteria is shown in Table 5-5. The weight evaluation calculation is shown in Figure 5-7; matrix analysis is shown Figure 5-8. As a result, A2 should be selected with the highest score.

Table 5-5 Weight matrix for selecting functions - Pipe making process

ID	Functions		Criteria	
		C1	C2	C3
		Profit in return	Initial cost	Reliability
A1	Prepare material	1	7	3
A2	Make pipe	6	3	9
A3	Correct pipe	2	3	9
A4	Polish pipe	3	4	3
A5	Paint surface	2	2	3
	Sum	14	19	27

Study title: Pipe making process		Determining weights for evaluation	
Goals, desired criteria, functions, features…		Raw score	Assigned weight
A	Profit in return	1	1
B	Initial cost	3	3
C	Reliability	6	5
D	Safety	1	1
	Sum	11	10

	B	C	D
A	*B2*	*C3*	*A1*
	B	*C3*	*B1*
		C	*D1*
			D

Importance Scale

3-Major preference

2-Medium preference

1-Minor preference

Figure 5-7 Pair-wise comparison for determining weights - Pipe making process

		Profit in return	*Initial cost*	*Reliability*	*Maintanbility*		
		Assigned weight					
	ø	1	3	5	1		
ID	Functions	Satisfaction factor (s)				$\sum \phi \cdot s$	Ranking
A1	Prepare material	1	7	3	0	37	3
A2	Make pipe	6	3	9	2	62	1
A3	Correct pipe	2	3	9	4	60	2
A4	Polish pipe	3	4	3	3	33	4
A5	Paint surface	2	2	3	8	31	5

Figure 5-8 Evaluation matrix with satisfaction factors – Pipe making process

Case 5. Site preparation

In this case, the site preparation project is studied. The Site preparation analysis diagrams were established in Chapter 4. The calculation followed the same steps as discussed previously. The importance of functions in fulfilling criteria is shown in Table 5-6. The weight evaluation calculation is shown in Figure 5-9; matrix analysis is shown in Figure 5-10. As a result, A1 should be selected with the highest score.

Table 5-6 Weight matrix for selecting functions - Site preparation

ID	**Functions**		**Criteria**	
		C1	**C2**	**C3**
		Environment	**Quality**	**Reliability**
A1	**Survey site**	1	9	9
A2	**Excavate trench**	8	2	3
A3	**Backfill earth**	7	4	2
A4	**Overhead line**	1	8	9
	Sum	17	23	23

Study title: Site preparation		**Determining weights for evaluation**	
Goals, desired criteria, functions, features...		Raw score	Assigned weight
A	Environment	1	1
B	Quality	6	5
C	Reliability	5	4
D	Maintainability	0	0
F	Sum	12	10

	B	C	D
A	*B3*	*C3*	*A1*
	B	*B1*	*B2*
		C	*C2*
			D

Importance Scale

3-Major preference

2-Medium preference

1-Minor preference

Figure 5-9 Pair-wise comparison for determining weights - Site preparation

		Environment	Quality	Reliability	Maintanbility		
		Assigned weight					
	$\varnothing$	1	5	4	0		
ID	Functions	Satisfaction factor (s)				$\sum \phi \cdot S$	Ranking
A1	Survey site	1	9	9	4	82	1
A2	Excavate trench	8	2	3	1	30	4
A3	Backfill earth	7	4	2	3	35	3
A4	Overhead line	1	8	9	3	77	2

Figure 5-10 Evaluation matrix with satisfaction factors -Site preparation

5.4. Summary of results

The following are the priorities of functions for each of the five cases discussed.

Case No.	**Functions ranked by priority for development**
1. construct concete fundation	A5, A4, A1, A2, A3
2. construct concrete column	A4, A3, A1, A2
3. small gas station	A5, A4, A3, A2, A1
4. pipe making process	A2, A3, A1, A4, A5
5. site preparation	A1, A4, A3, A2

5.5. Discussion

A decision maker should ensure that all the ideas or functions receive a better evaluation than simply being rejected by adopting a systematic approach. In the first stage of the method used in this section, the criteria were weighted and evaluated. Therefore, the impact of the criteria to the functions was determined precisely. Next, the matrix analysis method was applied on the basis of the evaluated criteria. As a result, this process received an improved evaluation from each stage. The accuracy upon the outcome ensures the persuasiveness and logic of the evaluation procedure.

CHAPTER 6. THE ANALYTIC HIERARCHY PROCESS

6.1. AHP methodology

Analytic Hierarchy Process (AHP), discovered by Tomas C. Saaty, is a logical methodology in analyzing the various situations of the complex environment and drawing a valid conclusion. AHP can be achieved by assigning weight, judging the consistency and acceptability of the weights. The AHP approach has been applied in different fields for decision-making by organizing the information and using judgments. The process solves complex problems by structuring a hierarchy of criteria and outcomes to develop priorities; therefore, it leads to a prediction of likely outcomes. Because of the interaction among the multitude of functions (or ideas) affecting a complex decision, the technique is performed to identify the important functions, to determine the degree to which they affect each other and to make the decision.

In addition, the technique offers a simple test of the consistency of the weights and it helps to test the validation of the decision-making.

Moreover, in solving the problems by the AHP method, three steps can be distinguished as shown in Table 6-1.

Table 6-1 Three steps of conducting AHP

Step 1	Structuring Hierarchies
Step 2	Establishing priorities
Step 3	Logical consistency

Hence, in an effort to complete the analytic hierarchy process, priorities will be established among the elements of the hierarchy. Also, this set of priorities will be synthesized and the consistency of the problems will be checked. A final decision will come out based on the results of this process. In a VE study, this method can be performed by a step-by-step procedure. A case study which has been used in the preceding section will be analyzed in the following paragraphs. It helps to apply the AHP methodology to select the valuable functions for development.

6.2. The application of AHP method in VE study

6.2.1. Structuring Hierarchies

<u>Case 1. Construction of concrete foundation</u>

For the construction of the concrete foundation case study, primary functions will be selected for development by applying AHP. The concept of structuring hierarchies is used.

In this example, a selection decision will be made from analyzing the following functions:

A1 - Layout building

A2 - Pour piles

A3 - Excavate warehouse

A4 - Pour caps

A5 - Pour beams

In considering the various alternatives, criteria from different views of the function analysis included the following aspects:

C1 - Initial cost

C2 - Profit in return

C3 - Reliability

C4 – Maintainability

Thus, the hierarchy with different levels can be developed as shown in Figure 6-2.

6.2.2. Establishing priorities

At first, the pair wise comparisons are considered, that is, to compare the elements in pairs against certain criterion. A matrix form of five elements is arranged in Figure 6-1 for offering a framework and testing the consistency. The matrix approach reflects the dual aspects of priorities: *dominating* and *dominated.* Compare the element A1 in the column on the left with the elements A1, A2… A5, and so on in the row on the top with respect to criterion C. Then repeat with the element A2 and so on.

C	A1	A2	…	A5
A1	1			
A2		1		
…			…	
A5				1

Figure 6-1 Sample matrix for pair wise comparison

Furthermore, the scale for the pair wise comparison is defined and explained in Table 6-2 according to the AHP methodology. In particular, since the weights must be determined among several criteria, the ranking procedure becomes complex; it is no longer simply sufficient to assign arbitrary numbers. Therefore, the numbers are selected carefully to ensure that the correct priorities will be obtained in the end. In short, for precise distinctions, the pair wise comparison matrix and scale provide a more satisfactory framework in analyzing complex situations.

The overall priorities for a decision are obtained by synthesizing the judgments made in the pair wise comparisons. The priority of each element is indicated by assigning weights. The calculation of the geometric mean recommended by Saaty was used. According to Saaty, the vector of normalized geometric means equates to the normalized eigenvector of the largest eigenvalue from the above matrix. The revised priorities are obtained from the geometric mean calculation.

As shown in Table 6-3, the weights of function A1 are assigned in the first row. A sample calculation of the geometric means for A1 is shown in the following:

Row A1: $(1*1/3*7*1/2*9)^{1/5} = 1.60$

Similarly, the geometric means for the other rows are:

Row A2: 1.53

Row A3: 0.51

Row A4: 2.99

Row A5: 0.27

Sum of all the geometric means is 6.9.

Thus, the normalized weights, or the priority vectors, for each function are respectively:

Row A1: 1.60/6.9 = 0.23. Similarly,

Row A2: 0.22

Row A3: 0.07

Row A4: 0.43

Row A5: 0.04

The result which is shown in Table 6-3 indicates that the function A4 – pour caps yields the max weight, and hence should be selected for further analysis. In general, computing the geometric mean is a good approximation procedure, particularly when the consistency is high. The consistency of this calculation will be evaluated next.

6.2.3. Logical Consistency

In decision-making, it's important to know how good the consistency is because the decision will not be expected to be based on judgments that have a low consistency that appears to be random. On the other hand, specific circumstances often influence preferences and they also change. This makes the perfect consistency hard to live up to. However, the judgments made upon the pair wise comparison matrix can not be so certain under the inconsistency. Therefore, a certain degree of consistency in setting priorities for activities with respect to their criteria is needed to get a valid result.

In order to check the consistency, the maximum eigenvalue of the matrix must be determined to help the calculation. Next, the calculation of a consistency index, CI, was recommended by Saaty. It yields,

$$CI = (\lambda_{max} - n) / (n-1)$$

In this equation, λ_{max} is the maximum eigenvalue of the matrix; n is the order of the matrix.

A Random Index, RI, is extracted using scales developed as a consistency index of a randomly generated matrix and provided by Saaty. Thus, a Consistency Ratio (CR) is determined as,

$$\text{The consistency Ratio (CR)} = \frac{(CI)}{(RI)}$$

The AHP measures the overall consistency of the judgments by means of a consistency ratio. The value of the consistency ratio should be 10% or less. If it is more than 10%, the judgments may be somewhat random and should perhaps be revised (Saaty, 1982). That is, if CR <= 0.1, then the weights have been consistently assigned and hence the weight allocation system is consistent and acceptable. Otherwise, it is not a good result and therefore the weights assignment has to be reconsidered until the consistency is achieved.

In this case, max. eigenvalue of the matrix is 5.974 (From using Texas Instruments calculator, TI-86).

$$\text{(CR)} = \frac{(CI)}{(RI)} = \frac{(5.974-5)/(5-1)}{1.22} = 0.2$$

CR=0.2> 0.1, thus, the judgments should be revised for a consistent result.

The modified matrix was shown in Figure 6-4. Max. eigenvalue of this matrix is 5.38 .

$$\text{(CR)} = \frac{(CI)}{(RI)} = \frac{(5.38-5)/(5-1)}{1.22} = 0.078$$

CR = 0.078 <0.1. Thus, the consistency is proved and the weighting system can be accepted. From the result, the function A3 – excavate warehouse - is selected with the max. normalized weight of 0.46. (Note: The modified weight matrix is only used in the AHP methodology for this chapter.)

Table 6-2 The pair wise comparison scale

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgement slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgement slightly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	Proration between two adjacent judgments
Reciprocals	If activity i has one of the preceding numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

Table 6-3 Decision Matrix - Construction of concrete foundation

ID	Functions	A1	A2	A3	A4	A5	Geometric Means	Nomalized weights
A1	Layout building	1	1/3	7	1/2	9	1.60	0.23
A2	Pour piles	3	1	2	1/5	7	1.53	0.22
A3	Excavate warehouse	1/7	1/2	1	1/6	3	0.51	0.07
A4	Pour caps	2	5	6	1	4	2.99	0.43
A5	Pour beams	1/9	1/7	1/3	1/4	1	0.27	0.04
								1.00

Table 6-4 Decision Matrix - Construction of concrete foundation

ID	Functions	A1	A2	A3	A4	A5	Geometric Means	Nomalized weights
A1	Layout building	1	5	1/5	1/3	1	0.80	0.12
A2	Pour piles	1/5	1	1/5	1/3	1	0.42	0.06
A3	Excavate warehouse	5	5	1	2	5	3.02	0.46
A4	Pour caps	3	3	1/2	1	3	1.68	0.26
A5	Pour beams	1	1	1/5	1/3	1	0.58	0.09
								1.00

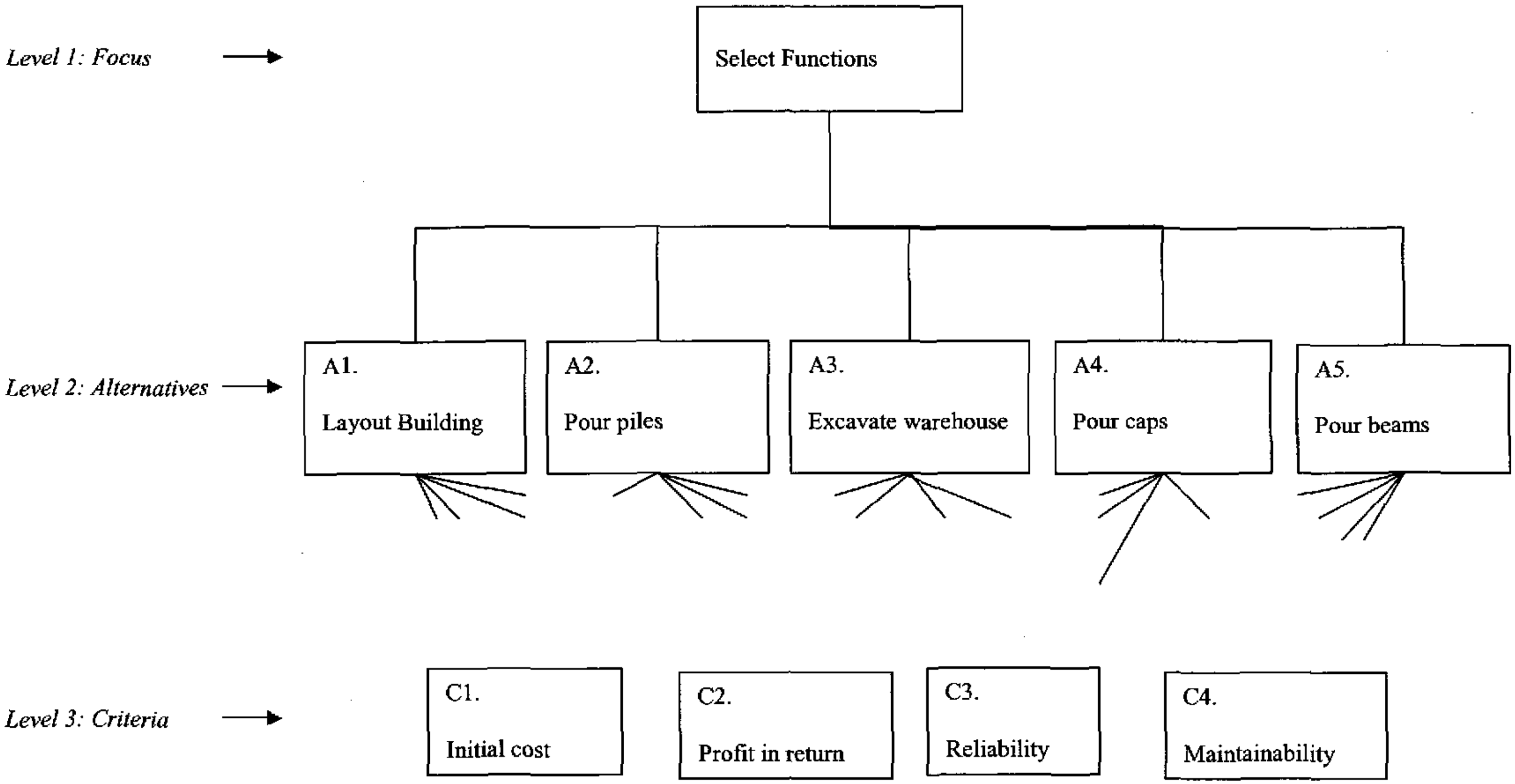


Figure 6-2 Structuring hierarchy - construction of foundation contract

Case 2. Construct concrete column

In this case, the construct concrete column project is studied. The analysis diagrams were established in Chapter 2. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following Table 6-5, Table 6-6, and Figure 6-3.

In this case, Max. eigenvalue of the matrix is 4.

$$(\mathrm{CR}) = \frac{(CI)}{(RI)} = \frac{(4-4)/(4-1)}{1.23} = 0$$

CR= 0 < 0.1, thus, the weight allocation system is consistent and acceptable. From the result, the function A2 is selected with the max. normalized weight 0.46.

Table 6-5 Weight matrix for selecting functions - Construct concrete column

ID	Functions	Criteria			
		C1	C2	C3	sum
		Initial cost	Safety	Reliability	
A1	Fabricate panels	7	1	4	12
A2	Erect panels	1	2	7	10
A3	Construct forms	3	4	8	15
A4	Cast concrete	9	2	8	19

Table 6-6 Decision matrix - Construct concrete column

ID	Functions	A1	A2	A3	A4	Geometric Means	Nomalized weights
A1	Fabricate panels	1	5/6	1 1/4	1 4/7	1.11	0.27
A2	Erect panels	1 1/5	1	1 1/2	1 8/9	1.28	0.31
A3	Construct forms	4/5	2/3	1	1 1/4	0.92	0.23
A4	Cast concrete	5/8	1/2	4/5	1	0.77	0.19
Sum						4.07	1.00

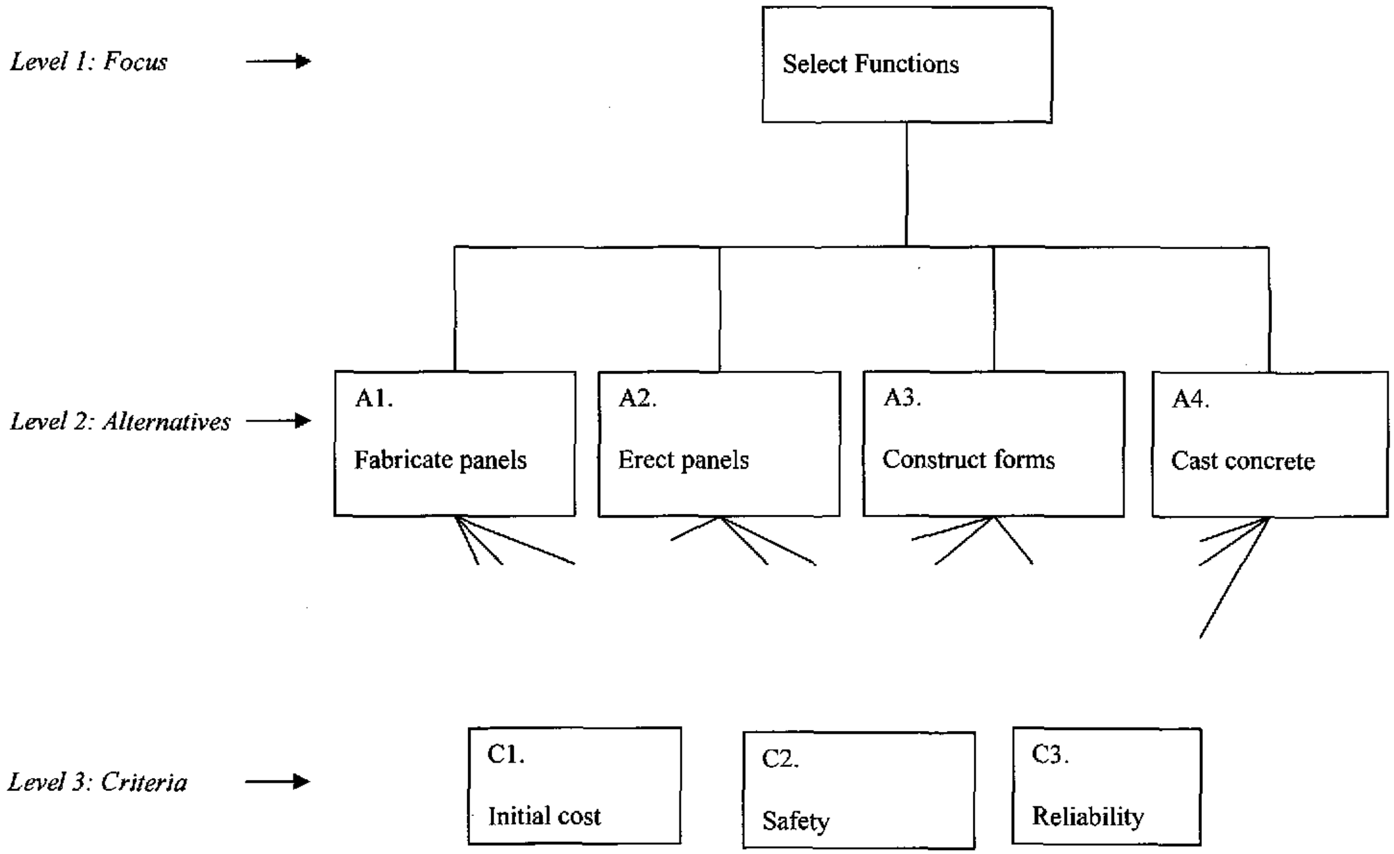


Figure 6-3 Structuring Hierarchy - Construct concrete column

Case 3. Small gas station

In this case, the small gas station project is studied. The analysis diagrams were established in Chapter 3. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following Table 6-7, Table 6-8 and Figure 6-4.

In this case, Max. eigenvalue of the matrix is 4.976.

$$(\mathrm{CR}) = \frac{(CI)}{(RI)} = \frac{(4.976-5)/(5-1)}{1.22} = 0.005$$

CR= 0.005< 0.1, thus, the weight allocation system is consistent and acceptable. From the result, the function A1 is selected with the max. normalized weight 0.58.

Table 6-7 Weight matrix for each decision alternative - Small gas station

ID	Functions	Criteria			
		C1	C2	C3	sum
		Safety	Quality	Environment	
A1	Obtain permits	1	1	1	3
A2	Excavate footers	3	5	2	10
A3	Pour slabs	7	7	4	18
A4	Install doors	6	10	7	23
A5	Construct roof	10	9	7	26
	Sum	27	32	21	

Table 6-8 Decision matrix - Small gas station

ID	Functions	A1	A2	A3	A4	A5	Geometric Means	Nomalized weights
A1	Obtain permits	1	3 1/3	6	7 2/3	8 2/3	4.21	0.58
A2	Excavate footers	2/7	1	1 4/5	2 2/7	2 3/5	1.26	0.18
A3	Pour slabs	1/6	5/9	1	1 2/7	1 4/9	0.70	0.10
A4	Install doors	1/8	3/7	7/9	1	1 1/8	0.55	0.08
A5	Construct roof	1/9	3/8	2/3	8/9	1	0.49	0.07
	Sum						7.22	1.00

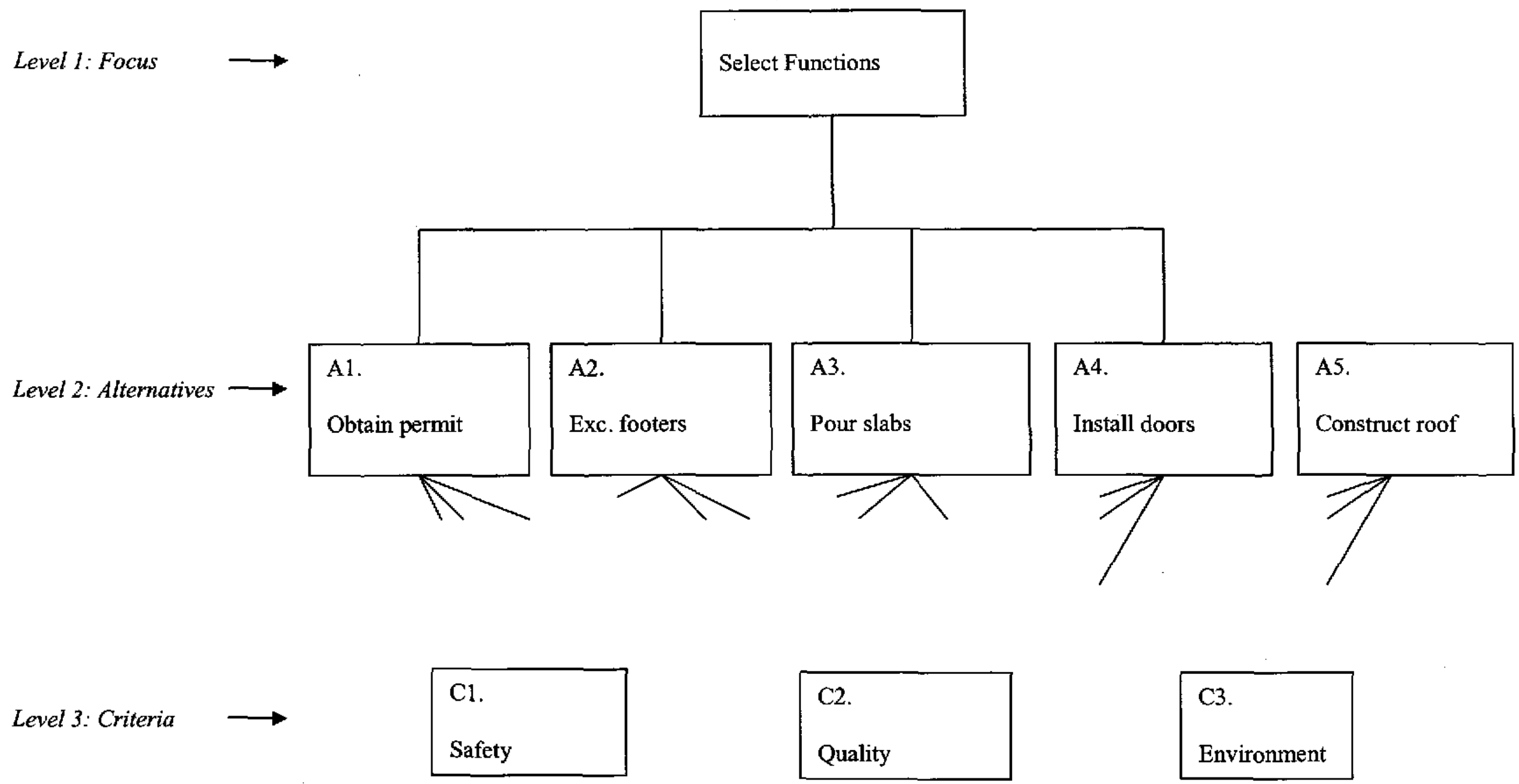


Figure 6-4 Structuring Hierarchy - Small gas station

Case 4. Pipe making process

In this case, the pipe making process is studied. The analysis diagrams were established in Chapter 4. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following Table 6-9, Table 6-10, and Figure 6-5.

In this case, Max. eigenvalue of the matrix is 4.934.

$$(\mathrm{CR}) = \frac{(CI)}{(RI)} = \frac{(4.934-5)/(5-1)}{1.22} = 0.014$$

CR= 0.014< 0.1, thus, the weight allocation system is consistent and acceptable. From the result, the function A4 is selected with the max. normalized weight 0.22.

Table 6-9 Weight matrix for each decision alternative – Pipe making process

ID	Functions	Criteria			
		C1	C2	C3	Sum
		Profit in retur	Initial cost	Reliability	
A1	Prepare material	1	7	3	11
A2	Make pipe	6	3	9	18
A3	Correct pipe	2	3	9	14
A4	Polish pipe	3	4	3	10
A5	Paint surface	2	2	3	7
	Sum	14	19	27	

Table 6-10 Decision matrix - Pipe making process

ID	Functions	A1	A2	A3	A4	A5	Geometric Means	Nomalized weights
A1	Prepare material	1	1 2/3	1 1/4	1	2/3	1.04	0.20
A2	Make pipe	3/5	1	7/9	5/9	2/5	0.63	0.12
A3	Correct pipe	4/5	1 2/7	1	5/7	1/2	0.82	0.16
A4	Polish pipe	1 1/9	1 4/5	1 2/5	1	2/3	1.14	0.22
A5	Paint surface	1 4/7	2 4/7	2	1 3/7	1	1.63	0.31
	Sum						5.26	1.00

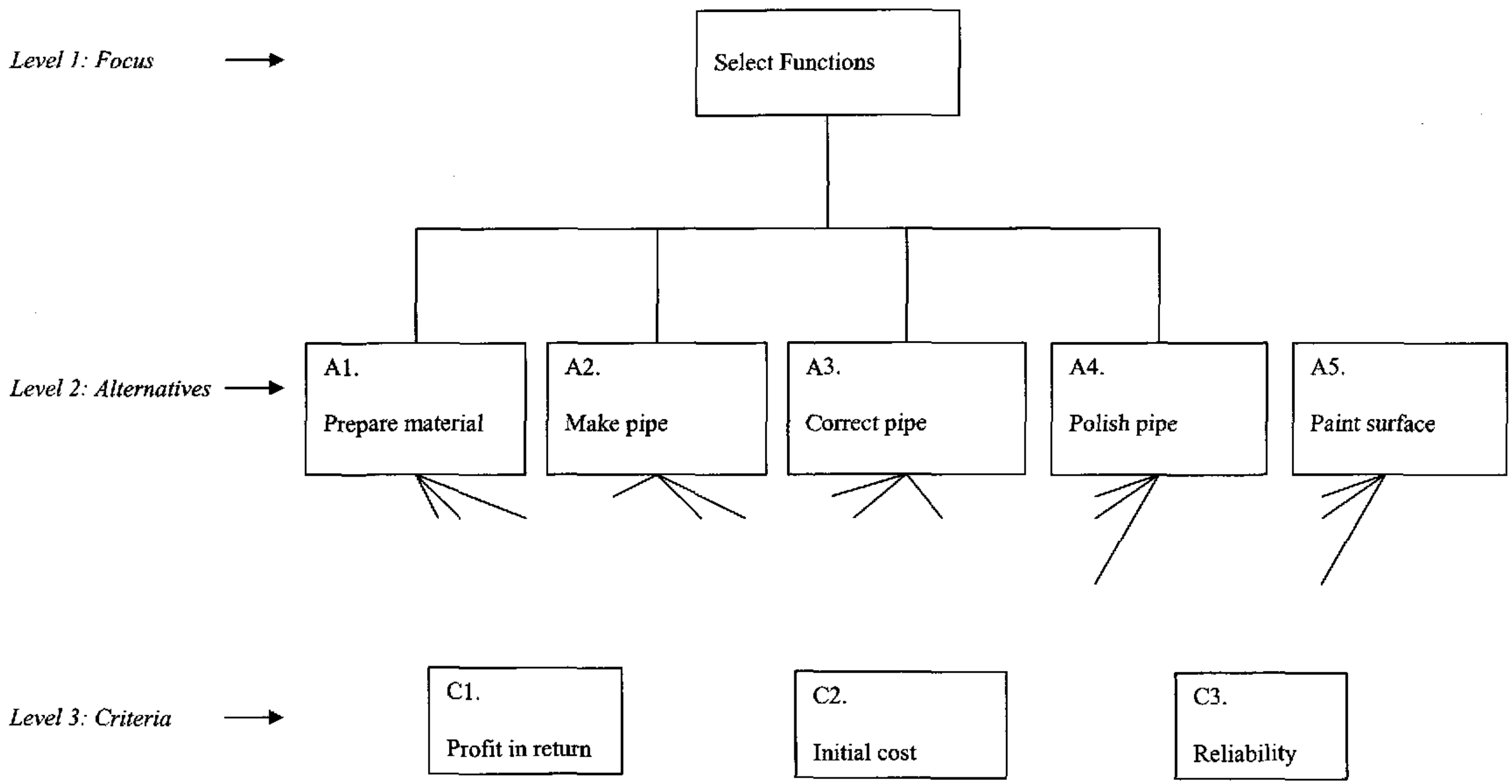


Figure 6-5 Structuring Hierarchy - Pipe making process

Case 5. Site preparation

In this case, the site preparation project is studied. The site preparation analysis diagrams were established in Chapter 4. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in Table 6-11, Table 6-12, and Figure 6-6

In this case, Max. eigenvalue of the matrix is 4.013.

$$(\mathrm{CR}) = \frac{(CI)}{(RI)} = \frac{(4.013-4)/(4-1)}{1.23} = 0.0035$$

CR=0.0035 < 0.1, thus, the weight allocation system is consistent and acceptable. From the result, the function A3 and A2 are selected with the max. normalized weight 0.29.

Table 6-11 Weight matrix for each decision alternative - Site preparation

ID	Funcions		Criteria		
		C1	C2	C3	Sum
		Environment	Quality	Reliability	
A1	Survey site	1	9	9	19
A2	Excavate trench	8	2	3	13
A3	Backfill earth	7	4	2	13
A4	Overhead line	1	8	9	18
	Sum	17	23	23	

Table 6-12 Decision matrix - Site preparation

ID	Description	A1	A2	A3	A4	Geometric Means	Normalized weights
A1	Survey site	1	2/3	2/3	1	0.85	0.21
A2	Excavate trench	1 1/2	1	1	1 3/8	1.15	0.29
A3	Backfill earth	1 1/2	1	1	1 3/8	1.15	0.29
A4	Overhead line	1	5/7	5/7	1	0.89	0.22
		Sum				4.04	1.00

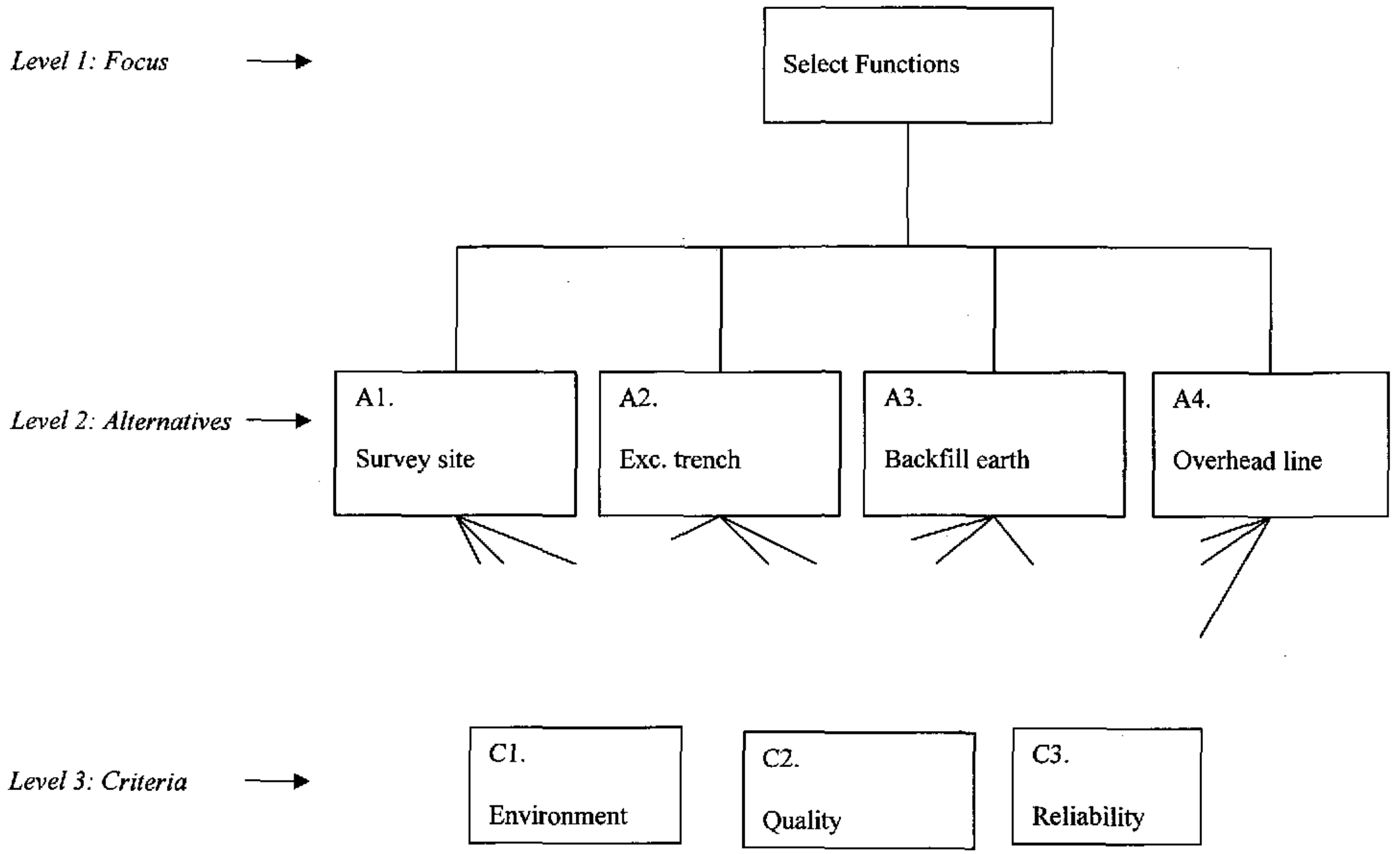


Figure 6-6 Structuring Hierarchy - Site preparation

6.3. Summary of results

The results are summarized in Table 6-13. The decision for development can be made according to these results. For instance, in case 4, the priorities show that the function A4 with the max. index 0.22 should be selected as the most valuable function for further analysis. The results of the process also provide the order of the importance of the functions. It is possible to select more than one function, if necessary, according to the capacity of the work needed to be done.

Table 6-13 Summary of results

Case no.	CR	Consistency Yes/No	CR(Revised)	Consistency Yes/No	*Final Highest* normalized weights	Decision
1. Construct concrete foundation	0.2	no	0.078	yes	0.46	A3
2. Construct concrete column	0	yes			0.23	A2
3. Small gas station	0.005	yes			0.58	A1
4. Pipe making process	0.014	yes			0.22	A4
5. Site preparation	0.004	yes			0.29	A3 and A2

Furthermore, the design of structuring the hierarchy simplifies the relationship of functions of a project from one level to another. The model is flexible enough to deal with the complex circumstances.

Moreover, the logical consistency checking of the judgments increases the accuracy of the results and avoids errors occurring during the decision making process. It provides a mathematical calculation to ensure the correct performance of the AHP in VE study.

CHAPTER 7. PAYOFF MATRIX

7.1. The concept of the Payoff matrix

A systematic approach of decision making under uncertainty is called decision-theory. This approach has the advantage of clearly formulating problems and anticipating the various consequences of the work processed. In order to perform the mathematical analysis of any problem, the problem is first translated into the language of mathematics; in this case, the given information is expressed in the terms of payoff tables. "Borrowing from the language of game theory, we refer to the entries in the table, the various profits, as the payoffs, and to the table itself as a payoff table or, sometimes, as payoff matrix."(Freund & Williams, 1977) The performance of the payoff matrix in VE studies will be presented in the following sections.

7.2. Application of the payoff matrix in VE studies

7.2.1. Maximum payoff

Case 1. Construction concrete foundation

The entries are stated in terms of the weight or the importance of the functions (A1, A2, A3…) under the circumstance of criteria (C1, C2, C3…). The decision maker will analyze the situation presented in the payoff table to arrive at a decision. One of the methods is to maximize the payoff values. The result is determined and shown in Table 7-1. The maximum payoff is simply the maximum weight assigned to any criteria for any given function.

Table 7-1. Maximum payoff for Construction concrete foundation

ID	Functions	Criteria				Max. payoff
		C1	C2	C3	C4	
		Initial cost	Profit in return	Reliability	Maintainability	
A1	Layout building	4	1	7	0.1	7
A2	Pour piles	5	2	6	3	6
A3	Excavate warehouse	6	1	4	0.1	6
A4	Pour caps	3	4	8	5	8
A5	Pour beams	7	6	9	3	9
	Sum	25	14	34	11.2	

From the Table 7-1, the maximum of the maximum payoff values, maximax, is 9 according to the results. It simply shows that the function A5-pours beams should be selected for further analysis. Therefore, the maximum of the maximum payoff values indicates the most valuable selection.

7.2.2. Opportunity losses

A sample calculation for opportunity loss is presented: for function A1, refer to the first column of numbers in the Table 7-1, the difference between the optimal payoff (7) and other payoff (such as 4) is referred to as the opportunity loss. Hence, the result is 7 - 4 =3 for C1 based on A1. The regret or opportunity loss is shown in the Table 7-2. The minimum of the maximum regret is carried out in the Table 7-3. Hence, the outcome of the minimum of the maximum regret is 2. The result simply tells what the consequence is if a certain function is selected. In this case, A5 is the choice with the minimum of the maximum opportunity loss.

Table 7-2 Regret or opportunity loss for Construction concrete foundation

		Regret or opportunity loss			
ID	**Functions**	**Criteria**			
		C1	**C2**	**C3**	**C4**
A1	**Layout building**	3	5	2	5
A2	**Pour piles**	2	4	3	2
A3	**Excavate warehouse**	1	5	5	5
A4	**Pour caps**	4	2	1	0
A5	**Pour beams**	0	0	0	2

Table 7-3 Maximum regret or opportunity loss for Construction concrete foundation

ID	**Functions**	**Maximum regret or opportunity loss**
A1	**Layout building**	5
A2	**Pour piles**	4
A3	**Excavate warehouse**	5
A4	**Pour caps**	4
A5	**Pour beams**	2

7.2.3. Expected Monetary value (EMV)

The expected monetary value of a decision is the sum of weighted payoffs for the alternatives. The expected monetary value can be calculated as shown in Table 7-4. For instance, assume the criterion C1 is assigned 40% of the importance of all the criteria, and criterion C2 is assigned 20%, and so on. Using the weights of Table 7-1, a sample calculation is stated as below:

EMV (A1) = 4x40% +1x20 % +7x35% + 0.1x5% = 4.255.

As a result, the function A5- pour grade beams with the highest expected monetary value 7.3 is the recommended decision.

7.2.4. Expected Opportunity loss (EOL)

The expected opportunity loss was also computed in Table 7-5. A sample calculation of expected opportunity loss is stated as below:

EOL (A1) = 3x40% + 5x20% + 2x35% + 5x5% = 3.15

Since the minimum expected opportunity loss is expected, the function A5- pour beams with the smallest loss 0.1 is recommended to be the choice. Thus, the optimal decision using the expected opportunity loss criterion will always be the same as the optimal decision.

Table 7-4 Expected Monetary Value (EMV) for Construction concrete foundation

		Weight Criteria				
		40%	**20%**	**35%**	**5%**	**EMV**
ID	**Functions**	**C1**	**C2**	**C3**	**C4**	
		Initial cost	**Profit in return**	**Reliability**	**Maintainability**	
A1	**Layout building**	4	1	7	0.1	4.255
A2	**Pour piles**	5	2	6	3	4.65
A3	**Excavate warehouse**	6	1	4	0.1	4.005
A4	**Pour caps**	3	4	8	5	5.05
A5	**Pour beams**	7	6	9	3	7.3

Table 7-5 Expected Opportunity Loss (EOL) for Construction concrete foundation

		Weight Criteria				
		40%	20%	35%	5%	EOL
ID	Functions	C1	C2	C3	C4	
A1	Layout building	3	5	2	5	3.15
A2	Pour piles	2	4	3	2	2.75
A3	Excavate warehouse	1	5	5	5	3.4
A4	Pour caps	4	2	1	0	2.35

Case 2. Construct concrete column

In this case, the construct concrete column project is studied. The analysis diagrams were established in Chapter 2. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following tables. As a result, the function A4 is selected for development.

Table 7-6 Maximum payoff for each decision alternative - Construct concrete column

ID	Functions	Criteria			Max. Payoff
		C1	C2	C3	
		Initial cost	Safety	Reliability	
A1	Fabricate panels	7	1	4	7
A2	Erect panels	1	2	7	7
A3	Construct forms	3	4	8	8
A4	Cast concrete	9	2	8	9
	Sum	20	9	27	

Table 7-7 Regret or opportunity loss - Construct concrete column

		Regret or opportunity loss		
ID	**Functions**	**Criteria**		
		C1	**C2**	**C3**
A1	**Fabricate panels**	2	3	4
A2	**Erect panels**	8	2	1
A3	**Construct forms**	6	0	0
A4	**Cast concrete**	0	2	0

Table 7-8 Maximum regret or opportunity loss - Construct concrete column

ID	Functions	Maximum regret or opportunity loss
A1	**Fabricate panels**	4
A2	**Erect panels**	8
A3	**Construct forms**	6
A4	**Cast concrete**	2

Table 7-9 Expected Monetary Value (EMV) - Construct concrete column

		Weight Criteria			
		40%	**20%**	**40%**	**EMV**
ID	**Functions**	**C1**	**C2**	**C3**	
		Initial cost	**Safety**	**Reliability**	
A1	**Fabricate panels**	7	1	4	4.6
A2	**Erect panels**	1	2	7	3.6
A3	**Construct forms**	3	4	8	5.2
A4	**Cast concrete**	9	2	8	7.2

Table 7-10 Expected Opportunity Loss (EOL) - Construct concrete column

		Weight Criteria			
		40%	20%	40%	EOL
ID	Functions	C1	C2	C3	
A1	Fabricate panels	2	3	4	3
A2	Erect panels	8	2	1	4
A3	Construct forms	6	0	0	2.4
A4	Cast concrete	0	2	0	0.4

Case 3. Small gas station

In this case, the small gas station project is studied. The analysis diagrams were established in Chapter 3. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following tables. As a result, the function A5 is selected for development.

Table 7-11 Maximum payoff -Small gas station

ID	Functions	Criteria			Max. payoff
		C2	C3	C4	
		Safety	Quality	Environment	
A1	Obtain permits	1	1	1	1
A2	Excavate footers	3	5	2	5
A3	Pour slabs	7	7	4	7
A4	Install doors	6	10	7	10
A5	Construct roof	10	9	7	10
	Sum	27	32	21	

Table 7-12 Regret or opportunity loss - Small gas station

Regret or opportunity loss				
ID	Functions	Criteria		
		C1	C2	C3
A1	Obtain permits	9	9	6
A2	Excavate footers	7	5	2
A3	Pour slabs	3	3	3
A4	Install doors	4	0	0
A5	Construct roof	0	1	0

Table 7-13 Maximum regret or opportunity loss - Small gas station

ID	Functions	Maximum regret or opportunity loss
A1	Obtain permits	9
A2	Excavate footers	7
A3	Pour slabs	3
A4	Install doors	4
A5	Construct roof	1

Table 7-14 Expected Monetary Value (EMV) - Small gas station

		Weight Criteria			
		40%	35%	25%	EMV
ID	Functions	C1	C2	C3	
		Initial cost	Profit in return	Reliability	
A1	Obtain permits	1	1	1	1
A2	Excavate footers	3	5	2	3.45
A3	Pour slabs	7	7	4	6.25
A4	Install doors	6	10	7	7.65
A5	Construct roof	10	9	7	8.9

Table 7-15 Expected Opportunity Loss (EOL) - Small gas station

		Weight Criteria			
		40%	35%	25%	EOL
ID	Functions	C1	C2	C3	
A1	Obtain permits	9	9	6	8.25
A2	Excavate footers	7	5	2	5.05
A3	Pour slabs	3	3	3	3
A4	Install doors	4	0	0	1.6

Case 4. Pipe making process

In this case, pipe making process project is studied. The analysis diagrams were established in Chapter 4. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following tables. As a result, the function A2 is selected for development.

Table 7-16 Maximum payoff for each decision alternative - Pipe making process

		Criteria			
ID	Functions	C1	C2	C3	Max. payoff
		Profit in return	Initial cost	Reliability	
A1	Prepare material	1	7	3	7
A2	Make pipe	6	3	9	9
A3	Correct pipe	2	3	9	9
A4	Polish pipe	3	4	3	4
A5	Paint surface	2	2	3	3
	Sum	14	19	27	

Table 7-17 Regret or opportunity loss - Pipe making process

Regret or opportunity loss				
ID	***Functions***	**Criteria**		
		C1	**C2**	**C3**
A1	**Prepare material**	5	0	6
A2	**Make pipe**	0	4	0
A3	**Correct pipe**	4	4	0
A4	***Polish pipe***	3	3	6
A5	**Paint surface**	4	5	6

Table 7-18 Maximum regret or opportunity loss - Pipe making process

ID	Functions	Maximum regret or opportunity loss
A1	**Prepare material**	6
A2	**Make pipe**	4
A3	**Correct pipe**	4
A4	**Polish pipe**	6
A5	**Paint surface**	6

Table 7-19 Expected Monetary Value (EMV) - Pipe making process

		Weight Criteria			
		40%	**35%**	**25%**	**EMV**
ID	**Functions**	**C1**	**C2**	**C3**	
		Profit in return	**Initial cost**	**Reliability**	
A1	**Prepare material**	1	7	3	3.6
A2	**Make pipe**	6	3	9	5.7
A3	**Correct pipe**	2	3	9	4.1
A4	**Polish pipe**	3	4	3	3.35
A5	***Paint surface***	2	2	3	2.25

Table 7-20 Expected Opportunity Loss (EOL) - Pipe making process

		Weight Criteria			
		40%	35%	25%	EOL
ID	Functions	C1	C2	C3	
A1	Prepare material	5	0	6	3.5
A2	Make pipe	0	4	0	1.4
A3	Correct pipe	4	4	0	3
A4	Polish pipe	3	3	6	3.75
A5	Paint surface	4	5	6	4.85

Case 5. Site preparation

In this case, the site preparation project is studied. The site preparation analysis diagrams were established in Chapter 4. The calculation followed the same procedure as discussed previously. The evaluation calculation is shown in the following tables. As a result, the function A1 is selected for development.

Table 7-21 Maximum payoff for each decision alternative - Site preparation

		Criteria			
ID	Functions	C1	C2	C3	Max. payoff
		Environment	Quality	Reliability	
A1	Survey site	1	9	9	9
A2	Excavate trench	8	2	3	8
A3	Backfill earth	7	4	2	7
A4	Overhead line	1	8	9	9
	Sum	17	23	23	

Table 7-22 Regret or opportunity loss - Site preparation

ID	Functions	Regret or opportunity loss		
		C1	C2	C3
A1	Survey site	7	0	0
A2	Excavate trench	0	7	6
A3	Backfill earth	1	5	7
A4	Overhead line	7	1	0

Table 7-23 Maximum regret or opportunity loss - Site preparation

ID	Functions	Maximum regret or opportunity loss
A1	Survey site	7
A2	Excavate trench	7
A3	Backfill earth	7
A4	Overhead line	7

Table 7-24 Expected Monetary Value (EMV) - Site preparation

		Weight Criteria			EMV
		C1	C2	C3	
		20%	25%	55%	
ID	Functions	Environment	Quality	Reliability	
A1	Survey site	1	9	9	7.4
A2	Excavate trench	8	2	3	3.75
A3	Backfill earth	7	4	2	3.5
A4	Overhead line	1	8	9	7.15

Table 7-25 Expected Opportunity Loss (EOL) - Site preparation

		Weight Criteria			
		20%	25%	55%	EOL
ID	Functions	C1	C2	C3	
A1	Survey site	7	0	0	1.4
A2	Excavate trench	0	7	6	5.05
A3	Backfill earth	1	5	7	5.3
A4	Overhead line	7	1	0	1.65

7.3. Discussion

In short, the application of the payoff matrix contributed a new mathematical method, not used earlier in VE studies. The decision can be made quickly on the basis of the maximum of the maximum payoff values and the minimum of the maximum regret calculation. In addition, the weight of each factor is considered when the computation of the expected monetary value and the expected opportunity loss is used.

The recommended decisions through this set of payoff matrix methods are identical. One function or one criterion is needed to be applied in a given decision-making situation. However, in this study other functions or ideas are also encouraged to be analyzed if necessary. For example, in case 1, A4 can be the second choice if necessary. The results might be varied on the basis of the individual needs.

Nevertheless, the payoff matrix is a set of fast decision-making methods. It can be used for decision-making in all kinds of situations, especially, when there is a time constraint for making a decision.

CHAPTER 8. BAYES' THEOREM

8.1. Bayes' theorem

8.1.1. Bayes' theorem

In the evaluation phase of VE studies, various mathematical methods are carried out to identify the best alternate. In this chapter, the Bayes' theorem is applied to the VE study. Symbolically, the general formula for Bayes' theorem is given by:

$$P(B_i / A) = \frac{P(B_i) \bullet P(A / B_i)}{P(B_1) \bullet P(A / B_1) + P(B_2) \bullet P(A / B_2) + \cdots + P(B_k) \bullet P(A / B_k)}$$

For $i = 1, 2, \ldots, or\ k$. (Freund & Williams, 1977)

This rule expresses a "backward" or "inverse" sort of reasoning from "effect to cause" or "output to input"; where the probabilities, P(B*i*/A) is calculated. P(A/B*i*) represents the probability going from "cause to effect". The expression in the denominator actually equals P(A); $P(B_1) \bullet P(A / B_1)$ is the probability of reaching A via the first branch B1; $P(B_2) \bullet P(A / B_2)$ is the probability of reaching A via the second branch B2; … and $P(B_k) \bullet P(A / B_k)$ is the probability of reaching A via the *k*th branch B*k*, and the sum of all these probabilities equals P(A). The tree diagram of Figure 8-1 illustrates a situation that is analyzed in Bayes' theorem (Freund & Williams, 1977).

(Note: 'TreeAge (DATA) 4.0' software was used to generate the decision tree diagram in this thesis.)

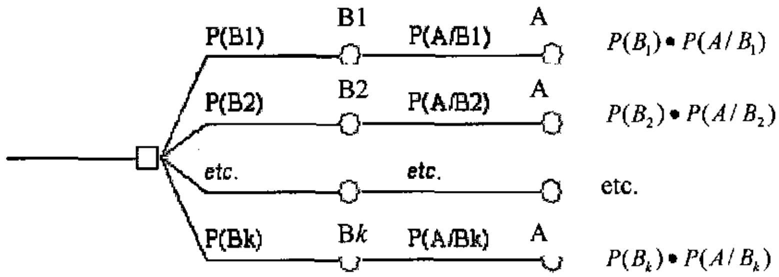


Figure 8-1 Tree diagram for Bayes' theorem

If A (A1, A2, ...An) represent the different available function alternates and C (C1, C2, ... Cm) represent the set of criteria, the decision making situation D (D11, D12, ... Dnm) can be described in the matrix as shown in Table 8-1.

Table 8-1 Decision matrix for selecting the functions

CRITERIA

ALTERNATIVES	C1	C2	...	...	Cm
A1	D11	D12	...	...	D1m
A2	D21	D22	...	...	D2m
...	...	...	...	...	...
...	...	...	...	...	...
An	Dn1	Dn2	...	...	Dnm

8.1.2. A Priori analysis and A Posteriori analysis

For *a priori* analysis, the decision maker chooses the alternatives on the basis of prior information without attempting to gather further information (Hamburg, 1985).

However, *prior probabilities* may be revised based on additional information. The revised probabilities are called *posterior probabilities*. For instance, the probability (or weight) is assigned to an event on the basis of whatever information is obtained at an earlier time. Later, it may be revised when additional information is received. The mechanics of making logical revisions of earlier probability assignments is the subject matter of *a posteriori probabilities analysis* (Freund & Williams, 1977).

The following figures help to explain the situation of a priori and a posteriori analysis. As shown in Figure 8-2, a prior probability of event A is assigned as P(A) before the outcome is known. When the additional information arrives, the additional probability is assigned as P(X/A), P(Y/A), P(X/B), or P(Y/B) as the case may be.

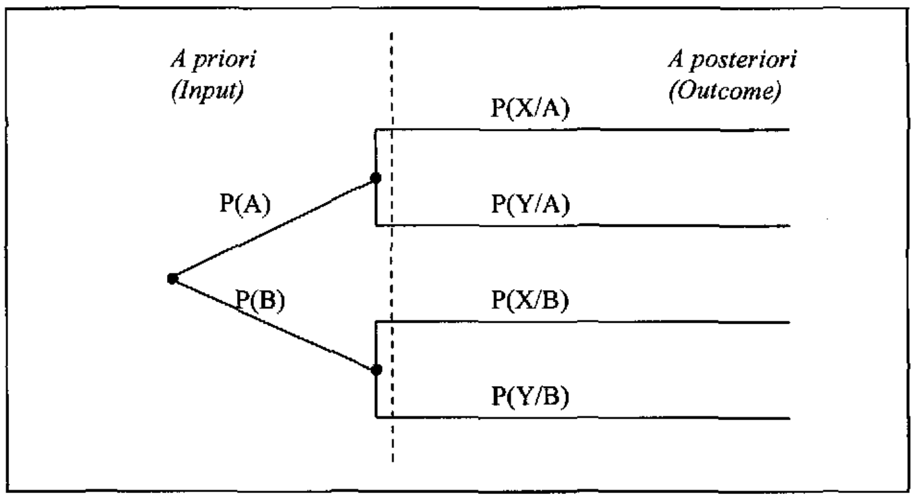


Figure 8-2 A priori and a posterior analysis before the outcome is known

After the outcome is known, the calculation of the above can be inversed as shown in Figure 8-3. Since the outcome P(X) is known, in this case, P(X) becomes a prior probability. After the additional information is received, P(A/X) is assigned after P(X) is known. Now, the prior probability can be revised by applying Bayes' theorem.

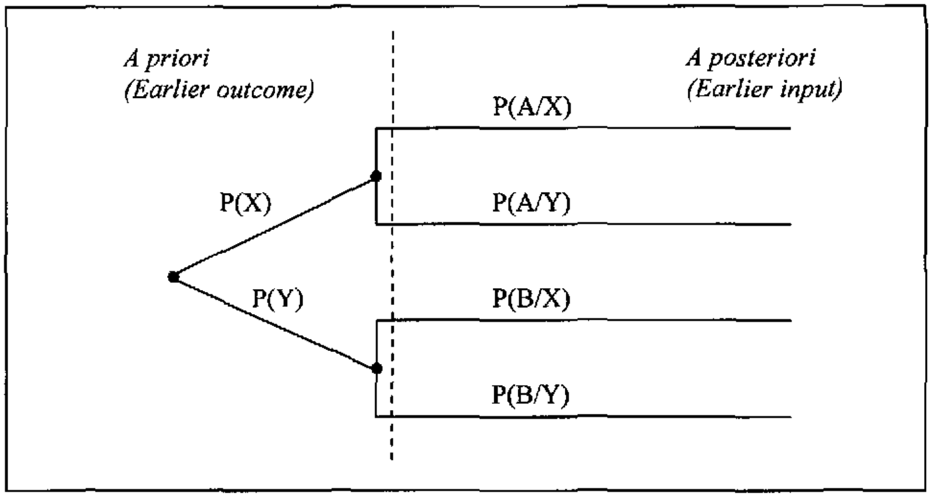


Figure 8-3 A priori and a posterior analysis after the outcome is known

EXAMPLE

Assume the prior probabilities of event A1, A2, A3 are 20%, 50%, 30%. Additional outcome probabilities (information) of B based on event A are received as P(B/A1) = 10%, P(B/A2) = 80%, and P(B/A3) = 20 (Hamburg, 1985). This situation is pictured in Figure 8-4. Therefore, the *prior probabilities* assigned to the original three events can be revised by Bayes' theorem.

$$P(Ai/B) = \frac{P(Ai) \bullet P(B/Ai)}{\sum P(B)}$$

The revised probabilities are illustrated in Table 8-2.

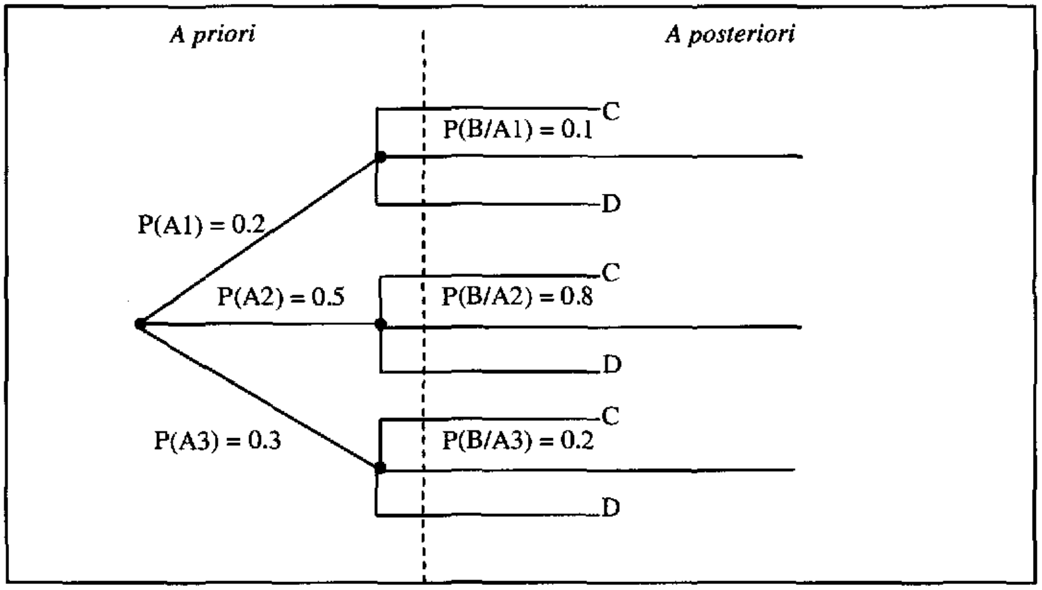


Figure 8-4 A priori and a posteriori analysis diagram for the example

Table 8-2 Computation of posterior probabilities (Hamburg, 1985)

Event A*i*	Prior probablility P(A*i*)	Conditional probability P(B/A*i*)	Joint probability P(A*i*)P(B/A*i*)	Posterior probability P(A*i*/B)
A1	20%	10%	2%	0.042
A2	50%	80%	40%	0.833
A3	30%	20%	6%	0.125
Total	100%		48%	1

Therefore, it can be discovered what a particular outcome is caused by. The probabilities of a particular cause can thus be determined. Such an analysis aids considerably in forensic analysis.

Therefore, in the case above, we can ascertain with 12.5% probability that A3 is the cause of event B, 4.2% is the probability that A1 is the cause of event B, and 83.3% is the probability that A2 is the cause of event B.

8.2. Application of Bayes' theorem in VE studies

8.2.1. The scope of application

In this paper, the alternate selection is not only concerned with the various ideas generated during the creativity phase but also with the consideration of selecting the valuable functions during the function analysis phase.

The function analysis phase is performed immediately following the information phase. Various functions of the project are identified; however, most of these functions do not represent problems that need to be solved. It is desirable to concentrate only on the specific areas where creative solutions are required in the problem-solving effort. Bayes' theorem is applied to identify and classify the candidate functions for further discussion.

Using Bayes' theorem in evaluation phase of VE study is the focus of the application here. Since the creativity phase has generated a large quantity of alternates, the purpose of the evaluation phase is to develop those ideas and make a final decision of the scheme that will be used. The decision tree will represent the decision making process through the Bayes' theorem calculation.

8.2.2. Case study

Case 1. Construction concrete foundation

For instance, in the construction of the concrete foundation project, the question arises as to what function should be developed for value analysis and implementation. The FAST diagram of the project is established in Chapter 3. The Bayes' theorem is used in order to select important functions.

Assume the functions of the foundation contract to be:

A1- Layout building

A2 – Pour piles

A3 – Excavate warehouse

A4 – Pour caps

A5 – Pour beams

And the criteria are concerned on:

C1- Initial cost

C2 – Profit in return

C3 – Reliability

C4 – Maintainability

Engineers provide weights for criteria of the matrix from comparing how much more important one variable is to another based on their knowledge of the job. For instance, in respect to each of the criteria, the weight of function A1- Layout building is determined as 4 against criterion C1- Initial cost. Thus, the matrix can be made, as given in Table 8-3. The full credit of the weight index could be created up to 10.

Table 8-3 Matrix for selecting the functions - Construction concrete foundation

ID	Functions	Criteria			
		C1	C2	C3	C4
		Initial cost	Profit in return	Reliability	Maintainability
A1	Layout building	4	1	7	0.1
A2	Pour piles	5	2	6	3
A3	Excavate warehouse	6	1	4	0.1
A4	Pour caps	3	4	8	5
A5	Pour beams	7	6	9	3

(Note: The maximum score of C is assigned as 10.)

Next, in respect to the function A1-layout building, the importance of C1-initial cost can be calculated here as: $P(C_i / A_i) = \frac{W(C_i)}{\sum_{i=1}^{n} C_i}$ (n=1, 2, 3 ...)

Thus, in the Table 8-4, P (C1/A1) = 4/ (4+1+7+0) *100% = 34%. The probability here is used to state how important the criterion is against a certain function. In this case, the criterion C1 contributes 34% importance to the function A1 among the total four criteria. Then other values of P (C2/A1), P (C3/A1), and P (C4/A1) were found respectively as 31.3%, 54.5%, and 15.0%.

In addition, *a prior probabilities* (or weights) of each function are assigned by engineers. For instance, through the project study, the VE team assigned 15% of the importance (weight) to the function A1- layout building among the five functions from the project. As the same, A2, A3, A4, A5 was assigned the weights as 10%, 10%, 20%, and 45%. In preparing to apply Bayes' theorem, the decision matrix is established in Table 8-4. This situation is pictured in decision tree diagrams in Figure 8-5.

In applying the Bayes' theorem, *a priori and a posteriori analyses* are performed with the assistance of decision tree diagrams. The purpose is to find the important functions for development through this calculation. For instance, since the *prior probability* of A1 is assigned as 15% without any further information at an earlier time, however, the additional information is received as 34% in this case. Therefore, the *prior probability* assigned to A1 (15%) can now be revised by using the Bayes' theorem formula,

$$P(A_1 / C_1) = \frac{P(A_1) \bullet P(C_1 / A_1)}{\sum P(C_1)} = \frac{15\% \bullet 34\%}{29.3\%} = 17.41\%$$

(From the Figure 8-5, ΣP (C1) is determined as 29.3%)

These revised or *posterior probabilities* are given in Table 8-5.

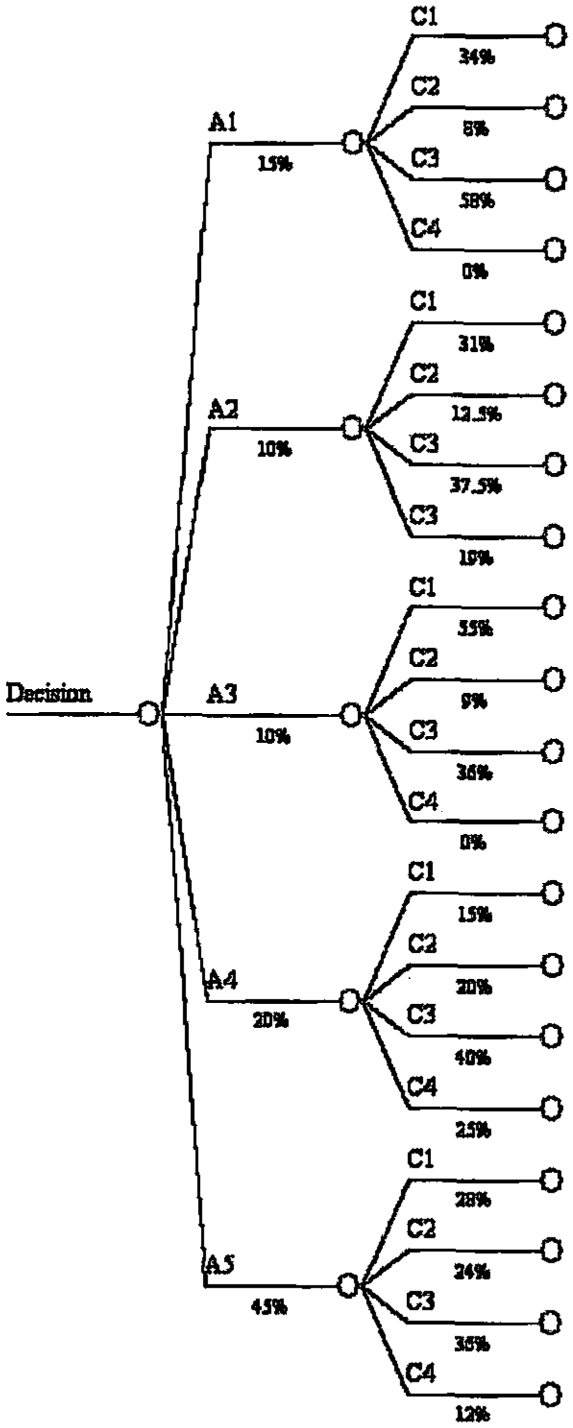
Corresponding expressions for P (A2/C1), P (A3/C1), P (A4/C1) and P (A5/C1) have results respectively as: 10.58%, 18.77%, 10.24% and 43%. From the result, the function of A5-pour beams is the most important function with the highest weight index as of 43% based on the criterion C1. So this also explains the results obtained on the basis of criterion C2, C3, C4. The sum of these weights determines the priority choice of the functions. The function of A5-pour beams is selected with the highest total weights index as186.66%. As shown in Table 8-5, this method provides significant data for decision making.

Table 8-4 Weight matrix for selecting the functions - Construction concrete foundation

ID	Weights	Functions	Criteria							
			Weight C1	P(C1/An)	Weight C2	P(C2/An)	Weight C3	P(C3/An)	Weight C4	P(C4/An)
			Initial cost	Profit in return			Reliability		Maintain-ability	
A1	15%	Layout building	4	34.0%	1	8.3%	7	58.3%	0	0.0%
A2	10%	Pour pies	5	31.3%	2	12.5%	6	37.5%	3	18.8%
A3	10%	Excavate warehouse	6	54.5%	1	9.1%	4	36.4%	0	0.0%
A4	20%	Pour pile	3	15.0%	4	20.0%	8	40.0%	5	25.0%
A5	45%	Pour beams	7	28.0%	6	24.0%	9	36.0%	3	12.0%

Table 8-5 Experiment results of Bayes' theorem - Construction concrete foundation

		P(C1/An)	P(An/C1)	P(C2/An)	P(An/C2)	P(C3/An)	P(An/C3)	P(C4/An)	P(An/C4)	Sum
P(A1)	15%	34%	17.41%	8%	6.61%	58%	22%	0%	0.00%	45.63%
P(A2)	10%	31%	10.58%	13%	6.89%	38%	9%	19%	15.45%	42.23%
P(A3)	10%	55%	18.77%	9%	4.96%	36%	9%	0%	0.00%	32.67%
P(A4)	20%	15%	10.24%	20%	22.04%	40%	20%	25%	40.65%	92.80%
P(A5)	45%	28%	43.00%	24%	59.50%	36%	40%	12%	43.90%	186.66%



P(C1/An) * P(An)	P(C2/An) * P(An)	P(C3/An) * P(An)	P(C4/An) * P(An)
5.1%	1.2%	8.7%	0%
3.1%	1.25%	3.75%	1.9%
5.5%	0.9%	3.6%	0%
3%	4%	8%	5%
12.6%	10.8%	16.2%	5.4%
$\sum$ P(C1)	$\sum$ P(C2)	$\sum$ P(C3)	$\sum$ P(C4)
29.3%	18.15%	40.25%	12.3%

A sample calculation:

$$P(A_1/C_1) = \frac{P(A_1) \bullet P(C_1/A_1)}{\sum P(C_1)}$$

$$= \frac{15\% \bullet 34\%}{29.3\%} = 17.41\%$$

Figure 8-5 Bayes' theorem and the revision of probabilities - Construction concrete foundation

Case 2. Construct concrete column

In this case, the construct concrete column project is studied. The analysis diagrams were established in Chapter 2. The basis of the calculation is the same as established in case 1, see chapter 8.2.2. The evaluation calculation is shown in the following tables and figures. As a result, A4 can be selected as the most important function for development.

Table 8-6 Weight matrix for selecting the functions - Construct concrete column

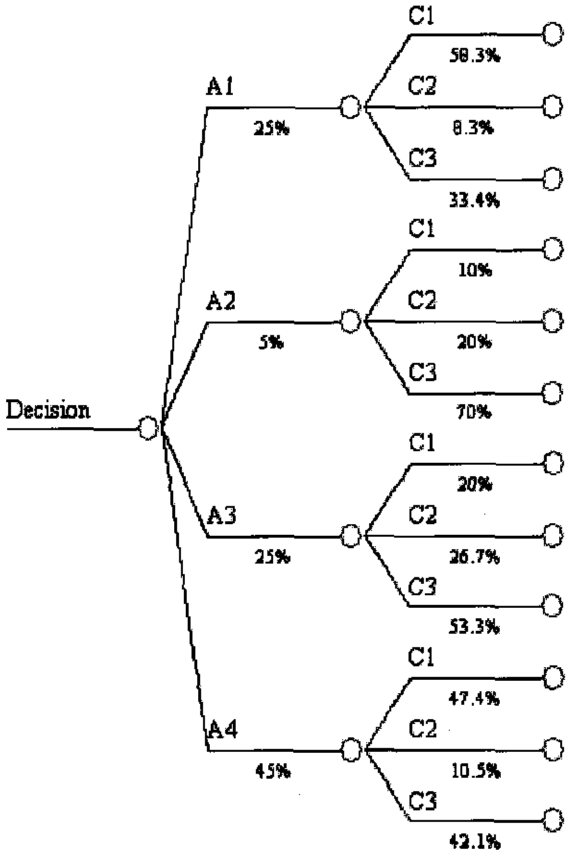
ID	Functions	C1	C2	C3
		Initial cost	Safety	Reliability
A1	Fabricate panels	7	1	4
A2	Erect panels	1	2	7
A3	Construct forms	3	4	8
A4	Cast concrete	9	2	8
	Sum	20	9	27

Table 8-7 Weight matrix for selecting the functions - Construct concrete column

ID	Weights	Functions	Criteria					
			Weight C1	P(C1/An)	Weight C2	P(C2/An)	Weight C3	P(C3/An)
			Initial cost		Safety		Reliability	
A1	25%	Fabricate panels	7	58.3%	1	8.3%	4	33.3%
A2	5%	Erect panels	1	10.0%	2	20.0%	7	70.0%
A3	25%	Construct forms	3	20.0%	4	26.7%	8	53.3%
A4	45%	Cast concrete	9	47.4%	2	10.5%	8	42.1%

Table 8-8 Experiment results of Bayes' theorem - Construct concrete column

		P(C1/An)	P(An/C1)	P(C2/An)	P(An/C2)	P(C3/An)	P(An/C3)	Sum
P(A1)	25%	58.30%	35.21%	8.3%	14.36%	33.3%	19%	68.47%
P(A2)	5%	10.0%	1.21%	20.0%	6.92%	70.0%	8%	16.08%
P(A3)	25%	20.0%	12.08%	26.7%	46.19%	53.3%	30%	88.53%
P(A4)	45%	47.4%	51.52%	10.5%	32.70%	42.1%	43%	127.25%



P(C1/An) * P(An)	P(C2/An) * P(An)	P(C3/An) * P(An)
14.6%	2.1%	8.35%
0.5%	1%	3.5%
5%	6.62%	13.3%
21.3%	4.73%	18.9%
$\sum$ P(C1)	$\sum$ P(C2)	$\sum$ P(C3)
41.4%	14.45%	44.03%

A sample calculation:

$$P(A_1 / C_1) = \frac{P(A_1) \bullet P(C_1 / A_1)}{\sum P(C_1)}$$

$$= \frac{25\% \bullet 58.3\%}{41.4\%} = 35.21\%$$

Figure 8-6 Bayes' theorem and the revision of probabilities - Construct concrete column

Case 3. Small gas station

In this case, the small gas station project is studied. The analysis diagrams were established in Chapter 3. The basis of the calculation is the same as established in case 1, see chapter 8.2.2. The evaluation calculation is shown in the following tables and figures. As a result, A5 can be selected as the most important function for development.

Table 8-9 Matrix for selecting the functions - Small gas station

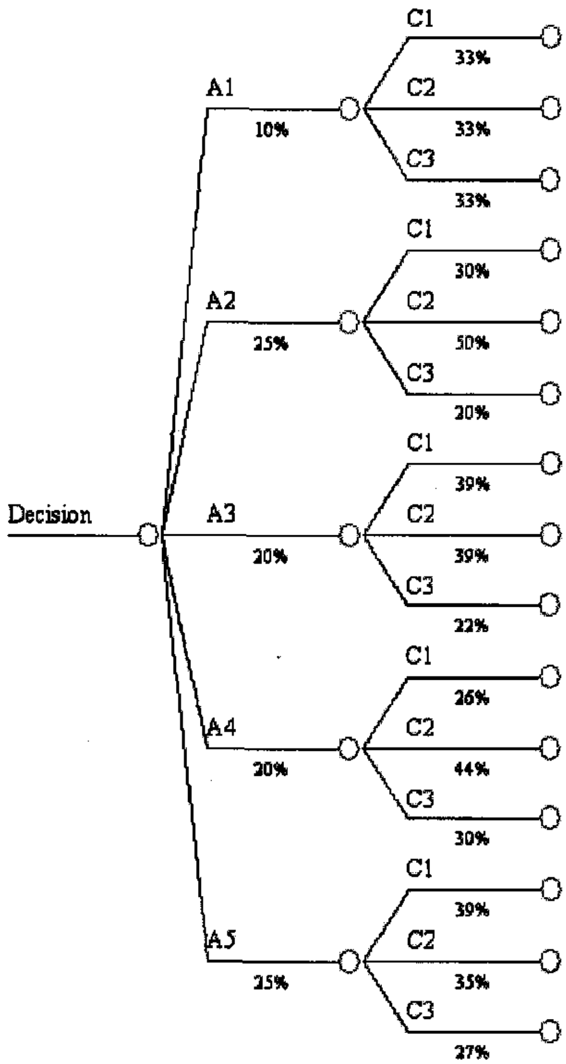
ID	Functions	C2	C3	C4
		Safety	Quality	Environment
A1	Obtain permits	1	1	1
A2	Excavate footers	3	5	2
A3	Pour slabs	7	7	4
A4	Install doors	6	10	7
A5	Construct roof	10	9	7

Table 8-10 Matrix for selecting the functions – Small gas station

ID	Weights	Functions	Criteria					
			Weight C1	P(C1/An)	Weight C2	P(C2/An)	Weight C3	P(C3/An)
			Safety		Quality		Environment	
A1	10%	Obtain permits	1	33.3%	1	33.3%	1	33.3%
A2	25%	Excavate footers	3	30.0%	5	50.0%	2	20.0%
A3	20%	Pour slabs	7	38.9%	7	38.9%	4	22.2%
A4	20%	Install doors	6	26.1%	10	43.5%	7	30.4%

Table 8-11 Experiment results of Bayes' theorem - Small gas station

		P(C1/An)	P(An/C1)	P(C2/An)	P(An/C2)	P(C3/An)	P(An/C3)	Sum
P(A1)	10%	33%	9.93%	33%	8.09%	33%	13%	31%
P(A2)	25%	30%	22.35%	50%	30.38%	20%	20%	72%
P(A3)	20%	39%	23.19%	39%	18.91%	22%	17%	60%
P(A4)	20%	26%	15.56%	44%	21.14%	30%	24%	61%
P(A5)	25%	39%	28.69%	35%	21.02%	27%	26%	76%



P (C1/An) * P(An)	P (C2/An) * P(An)	P (C3/An) * P(An)
3.3%		
	3.3%	
		3.3%
7.5%		
	12.5%	
		5%
7.8%		
	7.8%	
		4.4%
5.2%		
	8.8%	
		6%
9.75%		
	8.75%	
		6.75%
$\sum$ P(C1)	$\sum$ P(C2)	$\sum$ P(C3)
33.55%	41.15%	25.45%

A sample calculation:

$$P(A_1 / C_1) = \frac{P(A_1) \bullet P(C_1 / A_1)}{\sum P(C_1)}$$

$$= \frac{10\% \bullet 33\%}{33.55\%} = 9.93\%$$

Figure 8-7 Bayes' theorem and the revision of probabilities - Small gas station

Case 4. Pipe making process

In this case, the pipe making process project is studied. The analysis diagrams were established in Chapter 4. The basis of the calculation is the same as established in case 1, see chapter 8.2.2. The evaluation calculation is shown in the following tables and figures. As a result, A5 can be selected as the most important function for development.

Table 8-12 Weight Matrix for selecting the functions - Pipe making process

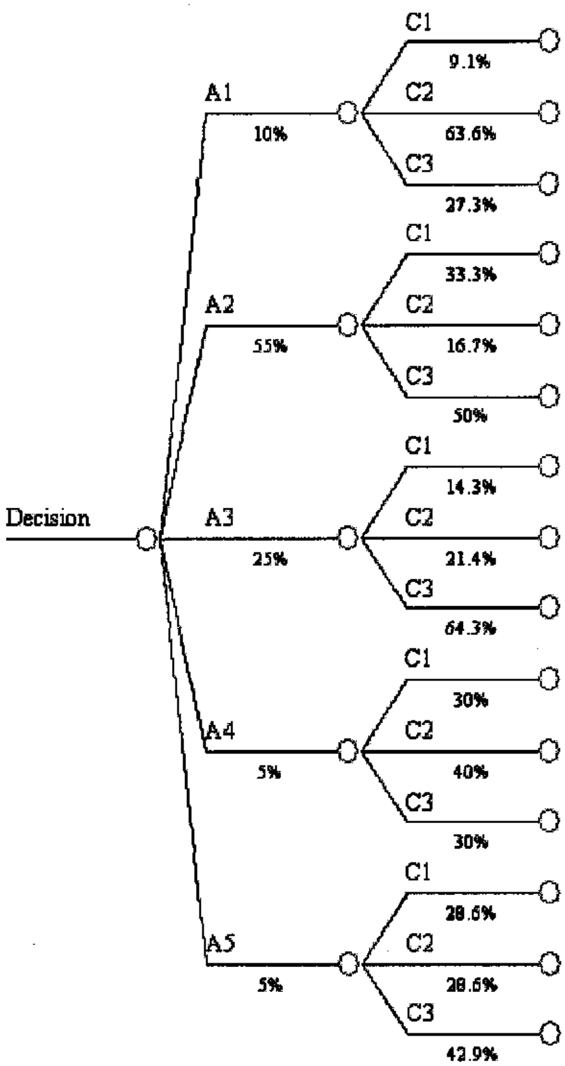
ID	Functions	C1	C2	C3
		Profit in return	Initial cost	Reliability
A1	Prepare material	1	7	3
A2	Make pipe	6	3	9
A3	Correct pipe	2	3	9
A4	Polish pipe	3	4	3
A5	Paint surface	2	2	3

Table 8-13 Weight Matrix for selecting the functions - Pipe making process

ID		Functions	Weight C1	P(C1/An)	Weight C2	P(C2/An)	Weight C3	P(C3/An)
			Profit in return		Initial cost		Reliability	
A1	10%	Prepare material	1	9.1%	7	63.6%	3	27.3%
A2	55%	Make pipe	6	33.3%	3	16.7%	9	50.0%
A3	25%	Correct pipe	2	14.3%	3	21.4%	9	64.3%
A4	5%	Polish pipe	3	30.0%	4	40.0%	3	30.0%
A5	5%	Paint surface	2	28.6%	2	28.6%	3	42.9%

Table 8-14 Experiment results of Bayes' theorem - Pipe making process

		P(C1/An)	P(An/C1)	P(C2/An)	P(An/C2)	P(C3/An)	P(An/C3)	Sum
P(A1)	10%	9%	3.53%	64%	26.28%	27%	5.46%	35.27%
P(A2)	25%	33%	32.27%	17%	17.25%	50%	25.00%	74.52%
P(A3)	20%	14%	11.09%	21%	17.69%	64%	25.72%	54.49%
P(A4)	20%	30%	23.26%	40%	33.06%	30%	12.00%	68.31%
P(A5)	25%	29%	27.71%	29%	29.55%	43%	21.45%	78.71%



P (C1/An) * P(An)	P (C2/An) * P(An)	P (C3/An) * P(An)
1%		
	6.36%	
		2.73%
18.3%		
	9.2%	
		27.5%
3.6%		
	5.35%	
		16.1%
1.5%		
	2%	
		1.5%
1.43%		
	1.43%	
		2.15%
$\sum$ P(C1)	$\sum$ P(C2)	$\sum$ P(C3)
25.8%	24.2%	50%

A sample calculation:

$$P(A_1/C_1)=\frac{P(A_1)\bullet P(C_1/A_1)}{\sum P(C_1)}$$

$$=\frac{10\%\bullet 9.1\%}{25.8\%}=3.53\%$$

Figure 8-8 Bayes' theorem and the revision of probabilities - Pipe making process

Case 5. Site preparation

In this case, the site preparation project is studied. The site preparation analysis diagrams were established in Chapter 4. The basis of the calculation is the same as established in case 1, see chapter 8.2.2. The evaluation calculation is shown in the following tables and figures. As a result, A4 can be selected as the most important function for development.

Table 8-15 Weight Matrix for selecting the functions - Site preparation

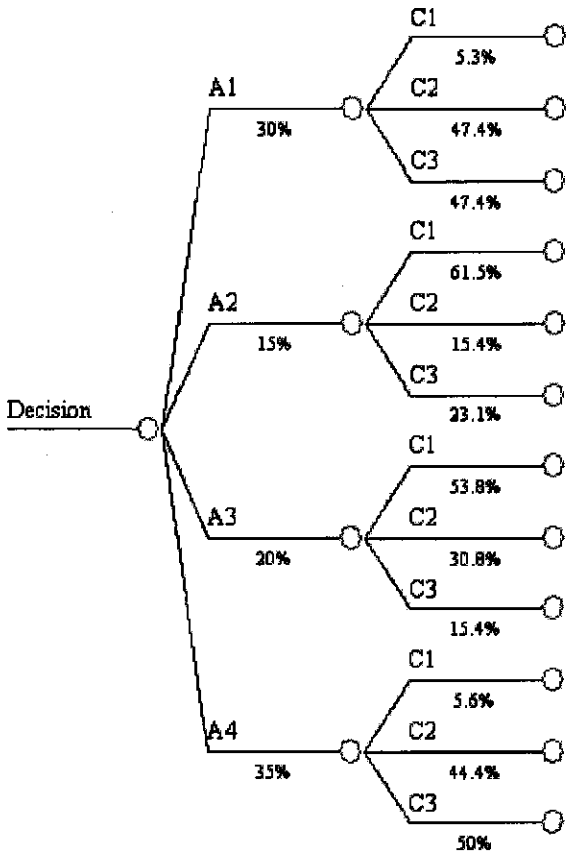
ID	Functions	C1	C2	C3
		Environment	Quality	Reliability
A1	Survey site	1	9	9
A2	Excavate trench	8	2	3
A3	Backfill earth	7	4	2
A4	Overhead line	1	8	9
	Sum	17	23	23

Table 8-16 Weight matrix for selecting the functions - Site preparation

ID	Weights	Functions	Criteria					
			Weight C1	P(C1/An)	Weight C2	P(C2/An)	Weight C3	P(C3/An)
			Environmnet		Quality		Reliability	
A1	30%	Survey site	1	5.3%	9	47.4%	9	47.4%
A2	15%	Excavate trench	8	61.5%	2	15.4%	3	23.1%
A3	20%	Backfill earth	7	53.8%	4	30.8%	2	15.4%
A4	35%	Overhead line	1	5.6%	8	44.4%	9	50.0%

Table 8-17 Experiment results of Bayes' theorem - Site preparation

		P(C1/An)	P(An/C1)	P(C2/An)	P(An/C2)	P(C3/An)	P(An/C3)	Sum
P(A1)	30%	5.30%	6.76%	47.4%	37.19%	47.4%	37%	81.14%
P(A2)	15%	61.5%	39.24%	15.4%	6.04%	23.1%	9%	54.34%
P(A3)	20%	53.8%	45.77%	30.8%	16.11%	15.4%	8%	69.93%
P(A4)	35%	5.6%	8.34%	44.4%	40.64%	50.0%	46%	94.74%



P (C1/An) * P(An)	P (C2/An) * P(An)	P (C3/An) * P(An)
1.59%		
	14.22%	
		14.22%
9.2%		
	2.31%	
		3.5%
10.76%		
	6.16%	
		3.08%
1.96%		
	15.54%	
		17.5%
$\sum$ P(C1)	$\sum$ P(C2)	$\sum$ P(C3)
23.51%	38.23%	38.24%

A sample calculation:

$$P(A_1 / C_1) = \frac{P(A_1) \bullet P(C_1 / A_1)}{\sum P(C_1)}$$

$$= \frac{30\% \bullet 5.3\%}{23.51\%} = 6.76\%$$

Figure 8-9 Bayes' theorem and the revision of probabilities - Site preparation

8.3. Discussion & Selection Analysis

There are many functions to be evaluated and selected for development in a VE study. Bayes' theorem provides a technique to make the selection decision based on a mathematical calculation.

In many situations, the weights are assigned to functions on the basis of whatever information provided about their likelihoods at the time. However, the later additional information will force the earlier appraisals to be revised. Sometimes something will cause even higher probabilities to be assigned to an event that is already considered very likely to happen; at another time, a probability of zero may be assigned to an event which was reasonably sure to happen. For instance, the weight or the importance of function A1-layout building was weighted as 15% by the engineers at an earlier time; however, it was weighted as P (A1/C1) of 17.41% after being revised on the basis of additional information of criterion C1-initial cost.

Furthermore, additional information such as P (C1/A1) limited the situation into more details in order to narrow the scope of analysis. Thus, the evaluation process may focus on a certain area and be preformed efficiently under a certain circumstance. As discussed in the case study, if the function A5-pour beams is going to be selected for development, the criterion C1 could be the first or only concentration with the largest weight index.

Apparently, Bayes' rule supports the reasoning from both effect to cause and cause to effect. It can be observed that there is a cause and effect relationship between the functions and the criteria. Bayes' theorem makes the situation easier to be analyzed.

Nevertheless, the result can not be more accurate when it comes from the mathematical calculation than from any other estimation or prediction.

Moreover, Bayes' theorem can be used in both a priori analysis and a posteriori analysis. It encourages multiple considerations in decision-making and provides different views. A posteriori probabilities also permit us to calculate the reversed probability once subsequent information becomes known.

Finally, the selection can be established on the basis of the given function or given criteria depending on individual needs. For instance, function A1 can be selected as the most important function for development based on given criteria C1. On the other hand, C1 will be selected to be concentrated with the largest weight on the basis of the function A1. Bayes' theorem provides significant data for making a decision.

CHAPTER 9. SYNTHESIS OF MATHEMATICAL RESULTS FROM PART II

The calculation results of the four mathematical technologies are listed in the following. The rank order indicates the priorities of the choices, enabling the function selection decision to be made according to the lowest sum of ranks.

The main purpose of the mathematical analysis is to determine the functions that are valid candidates for development. Each mathematical method produces a different answer. The question then arises as to which method is most reliable. However, given that all methods used have a valid basis, and are mathematically and functionally sound, it becomes difficult to eliminate any one particular method. Therefore, a comprehensive approach is adopted wherein all the mathematical methods are incorporated and used toward the final decision making.

Table 9-1 Rank order of functions that are candidates for a VE study - Construction concrete foundation

Case #1	Bayes' theorem	Payoff Matrix	AHP	Matrix analysis	$\sum$ Rank
Function A1	3	3	3	3	12
Function A2	4	4	5	4	17
Function A3	5	5	1	5	16
Function A4	2	2	2	2	8
Function A5	1	1	4	1	7
Discussion	The final decision can be made by adding the ranks from each method. Therefore, A5 is adjusted the most important function for development. The rank order of priorities of functions selected for development is A5, A4, A1, A3, A2.				

Table 9-2 Rank order of functions that are candidates for a VE study - Construction concrete column

Case #2	Bayes' theorem	Payoff Matrix	AHP	Matrix analysis	$\sum$ Rank
Function A1	3	3	2	3	11
Function A2	4	4	1	4	13
Function A3	2	2	3	2	9
Function A4	1	1	4	1	7
Discussion	The final decision can be made by adding the ranks from each method. Therefore, A4 is adjusted the most important function for development. The rank order of priorities of functions selected for development is A4, A3, A1, A2.				

Table 9-3 Rank order of functions that are candidates for a VE study – Small gas station

Case #3	Bayes' theorem	Payoff Matrix	AHP	Matrix analysis	$\sum$ Rank
Function A1	2	5	1	5	13
Function A2	5	4	2	4	15
Function A3	4	3	3	3	13
Function A4	3	2	4	2	11
Function A5	1	1	5	1	8
Discussion	The final decision can be made by adding the ranks from each method. Therefore, A5 is adjusted the most important function for development. The rank order of priorities of functions selected for development is A5, A4, A1 and A3, A2.				

Table 9-4 Rank order of functions that are candidates for a VE study – Pipe making process

Case #4	Bayes' theorem	Payoff Matrix	AHP	Matrix analysis	$\sum$ Rank
Function A1	5	3	3	3	14
Function A2	2	1	5	1	9
Function A3	4	2	4	2	12
Function A4	3	4	2	4	13
Function A5	1	5	1	5	12
Discussion	*The final decision can be made by adding the ranks from each method. Therefore,* A2 is adjusted the most important function for development. The rank order of priorities of functions selected for development is A2, A5 and A3, A4, A1.				

Table 9-5 Rank order of functions that are candidates for a VE study – Site preparation

Case #5	Bayes' theorem	Payoff Matrix	AHP	Matrix analysis	$\sum$ Rank
Function A1	2	1	3	1	7
Function A2	4	3	1	4	12
Function A3	3	4	1	3	11
Function A4	1	2	2	2	7
Discussion	The final decision can be made by adding the ranks from each method. Therefore, A1and A4 are adjusted the most important function for development. The rank order of priorities of functions selected for development is A1 and A4, A3, A2.				

CHAPTER 10. FINDINGS

10.1. Part I: FAST diagram, CPM, and cause-effect diagram

It has been discovered that it is possible to derive a CPM or a cause-effect diagram from the *FAST diagram*. The procedure is reasonable and logical. The relationship of the activities established by CPM diagram or cause-effect diagram is described effectively on the FAST diagram.

Next, the FAST diagram and cause-effect diagram can be derived from *CPM diagram*. The FAST diagram effectively explains the relationship of the activities that is on the CPM diagram. The cause-effect diagram accurately represents the sequence of given work in a CPM.

The process of developing the FAST diagram and CPM diagram from *cause-effect diagram* was conducted logically. It has been shown that the FAST diagram contributes equally as the cause-effect technique. CPM diagram and cause-effect diagram both show the sequence of the work.

Importantly, it was discovered that the FAST diagram is the exact inverse of the CPM diagram, and vice versa. Thus, the "how" question is answered in the CPM from right to left, while the "why" question is answered from left to right. No one seems to have discovered this simple connection over fifty years of value engineering, even though both FAST and CPM have been very widely used and continue to be in common use. There is simply no mention of this interrelationship anywhere in any book or proceedings. To the contrary, VE experts only state – at seminars and workshops – that CPM and FAST have no relation to each other (Kaufmann, 2002; Brezenski; 2002; Parker, 2002)

Therefore, FAST, CPM, and cause-effect diagrams can be represented inter alia. The common understanding in the VE industry that these techniques can not be derived one from another is shown through this study to be false.

10.2. Part II: Discussion on mathematical decision methodology

The whole purpose of the scientific and mathematical method was to obtain a comprehensive decision on selecting suitable functions for development during a VE study. It was discovered that all four mathematical techniques – Pair wise comparisons, AHP, Payoff Matrix, and Bayes' theorem – were able to be satisfactorily utilized in arriving at decisions. The final results are meaningful and fulfill the aims of this study. A short summary of each of the four methods follows.

1) Matrix analysis – pair wise comparisons & satisfaction factors - method

The criteria were weighted in the first stage of the matrix analysis method. The impact of the criteria to the functions was determined. Next, the matrix analysis method was applied on the basis of the evaluated criteria.

As a result, an improved evaluation is received from the two stages: evaluating criteria of functions through pair wise comparisons, and then evaluating functions by satisfaction factors. The accuracy upon the outcome ensures that the ideas or functions receive a better evaluation.

2) AHP

The three steps of AHP provide a systematical method in function selecting decision-making. The first step of structuring the hierarchy simplifies the relationship of activities of a project between higher and lower levels of the hierarchy.

Next, the priorities selection of the functions is determined by allocating weights and going through the calculation methods recommended by Saaty.

In the last step, the logical checking of the consistency of the judgments increases the accuracy of the result. It helps to avoid errors occurring during the decision making process.

3) Payoff matrix

Decisions can be made quickly on the basis of Maximum of the maximum payoff values, and the minimum of the maximum regret calculation. In addition, the weight of each factor in the analysis process is considered during the computation of the expected monetary value and the expected opportunity loss.

The payoff matrix method is a set of efficient decision-making methods. It can be used for decision-making in simple and complicated cases, or when there is a time constraint for making decisions.

4) Bayes' theorem

Bayes' theorem is a complex technique to make the selection decision. The weights are assigned to functions on the basis of whatever information is provided at the time. However, the later additional information will force the earlier appraisals to be revised. The later information limits the situation into more details in order to narrow the scope of analysis. Thus, the evaluation process may focus on certain function and be preformed efficiently under the certain circumstance. In practical, through the project study, VE team assigns the weights to the functions of the project. These weights assigned are based on VE team member's knowledge and experiences. Each member's opinion might be different; however, the common agreement can be achieved through the team work.

Therefore, the weights used in Bayes' calculation have the absolutely practical meaning for a project.

In addition, the Bayes' theorem supports the reasoning from both "effect to cause" and "cause to effect". It makes the situation easier to be analyzed and calculated by establishing the decision tree.

Bayes' theorem can be used in both 'a priori' and 'a posteriori' analysis. A posteriori probabilities permit us to calculate the reversed probability once subsequent information becomes known. The decision to select functions for development can be established on the basis of the given function or given criteria depending on individual needs.

In short, the use of the matrix analysis method is to ensure the correction of the decision-making process by weighting the criteria first then analyzing the elements next based on the former weighting result, thereby, improving the accuracy of the result. The application of the AHP method established the priority choices on the basis of the consistency consideration of the problem. Further, payoff matrix method is a calculation of a decision-making effort. The Bayes' theorem provides a technique to ensure the correction for the decision-making process by revising the earlier appraisals according to the additional information. Therefore, all four methods applied together enhance the decision making quality in VE study.

10.3. Observations

1) We observed that Payoff & Matrix analysis give identical results in most cases; Bayes' deviates slightly; while AHP gives significantly different results.

Case #1, The results from Bayes' theorem, Payoff matrix, and Matrix analysis are the same. The result from AHP is different.

Case #2, The results from Bayes' theorem, Payoff matrix, and Matrix analysis are the same. The result from AHP is different.

Case #3, The results from Payoff matrix and Matrix analysis are the same. The result from Bayes' theorem deviates slightly. The result from AHP is different.

Case #4, The results from Payoff matrix and Matrix analysis are the same. The results from Bayes' theorem and AHP are different.

Case #5, The results from Payoff matrix and Matrix analysis are close. The results from Bayes' theorem and AHP are different.

Form this observation, Payoff & Matrix analysis are identical in 80% of the cases.

2) The results in Bayes' theorem are sensitive to the input weights assigned. Thus, the likelihood of a function being selected for development is proportional to the initial weight assigned to it.

3) Weights are assigned to functions only in Bayes' theorem, not in others.

4) A posteriori probabilities permit us to calculate the revised probability once subsequent information (outcomes) becomes known. Therefore, we use Bayes' theorem to obtain accurate results. It is meaningful when we know an outcome and wish to determine what the likely cause of that outcome is.

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