LIFE CYCLE APPROACH TO BRIDGE DESIGN

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Industrial Engineering and Operations Research

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May 1988

Blacksburg, Virginia

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(ABSTRACT)

This thesis deals with the application of the Life Cycle concept to the design of bridges. Its focus is on methodology rather than on any particular application, with emphasis on the preliminary design stage.

With the help of conceptual equations for the construction, maintenance, and vehicle delay costs, a procedure for making decisions at the preliminary design stage is presented. Decisions are made on the basis of minimum present equivalent total cost and include the number of lanes to be provided, the span between piers, and the design alternative (type of bridge) to be adopted for detail design. Minimization is done by a total enumeration procedure.

Sensitivity of the decisions with respect to the interest rate and the study period is analyzed, and design decision reversals are noted. This includes a joint sensitivity analysis with respect to these design independent parameters. Limited analysis of errors in cost estimating equations is also performed.

A FORTRAN code, implementable on mainframe and personal computers is developed to aid calculations.

Acknowledgements

This thesis is dedicated to my parents, and my sister and brother-in-law, whose love and support have been a constant source of encouragement.

To Dr. Wolter J. Fabrycky, my advisor, my sincere thanks and deepest gratitude for everything. The experience of working with him shall remain as one of my cherished memories.

I am grateful to Dr. Y. J. Beliveau and Dr. H. J. Freeman for their advice and willingness to dedicate their time and efforts towards my research. I also thank them for having served on my committee.

Seldom has a person been as fortunate as I, in friends. My thanks to all of them for their support. Finally, I would be remiss in not thanking Almighty GOD for everything.

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1.0 INTRODUCTION

People have been designing products, systems, and structures to meet their needs since the beginning of civilization. With the progress of civilization, these systems have become more and more complex. There have also been considerable advances in the design techniques used to bring these systems into being. This is particularly true of the past two or three decades.

More and better tools are available to a designer to aid in the design process. With techniques like CAD and CAM, it is possible to produce good designs with reduced effort and time. Unfortunately these techniques have not been used to their full potential. Application of these methods has not resulted in better overall design of systems. There is room for improvement in the design process. Techniques like CAD and CAM, if properly incorporated, can result in truly optimized design.

A systems approach is needed for better design of systems. In this particular study, the application of the Life Cycle concept to the design of bridges is considered.

1.1 DESIGN AND CONSTRUCTION OF BRIDGES

Humans have been building bridges since time immemorial. There is evidence to show that all ancient cultures have built structures across bodies of water. The study of bridge building over the years is interesting in itself.

The earliest bridges were wooden logs placed across streams and brooks. Sometimes granite slabs were also used as piers and slabs. With the progress of time, other types of bridges began to evolve.

The first type was the suspension bridge. Twisted vines served as cables which were fastened to trees. Such bridges were common in China, India, Japan, and South America. Later, iron chains were used as cables. The span length of these bridges was limited due to lack of stronger building materials.

Cantilever spans were also among the earliest forms to be developed. Being of a more complex form than the suspension type bridge, these evolved later. The Egyptians and the Greeks are believed to have been the first to use this concept. But cantilever bridges became popular much later, with the development of the concept of trusses and the use of iron and steel as construction materials.

Romans, who were among the greatest of the bridge engineers of the past, perfected the masonry arch. Though the Egyptians and the Indians knew of the masonry arch, it was the Romans who used it extensively.

Even later were the pontoon bridges. These had to wait for the development of good navigation. Their application was primarily in the military. Alexander the Great is supposed to have used them extensively in his campaigns.

It is interesting to note that though there were dramatic improvements in the design of superstructures, the design and construction of substructures remained largely unchanged. In fact, the substructures were never as sophisticated as the superstructure.

With the decline of the Roman empire, bridge construction became dormant. No significant developments took place until the sixteenth century, when trusses were invented. This was a remarkable breakthrough in the field of bridge engineering. From this point onwards the field of bridge engineering grew rapidly. Though not a science until the beginning of this century, design and construction were carried out with a lot of planning and forethought.

In the present century, bridge engineering has developed into a very advanced and sophisticated field. The tools and techniques of analysis are much superior than at any time in the past. Design techniques have also kept pace with the advances in analysis. The most significant contribution to this process has been that of computers. Computer aided design is a very powerful tool and has immense potential.

At this juncture, one might be tempted to think that the only improvement possible is in the form of further refinements of these techniques. While this may be true for the detail design stage, it is certainly not true of the overall design process. More efficient approaches to the design process are possible. The Life Cycle approach is suggested in this thesis as a means to achieve good designs.

Designers in general concentrate on detail design. Usually, this results in the consideration of one particular design, without much thought being given to various other design alternatives. As a result, many other feasible systems that might meet the requirements more efficiently are rejected (by default).

Thus, there is room for improvement in the design process. A design approach that seeks the best possible solution to a need is required. Such an approach needs to go beyond the process of CAD and CAM. All the costs and benefits occurring over the entire Life Cycle should be taken into consideration in such an integrated process.

The Life Cycle approach suggested in this study is almost universal in it's application. A vast area of application is available in the various engineering disciplines. It's application to the area of bridge design forms the topic of this thesis.

1.2 MOTIVATION FOR THIS STUDY

In the field of bridge design, the problem of determining the economic span between piers is very important. A non-optimal span can result in costly and inefficient designs. Still it is a matter of surprise that there is no procedure for finding the optimal span length that takes into account all the relevant factors.

The problem of economic span length was considered as early as 1890. It was suggested by J. A. L. Waddell that, "For any crossing, the greatest economy occurs when the cost per lineal foot of the substructure is equal to the cost per lineal foot of the trusses and lateral systems"[15]. The assumption made was that the cost of piers and abutments is directly proportional to n, the number of spans[1].

Consider the problem of determining the optimal span between piers for a 1,550 foot steel bridge. Steel costs 9 cents per pound. Weight W of the superstructure (in pounds) is given by the formula $W = 9.25 L^2 + 150 L$, where L is the length of the span in feet. A pier costs $15,500.

Let n be the number of spans. Then (n + 1) is the number of piers needed. The total first cost of the bridge is

$$C = 0.09 W + (15{,}500)(n + 1).$$

This gives

$$C = 0.09 (9.25 L^2 + 150L) + 15{,}500 (n + 1).$$

But

$$n = \frac{1{,}550}{L}.$$

So

$$n + 1 = \frac{L + 1{,}550}{L}.$$

Which gives

$$C = 0.09 (9.25 L^2 + 150 L) + \frac{15{,}500}{L} (L + 1{,}550).$$

---

[1] Subsequent studies have shown this to be incorrect, the correct value being n + 1.

For minimum cost

$$\frac{dC}{dL} = 0.18x9.25xL + 0.09x150 - \frac{15{,}500^2}{10L^2} = 0.$$

Solving for L gives

L = 241 feet or 6 spans.

The preceding example from the New York State Professional Engineers examination of 1944, adapted from Taylor [13], clearly illustrates the point that the cost of piers and abutments are directly proportional to n + 1, and not n. Such an analysis could be extended to cover the comparison of two competing designs. As an illustration, two designs for a pedestrian bridge are compared. The first will result in the weight of superstructure per foot to be $W_1 = 22(S) + 800$. S is the span between piers of the bridge. Similarly for the second design, we have $W_2 = 20(S) + 1000$. The piers (regardless of the design selected) are expected to cost $ 220,000 each. Cost of erecting superstructure is $0.22 per pound. Length of the bridge is 1,200 feet. All other costs are assumed to be the same.

Total cost of superstructure and piers for the first design is

$$TC_1 = [\ 22(S) + 800\ ](\ 0.22\ )(\ 1{,}200\ ) + 220{,}000\ (\ \frac{1{,}200}{S} + 1\ )$$

$$TC_1 = 5{,}808\ (\ S\ ) + \frac{264{,}000{,}000}{S} + 431{,}200.$$

Similarly, for the second design

$$TC_2 = 5{,}280\,(S) + \frac{264{,}000{,}000}{S} + 484{,}000.$$

For minimum first cost

$$\frac{dTC}{dS} = 0.$$

This gives S = 213 feet at a cost of $2,908,000 for the first design, and S = 224 feet at a cost of $2,846,000 for the second design. As the number of spans has to be a number divisible into 1200, the best solution is S = 200 feet at a cost of $2,912,800 for the first design, and S = 240 feet at a cost of $2,851,200 for the second design. On the basis of lower cost alone, the second design is chosen.

This second example from Thuesen and Fabrycky [14], is a more comprehensive treatment of the problem in that multiple alternatives are considered. But it can be criticized (as Waddell's findings were) on the grounds that the costs occurring in the future, like maintenance costs, were not taken into consideration.

Waddell attempted to treat the problem in a more refined manner in his later book on economics of bridgework [16]. The refinements were in terms of different types of bridges being considered. No attempt was made to include all the costs occurring over the life of the bridge.

Scant attention has been paid to the problem of optimal span between piers since then. It finds it's way into Engineering Economy and Operations Research textbooks, in the given incomplete form. And even in it's incomplete form, the treatment is perfunctory.

This was the starting point for the present study. In addition to the span between piers, the width of the bridge was also incorporated in the study. Optimization is sought over these two variables. Incorporation of the costs occurring over the entire Life Cycle of the bridge is also sought. A more comprehensive approach to the entire bridge design process is thus attempted.

1.3 ORGANIZATION OF THE THESIS

The study advocates the Life Cycle approach to bridge design. The area of emphasis is the preliminary design stage. Required background material is presented before the actual definition and solution of the problem.

Chapter 2 reviews the existing literature on the subject. A general approach to the design of systems is discussed in Chapter 3. The problem is defined in Chapter 4, and the conceptual cost estimating equations are presented. Chapter 5 deals with the solution of the problem. Sensitivity analysis with respect to the interest rate, and the study period, and a limited error analysis is also performed. Summary of the results obtained, and areas of further research are the topics of discussion for Chapter 6. The FORTRAN code developed to aid calculations, and examples of computations can be found in the appendix.

2.0 LITERATURE REVIEW

The literature surveyed for this thesis falls into two categories; literature pertaining directly to the economic aspects of the design of bridges and literature concerning the systems approach to design in general.

Under the first category, literature was sought in the field of economics of bridge design and its application in achieving good designs. The methodology of design and the role of Life Cycle costs in the design process was of particular interest.

As mentioned in the previous chapter, it is a matter of considerable surprise that not much work has been done towards an integrated approach to the design of bridges. The pioneering work in this field was done by Waddell [16]. Waddell was a practicing bridge engineer of repute and his book is based on considerable experience in this field. The book emphasizes the critical role of engineering economics in all aspects of bridge design. Various types of bridges and their comparative economics are considered.

The problem of optimal span lengths of various types of bridges is also considered in some detail. Waddell was one of the earliest to recognize the importance of optimal span length of bridges. The book covers almost all facets of bridge engineering from the economic viewpoint, including a treatment of material and labor costs and the costs of repair and maintenance. Another important topic covered in the book (perhaps more important than optimal span length) is the impact of the costs occurring in the future on the design of bridges.

However, Waddell does not suggest any kind of approach that incorporates all these factors into the design process or philosophy. The accent is on economy at the detailed design stage and not at the conceptual or preliminary design stage. The book is still very valuable as a first attempt to include the economic aspects of bridge design in the design process and for the wealth of information on various facets of design.

A limited post design analysis of costs involved in a bridge design is available in the work of Canete [3]. Though only one chapter is devoted to a cost comparison of bridges, some important issues are mentioned in his analysis. Some of these are the impact of geographical location on the the cost of materials, the effect of location on the maintenance costs, and the type of structure. The analysis though seems to have been done more as an afterthought.

The basic formulation used in this thesis was adapted from one aspect of a research project funded by the Virginia Center for Innovative Technology [9]. The project report contains the Life Cycle approach to bridge design. A computer program to calculate the total costs was provided.

There seems to be no other material that deals with the economics of bridge design in any kind of detail. Periodicals, and handbooks for arriving at detailed estimates of costs are available in large numbers [8, 12]. But these give detailed estimates of the costs of the component parts of a bridge. These necessarily require the detail design to be available and are not directly relevant to a systems approach to bridge design, except as a verification of the estimates made in the initial stages.

Comparatively more material is available in the field of application of Life Cycle costing to the construction industry in general. Dell'Isola [5], and Kirk and Dell'Isola [6], are two good references. But the approach suggested is rather general in nature. Other related fields like traffic engineering, transportation, transportation engineering and planning, and transportation economics were also surveyed with none of the subjects addressing the issue even in an indirect manner.

In the second category of literature surveyed, the amount of information available is quite large. The most comprehensive treatment is to be found in Blanchard and Fabrycky [1]. The processes of bringing systems into being and improving already existing systems is discussed in detail with the aid of a large number of examples and case studies. The Life Cycle concept is emphasized throughout the book as being an integral part of the design process.

In conclusion, one finds that the literature seems to be concentrated on the detailed design aspect of the design process. Conceptual and preliminary design stages and their related economic aspects are almost totally ignored. Even when they are mentioned, the treatment is superficial and leaves much to be desired in most cases.

Such an attitude seems to dominate the practitioners too. There seems to be a "mindset" on this matter. A new line of thinking incorporating all the activities in the Life Cycle needs to be ushered in. Such an approach has immense potential and research in this matter should be actively pursued.

3.0 THE DESIGN PROCESS

Over the years considerable work has been done in the areas of detail design and analysis of systems. This has resulted in excessive emphasis on detail design in the overall design process. A systems approach to design, taking into account all the parameters and variables occurring over the entire Life Cycle of the system (or product), is unfortunately, more an exception than the rule. Ideally the design process should commence right from the time that a need for a product (or utility) is perceived. Such a concept is of increasing concern in present times, with costs spiralling in a seemingly endless manner. Of late, such a "big picture" approach is beginning to be appreciated.

As mentioned, the Life Cycle approach seeks to ensure the best solution to a need. Such an approach aims to integrate CAD and CAM to the Life Cycle process and thus extend the conventional definition of CAD and CAM. This will necessarily mean that the focus will be on a systems approach.

Effectiveness function and Life Cycle concepts are now presented.

3.1 EFFECTIVENESS FUNCTION

Any system should have some measure by which it's effectiveness is evaluated. Such a measure was first suggested by Churchman, Ackoff, and Arnoff [4]. It was defined as

$$E = f(X_i, Y_i)$$

where E represents the effectiveness of the system, X_i is the set of variables of the system, which are subject to control, and Y_i is the set of variables which are not subject to control.

For systems that need to be optimized under given constraints, the effectiveness function can be written with the appropriate constraints [11]. The constraints can be expressed as a function of the controllable and uncontrollable variables, and a set of constraint constants, B as

$$E = f(X_i, Y_i)$$

subject to

$$g(X_i, Y_i) = B$$

where the equality may also be $\geq$ or $\leq$.

A form of the effectiveness function applicable for design has been suggested by Fabrycky, et al. [10]. It is defined as:

$$E = f(D, X_i, X_d, Y)$$

where X_i is the set of parameters not under the control of the the designer. These are also referred to as the design independent parameters. X_d is the set of parameters under the control of the designer, the design dependent parameters. Y is the set of variables over which the optimal system design is sought. D is the demand or need to be met by the system which is being designed. Such an enhanced function is complete and more suited to a systems approach to design.

It is comparatively more easy to identify the demand and system variables than the identification of and classification of system parameters as independent or dependent. Parameters initially assumed to be independent may turn out to be dependent and vice versa. As a very rough "rule of thumb", one can assume that the parameters which are common among the set of system design alternatives are independent. For example, in the evaluation of different designs of cross sections of a copper conductor, the resistivity of copper can be assumed to be a system independent parameter. On the other hand, if the design comparison is expanded to include other materials like aluminum, then the resistivity of copper will be a system dependent parameter.

3.2 SYSTEM LIFE CYCLE[2]

All systems (or products) may have utility. Utility is defined as the power or ability to satisfy wants or needs. Hence systems (or products) are designed with the aim

[2] Most of this section is adapted from Blanchard and Fabrycky [1].

of providing some form of utility and fulfilling certain needs. This is rather obvious in the case of tangible things like a house or a car. It is not apparent for intangible things like pleasure derived from music, relationships, etc., though the concept is equally valid.

Utilities are created by altering the physical environment. The means of alteration is the basic concern of the engineering profession. The underlying principle guiding the engineering of new products (or systems) to satisfy needs is the concept of system Life Cycle.

Broadly, the Life Cycle starts with the identification of the need and ends with phase-out of the system that was designed to satisfy the need. Between the two end points, the system passes through several intermediate stages, which are of crucial importance from the viewpoint of good design. These stages are illustrated in Figure 1.

The two major intermediate phases are the acquisition phase and the operation phase.

3.2.1 ACQUISITION PHASE

The acquisition phase consists of conceptual design, preliminary design, detail design, and construction stages.

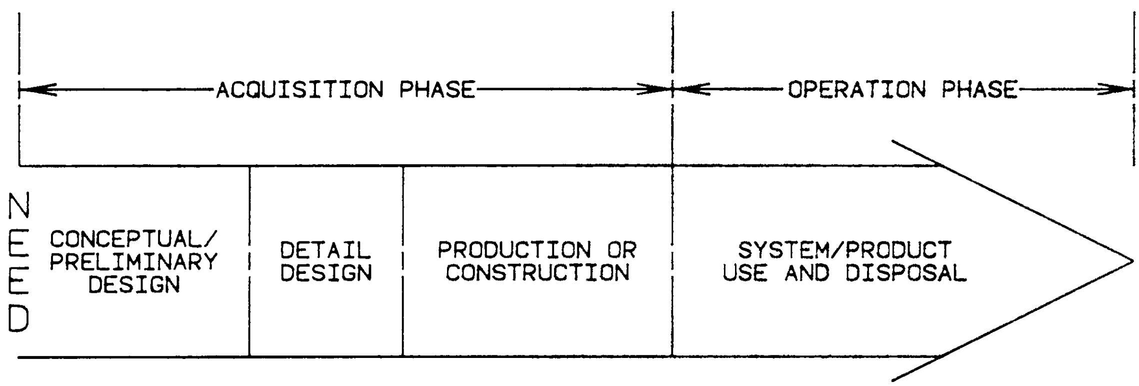

Figure 1. System Life Cycle.

CONCEPTUAL DESIGN

This is the first step in the system Life Cycle approach. It is initiated by the analysis of needs. The want or need for the system arises out of a perception of some kind of deficiency. Based on this perception, the function to be served by the system is defined.

The next step is the analysis of the feasibility of the system in the form of a feasibility study. The amount of detail that goes into the study depends upon the nature and complexity of the perceived need. In general, the following must be taken into consideration:

1. Definition and evaluation of the operational requirements of the system.
2. Discussion of the system maintenance concept.
3. Any other requirement(s) not covered by the above, which might be unique to the system.

The output from such an analysis can be thought of as a "Go/No Go" decision. If a decision is taken to go ahead with the system, then the results at this stage serve as guidelines for the entire design process. A decision not to go ahead may also be taken at this point, because of various factors identified during the feasibility study. The most common reasons are lack of resources and/or technology.

PRELIMINARY SYSTEM DESIGN

The results of the conceptual design stage are used as inputs to the preliminary design stage. The system requirements specified in the conceptual design stage are used to establish design requirements.

At this stage a functional approach which incorporates the functional description of the system and its operation is useful. Development of functional flow diagrams are helpful at this stage. The functional analysis should include both the operation and maintenance requirements in the form of operational and maintenance functions.

The completion of functional analysis leads to requirements allocation. This involves apportioning the top level requirements to the lower levels of the system. This is done with the objective of providing guidelines to the designer at each of the lower levels. These guidelines include various parameters, functional requirements, constraints, etc. This is a very important step. Without such an allocation, the different elements of the system may be designed (by the individual designers) with their own set of guidelines which, when combined, may not meet the requirements established for the whole system. The lower level requirements should be periodically monitored for compliance, during the progress of the design.

With the completion of the resource allocation phase, the designer may have several possible configurations to choose from. The best alternative has to be selected from the available alternatives. The evaluation of the best alternative on an equivalent basis has to be done with the help of evaluative criteria (which should be established by the designer). Often an effectiveness function is defined for the purposes of evaluation.

The final step in the preliminary design stage is the synthesis of all the elements considered so far. After synthesis, all the requirements for the detail design of the system should be available.

DETAIL DESIGN AND CONSTRUCTION

With the overall system configuration being identified, detail design commences. Further definition and description leading to the realization of the design needs to be done. This should include :

1. Detailed description of all the subsystems.
2. Detail drawings and specifications of all the elements in the system.
3. Development of prototype and its testing and evaluation.
4. Redesign and testing, if necessary.

During the detail design stage, the specifications and results obtained during the conceptual and preliminary design stage should be borne in mind. All activities at this stage should be in accordance with the previous two stages.

3.2.2 OPERATION PHASE

With the completion of detailed design and construction of the system, the acquisition phase comes to an end. The system now enters the operation phase. At this stage its working has to be analyzed and evaluated. This serves as feedback to the designer and helps him/her in the design of better systems in the future. The value of such feedback should not be underestimated. Any rectifiable drawbacks or deficiencies are also set right at this stage.

The system is of course phased out (discarded or replaced) after its economic life is over. Note that the economic life may be different from the physical life. The phasing out, however, should be done at the end of the economic life.

4.0 PROBLEM DEFINITION

In the approach suggested for the design of a bridge, we take into account the entire Life Cycle of the bridge. This study concentrates on the preliminary design stage. It aims to illustrate concepts rather than solve a specific problem of design.

4.1 SCOPE OF THE PROBLEM

It is assumed that the conceptual design stage has been completed with the following results:

1. The "needs" analysis for a crossing has been done.
2. Construction of a bridge has been preferred over other alternatives like tunnels and viaducts.
3. Based on the hydrographic and traffic surveys the exact location of the crossing has been determined.

In effect, the scope of the problem is the preliminary design stage. "Scoping" of the problem at each stage of the Life Cycle is very important. Not doing so can result in the consideration of problems not within the purview of the given design stage, and the omission of problems that should be considered, leading to inefficient and poor designs. Hence, it is very important to define the boundaries of the problem to be considered at each stage.

4.2 PROBLEM STATEMENT

In the preliminary design stage, decisions regarding the width to be provided and the span between piers has to be made. Thus the design variables considered in this problem are the span between the piers, and the width to be provided. Naturally the width will determine the number of lanes to be provided. The objective or effectiveness function is the present equivalent total cost of the bridge. Decisions are made on the basis of the present equivalent total cost, which is a function of the design variables, and the design dependent and the design independent parameters. Thus, the value of the design variables (span between piers, and the width to be provided) corresponding to the minimum present equivalent total cost is sought.

The exercise of evaluating the minimum is repeated for all the alternatives under consideration. The minimum among these minima is sought. The detail design is then carried out on the alternative so chosen.

The following assumptions are made at this point:

1. Spans are of equal length.

2. The alternatives under consideration have equal lives.
3. The residual value (salvage value) at the end of the study period is negligible.
4. Because of marked differences in the design and construction of large span bridges, only small and medium span bridges will be considered.

4.3 DEVELOPMENT OF COST FUNCTIONS

The total cost is made up of three components as follows:

1. The total construction cost of the bridge.
2. The cost of maintenance of the bridge. This cost is assumed to occur uniformly over the life of the bridge.
3. Cost of vehicular flow delay, occurring uniformly, over the life of the bridge.

These are presented below.

4.3.1 CONSTRUCTION COST

The cost of construction has two components as follows :

1. Cost of superstructure construction expressed as

   $$C_s L \left(A \times S + B + \frac{C}{S} + D \times W \right)$$

   where

   S = Span between piers in feet.

   W = Width of the bridge in feet.

L = Length of the crossing (the length of the bridge) in feet.

C_s = Construction cost per pound of superstructure in dollars per pound.

A, B, C, and D are constants with dimensions of pounds per square foot, pounds per foot, pounds, and pounds per square foot.

Terms involving "S" reflect the superstructure cost increasing (in an increasing manner) with an increase in the span between piers. This increase has been taken to be quadratic in this study. The "W" term represents an increasing linear relationship between the width and the superstructure cost.

2. Cost of substructure construction expressed as

$$C_{sb} \left[\left(1 + \frac{L}{S} \right) (AA \times S + BB) + \frac{L}{S} (CC \times W + DD) \right]$$

where

C_{sb} = Construction cost per pound of substructure in dollars per pound.

AA, BB, CC, and DD are constants with dimensions of pounds per foot, pounds, pounds per foot, and pounds.

The equation represents an increasing linear relationship between the substructure cost and the width, and the substructure cost and the span between piers.

Figure 2 depicts the behavior of the superstructure cost with respect to the width and the span between piers. Similarly, the relationship between the substructure cost, the span between piers, and the width is illustrated in Figure 3.

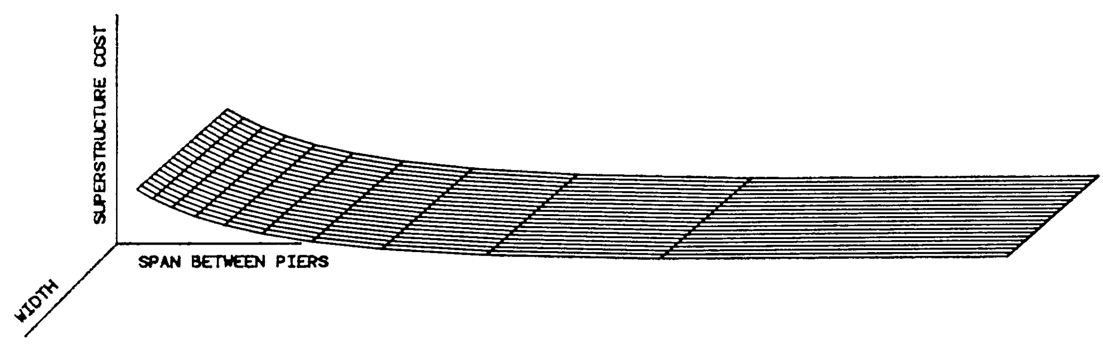

Figure 2. Superstructure construction cost vs Width vs Span length.

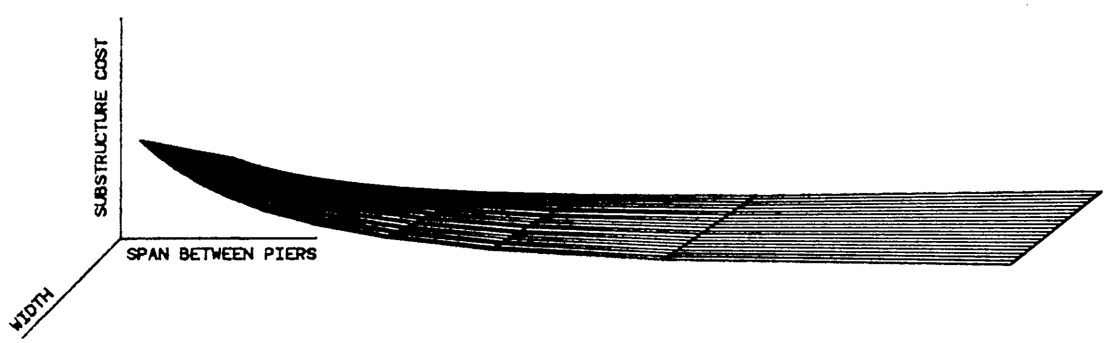

Figure 3. Substructure construction cost vs Width vs Span length.

4.3.2 MAINTENANCE COST

The maintenance cost has two components as follows :

1. Cost of superstructure maintenance expressed as

   $F [L \times W \times C_{sf} + \text{Facsup} \times (\text{Superstructure construction cost})]$

   where

   F = Uniform series present worth factor.

   C_{sf} = Annual maintenance cost per square foot of roadway in dollars per square foot.

   Facsup is a dimensionless factor, which is a function of the type of material used for construction, location of the structure, set up costs, type of traffic expected etc.

   In the expression, "$L \times W \times C_{sf}$" term represents the cost of maintenance of the roadway. The other component represents a fraction of the superstructure construction cost.

2. Cost of substructure maintenance expressed as

   $F [(1 + \frac{L}{S}) (M_p) + \text{Facsub} \times (\text{Substructure construction cost})]$

   where

   M_p = Maintenance cost per pier.

   Facsub is a dimensionless factor, which is a function of the stream characteristics, location of the bridge, length of the bridge etc.

   In the equation, "$(1 + \frac{L}{S}) (M_p)$" term expresses the maintenance cost of all the piers. The other component represents a fraction of the substructure cost.

Maintenance cost is an annual cost and it needs to be multiplied by the suitable uniform series present worth factor to get the present equivalent cost. The factor will of course depend on the life of the bridge and the prevailing interest rate.

4.3.3 COST OF VEHICULAR DELAY

The flow of traffic occurs throughout the day, but the flow of traffic will not be uniform throughout the 24 hour period. A cost penalty needs to be assigned for the delay experienced by the traffic by a suitable function for evaluating the delay. One such method is the use of a multiple channel queuing model. Another method of estimating the delay is through traffic studies. Campbell [2] and Edie [7] were among the first to deal with the influence of toll booths on the traffic flows. Though not directly addressing the issue, these serve as good guidelines for the traffic delay that can be expected. Once the delay is known, a suitable penalty can be assigned. There is no standard method of assigning this penalty and it is only natural that the delay cost assigned will depend on the location of the bridge. In practice, the delay is calculated with the help of empirical formulae based on past experience and data.

In this particular study, the multiple channel queuing model (M/ M / c) is used to estimate the delay. By this model, the delay cost is given by the following expression:

$$F (W_q \times C_d \times 24 \times 365 - (WP - WM) Z)$$

where

F = Uniform series present worth factor.

W_q = Average hourly delay in hours.

C_d = Average cost of delay in dollars per hour per hour.

WP = Lane width actually provided in feet.

WM = Total width, if only the minimum lane width is provided.

Z = Annual benefit obtained by widening a lane by a foot in dollars per foot.

The "(WP - WM)Z" term represents the benefit derived by providing additional width, without increasing the number of lanes. The "$W_q \times C_d \times 24 \times 365$ " term gives the annual vehicle delay cost.

Average hourly delay (W_q) is given by the expression

$$\frac{(\frac{\lambda}{\mu})^m \mu P_0}{(m-1)!\,(m\mu-\lambda)^2}$$

where P_0 is

$$\frac{1}{\frac{\lambda^m m\mu}{m!\mu^m(m\mu-\lambda)} + \sum_{n=0}^{m-1} \frac{\lambda^n}{n!\mu^n}}$$

and λ, μ, and m are the average arrival rate per hour in both directions, average service rate per hour per channel, and the number of lanes (channels available), respectively. In practice, the arrival rate is determined with the help of traffic studies. One of the common methods is the 30^{th} hour volume. This is the 30^{th} heaviest hour of traffic observed. Details about highway capacity estimation can be found in the Highway Capacity Manual [15].

Strictly speaking, it is not advisable to use the combined two directional flow rate to obtain the number of lanes required for both directions, with the above mentioned delay equations. It might be better to design the number of lanes for each direction separately and then combine them to get the total number of lanes. Due to the pattern of traffic over the course of the day in one direction being the reverse of the pattern in the other direction over the course of the day in most cases, such an approach is likely to lead to an even number of lanes. An even number of lanes is not undesirable in itself. But a procedure that gives an an even number of lanes, ignoring a possible solution which gives a lower odd number of lanes is not very attractive. Such a situation is likely to occur due to the fact that seldom does the peak flow in both the directions occur at the same time. This being the case, the extra lane (in case of odd number of lanes) can be assigned to the direction of peak flow and suitably reversed when the peak switches to the other direction. A potential pitfall in such an approach is the occurrence of almost equal flows in both directions for most of the day. Such an occurrence can be overcome by opting for the next best solution with an even number of lanes.

In summary, the following approach is used for the delay cost evaluation and the provision of lanes :

1. The number of lanes is determined by assuming the flows to be unidirectional.
2. If the solution results in an odd number of lanes, then a suitable decision regarding assigning the extra lane has to be made. This is most likely to involve reversible lanes[3]. If however, the traffic is likely to be equal in both directions,

[3] The number of lanes is derived by dividing the total width (after making allowances for shoulders and median) by the minimum width required of a lane.

then the suitable (higher or lower) even number of lanes can be chosen depending on the total cost.

The total cost is the sum of the construction, maintenance, and the delay cost components. Its behavior is depicted graphically in Figures 4 and 5.

It is important to note that the cost equations mentioned are conceptual in nature. More accurate and better equations may be derived, based on empirical data. However, the procedure suggested is independent of the estimating equations used. This is in keeping with a systems approach to design.

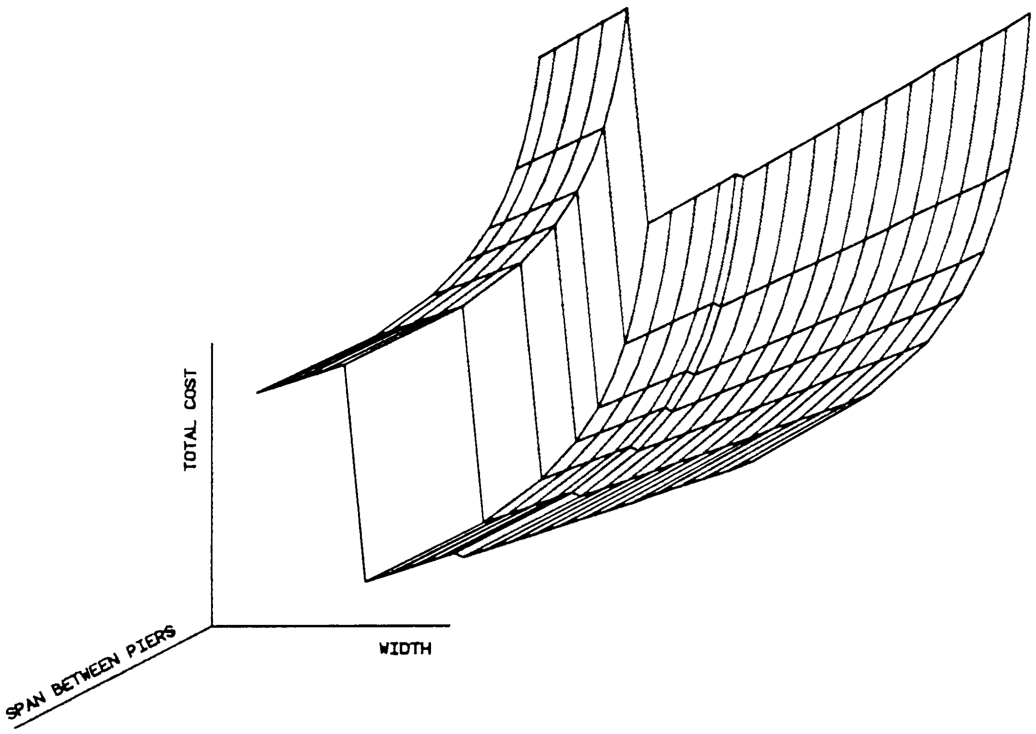

Figure 4. Total cost vs Width vs Span length.

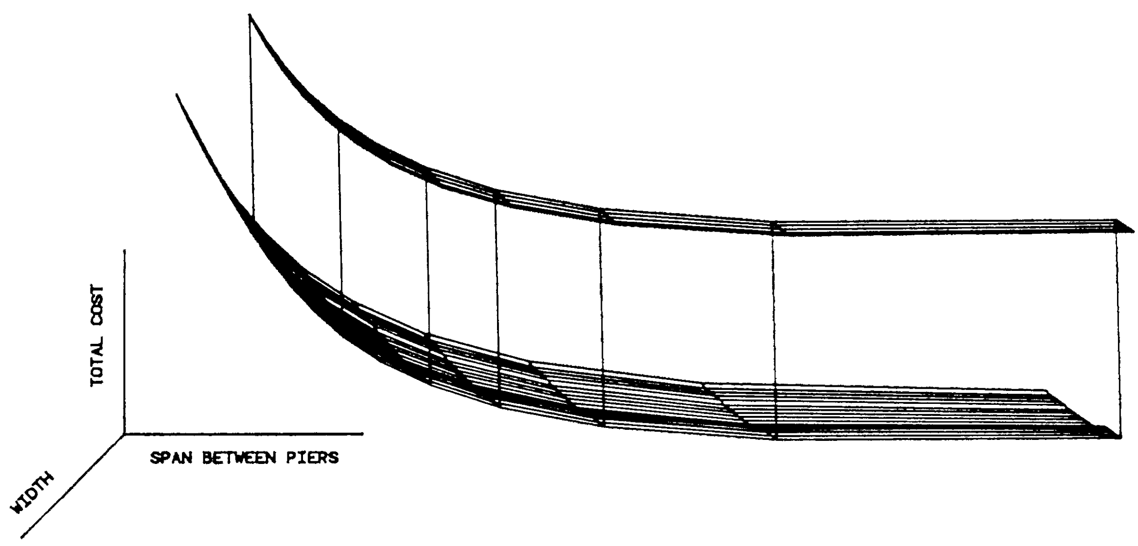

Figure 5. Total cost vs Width vs Span length.

5.0 PROBLEM SOLUTION

The problem to be solved at the preliminary design stage has been defined in the previous chapter. It is essentially one of minimizing the present equivalent total cost. This chapter considers the solution with the help of a few examples. Sensitivity analysis with respect to selected design independent parameters is also performed. A computer code written in FORTRAN is used to perform the calculations required to arrive at the decision. Only the results are presented in this chapter. The code and sample run are included in the appendices.

Total cost increases with an increase in width. It might therefore seem reasonable to design a bridge with the width kept to a certain prescribed (required) minimum. But doing so can lead to increased delay cost. Conversely, an increase in the width will decrease the delay cost but will increase the construction and maintenance cost component of the total cost. Thus one needs to search for a trade off point between the increasing construction and maintenance cost and decreasing delay cost. It is important to note that the span between piers has no effect on the delay cost component, though it surely has an important role to play in the total cost.

The remainder of the chapter is devoted to consideration of some specific cases. It is important to note that the examples serve as illustration of the methodology rather than as an actual application.

5.1 COMPARISON OF THREE DESIGN ALTERNATIVES

To illustrate the solution, consider the following example. In the preliminary design stage, three competitive design alternatives are being considered. One of them is to be chosen for detail design. The relevant data for the competing designs are given in Table 1. The dimensions are as given in Chapter 4.

Table 1. Data for comparision of three bridges.

	Alternative 1	Alternative 2	Alternative 3
C_s	0.72	0.48	1.24
A	20.0	40.0	12.0
B	4,224	8,100	2,272
C	156,960	348,961	84,408
D	12.0	27.0	7.00
C_{sb}	0.50	0.50	0.51
AA	6,000	10,000	8,700
BB	2,108	5,457	3,065
CC	3,500	6,000	5,093
DD	2,107	5,460	3,068
C_{sf}	12.0	8.0	10.0
Facsup	0.05	0.005	0.01
Maint/Pier	6,500	6,500	6,500
Facsub	0.03	0.03	0.03

In addition, the following values, which are common to all the three designs (design independent) are assumed:

1. An arrival rate of 1850 vehicles per hour and service rate of 985 vehicles per hour per channel.

2. An interest rate of 10 % (design independent parameter).

3. A study period of 20 years (design independent parameter).

4. A delay cost penalty of $ 2.6 per hour per vehicle (design independent parameter).

5. A 240 foot crossing with the width of the shoulders and median being 14 feet.

6. A minimum width of 12 feet per lane.

Table 2 summarizes the solution based on the above data.

Table 2. Optimal solution.

	Alternative 1	Alternative 2	Alternative 3
Span Length	80.0 feet	80.0 feet	80.0 feet
Width	50.0 feet	50.0 feet	50.0 feet
Lanes	3	3	3
Total Cost	$5,183,204	$5,805,382	$5,151,763

Among the minima, Alternative 3 is the least costly. Hence, Alternative 3 is the best solution and it should be chosen for detail design with a span length of 80 feet and a width of 50 feet (3 lanes). It is interesting to note that though the construction cost of Alternative 3 is higher than that of Alternative 1, the overall cost of the former is lower than the latter. (Detailed calculations can be found in Appendix B). This is due to the lower maintenance cost of Alternative 3. Thus a high first cost may be reasonable (in such cases) due to low maintenance cost in the future leading to lower overall cost.

5.2 SENSITIVITY ANALYSIS

Once the optimal value has been obtained, it is important to perform sensitivity analysis on the design independent parameters. For example, the sensitivity of the solution to the interest rate under consideration can be done, and any decision reversal noted. Other parameters include the life of the bridge and the delay cost. These decision reversals (if any) should be noted and suitably incorporated into the decision process at the preliminary design stage in particular, and the Life Cycle design in general. Some examples of such a sensitivity analysis and decision reversal follow. The analysis is done on the example from the previous section.

5.2.1 SENSITIVITY WITH RESPECT TO INTEREST RATE

The alternatives can be evaluated under varying interest rates. The comparison of the alternatives in the previous section was done with an interest rate of 10 percent. For the sensitivity analysis, the interest rate was varied from 1 to 19 percent in increments of 1 percent. The switches observed are summarized in Table 3.

Table 3. Sensitivity with respect to interest rate.

Interest rate	Best Alternative	Switches ?	Switch from
1 %	3	NO	-
2 %	3	NO	-
.	.	..	.
.	.	..	.
.	.	..	.
10 %	3	NO	.
11 %	1	YES	3 to 1
12 %	1	NO	-
.	1	..	.
.	1	..	.
19 %	1	NO	-

It can be seen from Table 3 that a switch does occur at 11 percent. This means that the decision assuming 10 percent interest rate should be interpreted with caution. With the study period being 20 years, an interest rate increase of 1 percent is quite possible. On the other hand, if the interest rate falls, then a decision switch will not occur.

5.2.2 SENSITIVITY WITH RESPECT TO STUDY PERIOD

In the previous section, a study period of 20 years was used. The sensitivity of the decision to the study period is summarized in Table 4. The study period was varied between 12 and 28 years. It can be seen that a decision reversal takes place if the study period is 17 years.

Table 4. Sensitivity with respect to study period.

Study period	Best Alt.	Switches ?	Switch from
12 years	1	NO	-
13 years	1	NO	-
.	.	..	.
.	.	..	.
.	.	..	.
17 years	1	NO	-
18 years	3	YES	1 to 3
19 years	3	NO	-
20 years	3	NO	-
21 years	3	NO	-
.	.	..	.
.	.	..	.
.	.	..	.
28 years	3	NO	-

5.2.2 SENSITIVITY WITH TWO PARAMETERS

In the two cases considered above, only one parameter at a time has been analyzed. Sensitivity with respect to two parameters is performed next, with the parameters being interest rate and study period. Two decision reversals are summarized in Table 5.

Table 5. Sensitivity with respect to interest and study period.

Interest rate	Study period	Best Alt.	Switch from
.	.	.	.
10 %	14 years	1	-
10 %	15 years	1	-
9 %	14 years	1	-
9 %	15 years	3	1
.	.	.	.

This kind of an analysis is useful as more than one parameter is likely to change. Such changes might result in decision reversals, even though the changes taken one at a time may not. For example, at an interest rate of 10 percent, Alternative 1 would be desirable if the study period is 14 years. But, if the study period is increased to 15 years and interest rate reduced to 9 percent, then a decision switch to Alternative 3 is observed. However, if either interest rate alone is reduced to 9 percent or the study period alone is increased to 15 years, then Alternative 1 remains best with no switches observed.

At the discretion of the designer, such an analysis can be extended to as many parameters as necessary. For example, a three parameter analysis could be done with the parameters being interest rate, study period, and vehicle delay cost.

5.3 ANALYSIS FOR ERROR

The equations used to estimate the costs are usually based on available data. These equations are bound to have some amount of error. The errors may also result in the decisions getting switched. For example, if the superstructure construction cost of alternative 3 is 10 percent more than the value given by the estimating equation, (10 percent error), then Alternative 1 would be best. Similar switches can be observed if the cost estimating equations give inflated values. For example, if the superstructure construction cost of Alternative 1 is 10 percent less than the value given by the estimating equation, (-10 percent error), then Alternative 1 would be better than Alternative 3. Table 6 illustrates some of these switches.

Table 6. Analysis of error in superstructure cost.

Percentage error in			Decision switch	
Alt. 1	Alt. 2	Alt. 3	From	To
0 %	0 %	0 %	-	-
0 %	0 %	10 %	3	1
.	.	.	.	.
.	.	.	.	.
-10 %	0 %	-10 %	-	-
-10 %	0 %	-20 %	1	3
.	.	.	.	.
.	.	.	.	.
0 %	0 %	0 %	-	-
-10 %	0 %	0 %	3	1

5.4 DECISION AT THE PRELIMINARY STAGE

At the end of the preliminary design stage, a decision regarding the design concept, the span length, and the number of lanes to be provided can be made on the basis of the procedure suggested above. Once such a decision has been made, the detail design can commence on the basis of these results. For example, the designer may arrive at a decision to build a steel bridge with 4 lanes and a span length of 40 feet. Detail design can then be carried out on this configuration. Techniques like CAD and CAM can be profitably employed at this stage to get a good detail design. On the other hand if the detail design is commenced without proper attention paid to conceptual design and / or preliminary design, then such powerful techniques may be used on configurations which are not very attractive to start with. Since close to two thirds of the total cost is committed by the end of the preliminary design stage, lack of attention to the events occurring in the entire Life Cycle can lead to costly and inefficient designs. This is especially true of bridges.

6.0 CONCLUSION

This study focused on a Life Cycle methodology for bridge design with emphasis on the preliminary design stage. The methodology was illustrated with the help of examples. The work has been subject to it's own set of assumptions and constraints. This chapter consists of a summary of the results obtained by the study, and provides suggestions for further work which might be done as extensions.

6.1 SUMMARY OF RESULTS

Preliminary design is a very important, though often a neglected stage in the Life Cycle process. The decisions to be made at this stage in a bridge design have been examined in this study. The first three chapters provided the introduction, literature survey, and a general discussion on the design process. Chapters four and five dealt with the definition and solution of the decision problem.

The solution not only involved finding the optimal value of the span between piers, and the number of lanes to be provided (derived from the width), but also deciding among the various available design alternatives. This was done by comparing the optimal values of the alternatives among each other and selecting the best among them. The best among the best was selected.

Further analysis was done by examining the sensitivity of the decision to changes in the interest rate and the study period. The possibility of decision reversals was also discussed. An enumeration approach was adopted for the sensitivity analysis. Reversals arising due to errors in the cost estimating were also illustrated, though in a very limited manner.

6.2 EXTENSIONS

More work has to be done to actually implement the approach, since this study is an illustration of procedure. An important step that needs to be taken is the setting up of a database of all the costs involved. Though the costs considered are very important, and run to very high values, there is a certain lack of a good database. Some of this is due to the very nature of the cost. For example, maintenance cost is very difficult to define and hence the difficulty in the maintenance of any kind of database. Even the availability of the data does not ensure it's applicability. At the preliminary design stage for example, the data is likely to be needed in the form of unit costs. These may be difficult to get in spite of the availability of cost data.

Conceptual cost estimating equations have been used in this study. Available data can be used to estimate the parameters of these equations. For example, the construction cost estimating equations can be "fitted" with help of the construction cost database. Similar treatment of the other cost estimating equations is possible. This is the most important extension.

With the availability of computers that are inexpensive, yet powerful, maintaining databases and performing the required cost analysis on them should become easier. Collection of fresh data and retrieval and storage of existing data should be done as part of the Life Cycle approach. This can be done at the detail design stage and the operation phase. The data collected at the operation phase and the detail design stage, for example, can result in better cost estimating equations for future designs.

Sensitivity analysis can be extended to cover the three parameters involved, namely, the interest rate, the study period, and the traffic delay cost. A multi-parameter sampling procedure, instead of the total enumeration approach could be adopted for performing such an analysis. This would involve sampling from the distributions of the three parameters.

The single most powerful tool available to the designers of the latter half of this century is the computer. Its potential in obtaining good designs has been partially achieved by the process of CAD and CAM. If it is integrated to all the stages of the Life Cycle, then better and more competitive designs of not only bridges, but all engineered products is possible.

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APPENDIX A. PROGRAM DESCRIPTION

The program to calculate the minimum costs, and the associated decision variables is presented here. It is written in FORTRAN and should be implementable on most computers (both mainframes and personal computers). Input to the program is in the form of data files. Once the data file has been prepared, the program can be run with minimum of effort. The format of the data file is given below in Table 7. For a successful run, the syntax shown should be strictly followed. The values of variables and parameters shown in the table are for the example considered in Chapter 5.

The logic of the program is rather simple. As the first step the input data is read. Based on the arrival and service rate, the minimum number of lanes is decided by setting the traffic intensity to be less than one. Based on the minimum width of a lane and the width of the medians and shoulders, the lower bound (minimum acceptable) value of the width of the bridge is calculated. The enumeration of the total cost as a sum of the construction, maintenance, and the delay cost is calculated for successive values of width and span lengths. The width is varied up to five successive values of lanes, and span lengths corresponding up to 12 spans. The minimum cost is thus

Table 7. Format for data file.

```
'INT RATE( DECIMAL)  YEARS     LENGTH     # OF ALTERNATIVES  '
    .10,                  20.,      240.,          3
'ARRIVAL RATE(#/HRS)     SERVICE RATE(#/HRS)'
     1850.,                     985.
'                                         '
'    CS        A        B         C        D '
   .72,       20.,     4224.,  156960.,  12.
'   CSB        AA       BB        CC        DD'
   .50,       6000.,    2108.,    3500.,   2107.
'   CSF        FACSUP'
    12.,        .05
' MAINT/PIER    FACSUB'
   6500.,        .03
'  '
'    CS        A        B         C        D'
   .48        40.,     8100.,  348961.,  27.
'   CSB        AA       BB        CC        DD'
    .50,     10000.,    5457.,    6000.,    5460.
'   CSF        FACSUP'
    8.,        .005
' MAINT/PIER    FACSUB'
    6500.,        .03
'  '
'    CS        A        B         C        D'
  1.24,       12.,     2272.,   84408.,  7.0
'   CSB        AA       BB        CC        DD'
   .51,       8700.,    3065.,    5093.,    3068.
'   CSF        FACSUP'
    10.,        .01
' MAINT/PIER    FACSUB'
   6500.,        .03
'  '
```

found by total enumeration and the corresponding values of the variables noted. Total enumeration is a suitable approach because of a relatively few simple computations to be done, and the availability of computers which can do the job accurately and swiftly.

The sensitivity procedure is driven by an outer "DO" loop, which runs through the program with various values of the design independent parameters.

PROGRAM

```
C*-----------------------------------------------------------------
C*                                                                *
C* BEFORE YOU RUN THIS PROGRAM, BE SURE YOU HAVE DONE THE FOLLOWING:  *
C*                                                                *
C* 1. DEFINED UNIT 5 FOR INTPUT OF DATA.                          *
C* 2. DEFINED UNIT 6 AND 7 FOR OUTPUT.                            *
C* I. UNIT 6 WILL BE  USED FOR  SENSITIVITY ANALYSIS.             *
C* II. UNIT 7 FOR DETAILED CALCULATIONS OF VARIOUS COST COMPONENTS FOR *
C*    EACH COMBINATION OF WIDTH AND SPAN.                         *
C* 3. CREATED DATA FILES AS PER THE REQUIRED FORMAT.              *
C*                                                                *
C*-----------------------------------------------------------------
C*
C*-S IS THE SPAN, IT IS OBTAINED BY DIVIDING THE LENGTH BY 2, 3,.., 12.
C*-W IS THE WIDTH, IT IS MADE TO VARY UPTO FIVE SUCCESSIVE VALUES
C*-OF THE LANE WIDTH REQUIRED BY THE QUEUING EQUATIONS.
C*---TCSP IS THE TOTAL COST OF SUPERSTRUCTURE CONSTRUCTION.
C*--WW IS UTHE MIN WIDTH IN THE INNER LOOP, BWW IS THE WIDTH.
C*--CORRESPONDING TO THE OVERALL MINIMUM.
C*--SUP, SUB ARE THE RESPECTIVE MAINTENANCE COSTS FOR THE SUPER AND SUB
C*--STRUCTURES.
C*--TCSP, AND TCSB ARE THE CONSTRUCTION COST FOR SUPER AND SUB STRUCTURE
C*--LAMBDA AND MU FROM QUEUING THEORY EQUATIONS.
```

```
C*--TOTAL IS THE TOTAL OF ALL COST COMPONENTS.
C*--TT IS THE MIN TOTAL COST FOR THE INNER LOOP.
C*--BTT IS THE OVERALL MIN TOTAL COST.
C*--MINEE, MINEZ, MINED ARE THE INDICES FOR THE ERROR DO LOOP
C*--RMINEE, RMINEZ, RMINED ARE FOR CONVERTING THE ABOVE TO DECIMALS
C*
C*
      CHARACTER BLANK
      INTEGER NU,WSATHI,JSATHI,MINEE,MINEZ,MINED,FALT,ALT,BESTALT,BWIDTH
      INTEGER W(3),J(3),WW(3),BWW(3),MW(3),M(3)
      REAL S(3),SUP(3),SUB(3),TCSP(3),TCSB(3),CSF(3),FACSUP(3),FACSUB(3)
      REAL SS(3),TOTAL(3),BSS(3),PIER(3),BTT(3),TT(3),X(3)
      REAL WQ(3),TOT(3),DELCST(3),CSP(3),CSB(3),CON(3)
      REAL LAMBDA,MU,RATE,YEARS,RMINEE,RMINEZ,RMINED,L
      REAL A(3),AA(3),B(3),BB(3),C(3),CC(3),D(3),DD(3)
C*
C*----------READS THE CONSTANTS FOR THE EQUATION--------------------
C*
      READ(5,*)BLANK
      READ(5,*)RATE,YEARS,L,NOA
      READ(5,*)BLANK
      READ(5,*)LAMBDA,MU
      READ(5,*)BLANK
      DO 22 JAT = 1,3
        READ(5,*)BLANK
        READ(5,*)CSP(JAT),A(JAT),B(JAT),C(JAT),D(JAT)
```

```
        READ(5,*)BLANK
        READ(5,*)CSB(JAT),AA(JAT),BB(JAT),CC(JAT),DD(JAT)
        READ(5,*)BLANK
        READ(5,*)CSF(JAT),FACSUP(JAT)
        READ(5,*)BLANK
        READ(5,*)PIER(JAT),FACSUB(JAT)
        READ(5,*)BLANK
22    CONTINUE
      WRITE(6,*)'NUMBER OF ALTERNATIVES = ',NOA
      WRITE(6,*)'LAMBDA =  ',LAMBDA,'MU = ',MU
C*---------------ALL CONSTANTS HAVE BEEN READ----------------------
C*THE MINIMUM WIDTH REQUIRED IS EVALUATED BASE ON THE QUEUING EQUATIONS.
      MAHA = INT(LAMBDA)/INT(MU)
      RMAHA = LAMBDA/MU
      IF(RMAHA.EQ.REAL(MAHA)) THEN
        MAHASATH = MAHA
      ELSE
        MAHASATH = MAHA + 1
      ENDIF
      IX = MAHASATH
      MAHASATH = MAHASATH*12 + 14
      WRITE(6,*)'MINIMUM NUMBEROF LANES = ',IX
C
      XXRATE = RATE
      XXYEARS = YEARS
C*THE BASIC INFORMATION IS NOW WRITTEN TO THE OUTPUT FILE
```

```
      IF(RATE.EQ.XXRATE.AND.YEARS.EQ.XXYEARS) THEN
      WRITE(7,140)
      WRITE(7,142)
      ELSE
      ENDIF
C
      YEARS = YEARS + 1
      RATE = RATE + .01
      XT = YEARS
      DO 19 MYY = 1,9
        RATE = RATE -.01
        YEARS = XT
      DO 19 MY = 1,9
        YEARS = YEARS - 1
        F = FACTOR(RATE,YEARS)
        WRITE(6,111)YEARS,RATE
111     FORMAT(///'YEARS  = ',F6.2 ,'   RATE = ',F6.2 )
C*-THE ERROR LOOP STARTS HERE
      III = 1
      DO 2200 MINEE = 0,0
      DO 2200 MINEZ = 0,0
      DO 2200 MINED = 0,0
      BCOST = 29E29
      RMINEE = -REAL(MINEE)/10.
      RMINEZ = -REAL(MINEZ)/10.
      RMINED = -REAL(MINED)/10.
```

```
 WRITE(6,120)
 WRITE(6,122)
 DO 500 KKK = 1,3
   BTT(KKK) = 99E28
   DO 10 WSATHI = MAHASATH,MAHASATH + 60
     W(KKK) = WSATHI
     TT(KKK) = 99E25
     DO 8 JSATHI = 12,2,-1
       J(KKK) = JSATHI
       S(KKK) = L/J(KKK)
       TCSP(1) = CSP(1)*L*(A(1)*S(KKK) + B(1) +
$(C(1)/S(KKK)) + D(1)*W(KKK))*(1. + RMINEE )
       TCSP(2) = CSP(2)*L*(A(2)*S(KKK) + B(2) +
$(C(2)/S(KKK)) + D(2)*W(KKK))*(1. + RMINEZ)
       TCSP(3) = CSP(3)*L*(A(3)*S(KKK) + B(3) +
$(C(3)/S(KKK)) + D(3)*W(KKK))*(1. + RMINED)
       TCSB(1) = CSB(1)*((1 + (L/S(KKK)))*(AA(1)*
$S(KKK) + BB(1)) + (L/S(KKK))*(CC(1)*W(KKK) + DD(1)))
       TCSB(2) = CSB(2)*((1 + (L/S(KKK)))*(AA(2)*
$S(KKK) + BB(2)) + (L/S(KKK))*(CC(2)*W(KKK) + DD(2)))
       TCSB(3) = CSB(3)*((1 + (L/S(KKK)))*(AA(3)*
$S(KKK) + BB(3)) + (L/S(KKK))*(CC(3)*W(KKK) + DD(3)))
       CON(KKK) = TCSP(KKK) + TCSB(KKK)
       SUP(KKK) = L*W(KKK)*CSF(KKK) + FACSUP(KKK)*TCSP(KKK)
       SUB(KKK) = (1 + L/S(KKK))*PIER(KKK) + FACSUB(KKK)*
$TCSB(KKK)
```

```
          TOT(KKK) = (SUP(KKK) + SUB(KKK))*F
          MW(KKK) = W(KKK) - 14
          M(KKK) = MW(KKK)/12
          X(KKK) = REAL(MW(KKK))/REAL(M(KKK))
          P0 = (1./FACT(M(KKK)))*((LAMBDA/MU)**M(KKK))*M(KKK)*MU/
     $(M(KKK)*MU - LAMBDA)
          P0SUM = 1.
          DO 20 I = 1 , M(KKK) - 1
            P0SUM = P0SUM + (1./FACT(I))*((LAMBDA/MU)**I)
20         CONTINUE
          PZERO = 1./(P0 + P0SUM)
          WQ(KKK) = (((LAMBDA/MU)**M(KKK))*MU*PZERO)/
     $(FACT(M(KKK) - 1)*((M(KKK)*MU - LAMBDA)**2))
          DELCST(KKK) = (WQ(KKK)*2.5945946*24.*365.*LAMBDA
     $- (MW(KKK) - M(KKK)*12.)*200.)*F
          TOTAL(KKK) = TOT(KKK)+TCSP(KKK)+TCSB(KKK)+DELCST(KKK)
C          WRITE(6,*)W(KKK),S(KKK),M(KKK),
C    $TCSP(KKK),TCSB(KKK),TOT(KKK),DELCST(KKK),TOTAL(KKK)
          IF(MINEE.EQ.0.AND.MINEZ.EQ.0.AND.MINED.EQ.0.AND.MY.EQ.1
     $.AND.MYY.EQ.1) THEN
            WRITE(7,144)W(KKK),S(KKK),M(KKK),CON(KKK),TOT(KKK),
     $DELCST(KKK),TOTAL(KKK)
          ELSE
          ENDIF
          TT(KKK) = MIN(TT(KKK),TOTAL(KKK))
          IF(TT(KKK).EQ.TOTAL(KKK)) THEN
```

```
            WW(KKK) = W(KKK)
            SS(KKK) = S(KKK)
           ELSE
           ENDIF
C=           WRITE(6,*)F,W(KKK),S(KKK),TOT(KKK)
8         CONTINUE
C          WRITE(6,*)'SPAN = ',SS(KKK),'WIDTH = ',WW(KKK),
C    $'MINCOST = ',TT(KKK)
C          WRITE(7,*)'LOCAL MIN AT SPAN = ',SS(KKK),
C    $'AT A COST OF ',TT(KKK)
          BTT(KKK) = MIN(TT(KKK),BTT(KKK))
          IF(BTT(KKK).EQ.TT(KKK)) THEN
           BWW(KKK) = WW(KKK)
           BSS(KKK) = SS(KKK)
          ELSE
          ENDIF
10       CONTINUE
        BCOST = MIN(BCOST,BTT(KKK))
        IF(BCOST.EQ.BTT(KKK)) THEN
          BESTALT = KKK
          BWIDTH = BWW(KKK)
          BSPAN = BSS(KKK)
          III = III -1
        ELSE
        ENDIF
C=       WRITE(6,*)' THIS IS THE BEST SOLUTION!'
```

```
C=      WRITE(6,*)KKK,'WIDTH = ',BWW(KKK),'SPAN = ',BSS(KKK),'LANES =',
C=   $,'AT A COST OF',BTT(KKK)
        NL = (BWW(KKK) - 14)/12
        MEE = -MINEE*10
        MEZ = -MINEZ*10
        MED = -MINED*10
        WRITE(6,124)KKK,MEE,MEZ,MED,BWW(KKK),BSS(KKK),NL,BTT(KKK)
500   CONTINUE
      IF(ALT.NE.BESTALT) THEN
        ALT = BESTALT
        WRITE(6,126)
        ELSE
      ENDIF
      WRITE(6,128)BESTALT
2200  CONTINUE
19    CONTINUE
C......................FORMAT STATEMENTS.............................
120   FORMAT(/'          % ERROR IN  ')
122   FORMAT('ALT #  ALT 1 ALT 2 ALT 3   WIDTH    SPAN      LANES  TOTAL
    $ COST')
124   FORMAT(3X,I1,2X,2X,I3,3X,I3,3X,I3,5X,I3,3X,F11.7,3X,I2,3X,F11.1)
126   FORMAT('                 A SWITCH HAS OCCURRED   ')
128   FORMAT('  AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # ',I2)
140   FORMAT('          DETAILED CALCULATIONS FOR THE NO ERROR CASE '/)
142   FORMAT('WIDTH   SPAN    LANES  CONST    MAINTENANCE    DELAY
```

```
     $    TOTAL'/)
144  FORMAT(1X,I2,3X,F10.6,2X,I2,1X,F11.1,2X,F11.1,2X,F11.1,2X,F11.1)
      STOP
      END
C***************SUBPROGRAM TO EVALUATE FACTORIALS******************
     FUNCTION FACT(C)
     INTEGER C,F
     F = 1
     DO 10 I = 1,C
       F = F*I
10    CONTINUE
     FACT = F
     RETURN
     END
C***********SUBPROGRAM TO EVALUATE (P/A,I,N)*************************
     FUNCTION FACTOR(R,Y)
     REAL R,Y
     FACTOR = ((1. + R)**Y - 1.)/(R*((1 + R)**Y))
     RETURN
     END
```

The program calculates most of the information needed by the designer to arrive at a decision at the preliminary design stage. Some of the "WRITE" statements needed to output some of the intermediate results have been "commented out". An example is the calculation of local minimum at each possible width. This is done to prevent distraction from the most important results and also to avoid "storage" problems in computers with limited memory.

APPENDIX B. PROGRAM RUNS

The program runs (detail calculations) for the results presented in Chapter 5 are given here. Detailed calculations for each of the alternatives considered are presented in Table 8. The program run giving the summary of the optimal solutions is presented Table 9. Some sample runs of the sensitivity analysis can be found in Tables 10 and 11. "NO ERROR CASE" refers to a zero error in the cost estimating equations. All the outputs have been abbreviated due to constraints of space.

Table 8. Detailed calculations.

DETAILED CALCULATIONS FOR THE NO ERROR CASE

WIDTH	SPAN	LANES	CONST	MAINT.	DELAY	TOTAL
38	20.000000	2	3838302.0	3011823.0	2713431.0	9563556.0
33	21.818176	2	3668420.0	2894923.0	2713431.0	9276774.0
38	24.000000	2	3500889.0	2778838.0	2713431.0	8993158.0
38	26.666656	2	3336485.0	2663837.0	2713431.0	8713753.0
38	30.000000	2	3176387.0	2550327.0	2713431.0	8440145.0
38	34.285706	2	3022436.0	2438949.0	2713431.0	8174816.0
38	40.000000	2	2877710.0	2330767.0	2713431.0	7921908.0
38	48.000000	2	2747739.0	2227698.0	2713431.0	7688868.0
38	60.000000	2	2643592.0	2133579.0	2713431.0	7490602.0
38	80.000000	2	2591093.0	2057359.0	2713431.0	7361883.0
38	120.000000	2	2667715.0	2025887.0	2713431.0	7407033.0
39	20.000000	2	3861376.0	3042588.0	2711728.0	9615692.0
39	21.818176	2	3689744.0	2925242.0	2711728.0	9326714.0
39	24.000000	2	3520462.0	2808709.0	2711728.0	9040899.0
39	26.666656	2	3354309.0	2693261.0	2711728.0	8759298.0
39	30.000000	2	3192461.0	2579305.0	2711728.0	8483494.0
39	34.285706	2	3036759.0	2467479.0	2711728.0	8215966.0
39	40.000000	2	2890283.0	2358850.0	2711728.0	7960861.0
39	48.000000	2	2758562.0	2255334.0	2711728.0	7725624.0
39	60.000000	2	2652666.0	2160769.0	2711728.0	7525163.0
39	80.000000	2	2598417.0	2084102.0	2711728.0	7394247.0
39	120.000000	2	2673289.0	2052183.0	2711728.0	7437200.0

Table 9. Sample run for comparison of 3 Alternatives.

NUMBER OF ALTERNATIVES = 3
LAMBDA = 1850.00000 MU = 985.000000
MINIMUM NUMBER OF LANES = 2
YEARS = 20.00 RATE = 0.10

	% ERROR IN						
ALT #	ALT 1	ALT 2	ALT 3	WIDTH	SPAN	LANES	TOTAL COST
1	0	0	0	50	80.0000000	3	5183204.0
2	0	0	0	50	80.0000000	3	5805382.0
3	0	0	0	50	80.0000000	3	5151763.0

A SWITCH HAS OCCURRED
AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # 3

Table 10. Sensitivity calculations (Study period).

NUMBER OF ALTERNATIVES = 3
LAMBDA = 1850.00000 MU = 985.000000
MINIMUM NUMBER OF LANES = 2

YEARS = 20.00 RATE = 0.10

	% ERROR IN						
ALT #	ALT 1	ALT 2	ALT 3	WIDTH	SPAN	LANES	TOTAL COST
1	0	0	0	50	80.0000000	3	5183204.0
2	0	0	0	50	80.0000000	3	5805382.0
3	0	0	0	50	80.0000000	3	5151763.0

A SWITCH HAS OCCURRED
AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # 3

....
....

YEARS = 17.00 RATE = 0.10

	% ERROR IN						
ALT #	ALT 1	ALT 2	ALT 3	WIDTH	SPAN	LANES	TOTAL COST
1	0	0	0	50	80.0000000	3	5038480.0
2	0	0	0	50	80.0000000	3	5702716.0
3	0	0	0	50	80.0000000	3	5038991.0

A SWITCH HAS OCCURRED
AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # 1

....
....

Table 11. Joint Sensitivity calculations.

NUMBER OF ALTERNATIVES = 3
LAMBDA = 1850.00000 MU = 985.000000
MINIMUM NUMBER OF LANES = 2

YEARS = 20.00 RATE = 0.10

ALT #	% ERROR IN ALT 1	ALT 2	ALT 3	WIDTH	SPAN	LANES	TOTAL COST
1	0	0	0	50	80.0000000	3	5183204.0
2	0	0	0	50	80.0000000	3	5805382.0
3	0	0	0	50	80.0000000	3	5151763.0

A SWITCH HAS OCCURRED
AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # 3

....
....

YEARS = 17.00 RATE = 0.10

ALT #	% ERROR IN ALT 1	ALT 2	ALT 3	WIDTH	SPAN	LANES	TOTAL COST
1	0	0	0	50	80.0000000	3	5038480.0
2	0	0	0	50	80.0000000	3	5702716.0
3	0	0	0	50	80.0000000	3	5038991.0

A SWITCH HAS OCCURRED
AT THIS POINT THE BEST SOLUTION IS ALTERNATIVE # 1
YEARS = 20.00 RATE = 0.09

....
....

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