A CONTRIBUTION TO DESIGN LIFE AND LIFE CYCLE CONSIDERATIONS OF STRUCTURES

by

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ABSTRACT

The cost of a structure throughout its entire useful life has become an important issue in light of the deteriorating infrastructure and skyrocketing maintenance costs. As a result there has been an emergence of research interest in the field of life cycle analysis. In the last few decades researchers have begun to investigate the service life of existing structures which suffer from a real and perceived lack of performance. To address this issue, it has been suggested that, as part of the design process, more emphasis should be given to in-service performance of a structure which could possibly be based on design life concepts. Applying such concepts, considering the numerous variables and parameters involved, is undoubtedly a complex issue. This thesis summarizes the findings of recent research by the author, showing alternative approaches to the consideration of design life concepts as well as some discussion of the difficulties associated with them. Case studies are presented from the aerospace and nuclear industries, who have been applying design life considerations in one form or another for quite some time. Applicability of the methods used in these two industries to civil engineering structures have been considered and are explained. In considering civil engineering applications, the life span of a structure was broken up into the typical stages of progression, i.e. conceptual design, final design, construction, maintenance and repair, with the various influences identified and discussed at each of these stages. It followed from this research that quality control and quality assurance procedures at the design and construction stage have considerable influence on the design life of a structure. It was found that further research and development in these areas is required to propose a practical and effective means of assessing the durability of a structure.

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INTRODUCTION

Serviceability failures and lack of performance in structure that have been constructed over the last 40 years or so, have drawn attention in the structural engineering field. It has been suggested that these issues could be dealt with using design life and life cycle considerations. Such consideration is not totally new to engineering design, but it may be time to give it more attention so that improved designs will be realized

The concept of ultimate limit states of structures has been extensively researched, using the most common building materials, which in turn has reduced drastically the occurrence of structural collapse. However, violation of serviceability criteria occurs much more frequently. This gave rise to the question of the cause of these serviceability problems and what could be done (if anything) to improve the situation for the future. Through perusing literature from the aerospace, nuclear, and civil engineering industries, it was found that there are areas where improvements could be made which would make designers more aware of where possible problems could occur and how to take them into account in the design process. The life cycle of a structure was broken up into the typical stage of progression, i.e. conceptual design, detailed design, construction, maintenance and repair. At each of these stages considerations was given to the influence of decisions made and what could be done to improve the performance. It became apparent that there are numerous variables and influences that affect the design life of a structure, but many cannot be quantified with great accuracy. Hence, their influence on the overall life cycle is only known in broad general terms. Besides seeking out the problems with current design approaches, an effort was made to give an indication of where further research effort should be directed to address the issue of improving the performance of structures.

Review of literature dealing specifically with design life issues of civil engineering structures revealed the lack of information on this topic. There have been, in recent years, suggestions on possible approaches that could be taken, but none have been implemented in codes or formal guidelines.

The aerospace industry has applied life cycle analysis to their projects since the early 1970's. This evolved due to pressure from the US Department of Defense, which is a very large client of the industry. The government wanted more control over their spending, so they imposed "Design-to-Cost" guidelines which forced the industry to use life cycle costing techniques to compete for government contracts. They have met with success using such techniques and these will be discussed later on. The nuclear industry requires rather long service lives for many of their structures which forced them to seriously look at design life considerations. Quality assurance and quality control aspects in all phases of a project also contribute significantly to the design life of a structure. There has been much development in quality control and assurance programs for factory production line type processes, but implementing such programs in the design and construction phases of civil engineering structures still requires further research effort. These types of projects fall into the category of one-of-a-kind products, and hence, the procedures used in large production runs are not directly applicable to these situations.

CHAPTER 1

LITERATURE REVIEW

1.1 Aerospace Industry

The aerospace industry implemented life cycle cost analysis as standard practice in the early 1970's by request of the U.S. Department of Defense (Lewis et al 1980[1]). With reduced budgets for military acquisition, the government needed a tool to compare various proposals from contractors on an equal basis and choose the option with the lowest life cycle cost that met the performance objectives. This industry typically has large production runs of single items and hence, enormous savings can be realized with the implementation of life cycle analysis. Therefore it would be advantageous for the designers to get the most efficient design with the lowest life cycle cost into production. The civil engineering field is different in this aspect since the engineer normally produces one-of-a-kind structures, perhaps similar but seldom identical, which should be kept in mind as the discussion of the aerospace industry is given. Life cycle analysis will help to assist in the evaluation of the performance aspect of the structure which is what we are currently concerned about.

1.1.1 Life Cycle Cost Analysis

Life cycle cost analysis has been around for about 25 years and implemented in various capacities in the aerospace industry. In the early to mid 1970's, the U.S. Department of Defense issued guidelines to implement design-to-cost designs for evaluation and award of contracts. Up to that point in time, contractors were usually only concerned with the performance aspects of the design with secondary consideration given to operation and maintenance aspects of the product. With the concept of design-to-cost, life cycle analysis had to be included in the design process since it was the entire cost of the product that now had to be estimated and predicted. In general terms the life cycle of a product can be defined as:

Life Cycle = Development + Production + Ownership(Usage)

This requires a joint effort across multiple disciplines to come up with a balance of performance and features that met the objectives set out at the start of the project and is still within budget. It was apparent that trade-offs had to be made in such a development environment, but design-to-cost would assure the government that it had control over its expenditures in this area. At this point it was also realized that the choices made early in the conceptual phase have a large influence on life cycle costs of the product. Figure 1.1.1 shows these functions.

It has been found that when the design has reached the end of the conceptual stage, about 65% of the life cycle costs have been defined or frozen. By the end of the definition phase, 80% of the life cycle costs have been defined or frozen. This means that the decisions made at these stages dictates the given percentage of over all costs that can no longer be influenced in the later stages of development. This reinforces the fact that life cycle considerations should be implemented as early in the design process as possible to help in making the choices to arrive at the lowest possible cost for the given objectives.

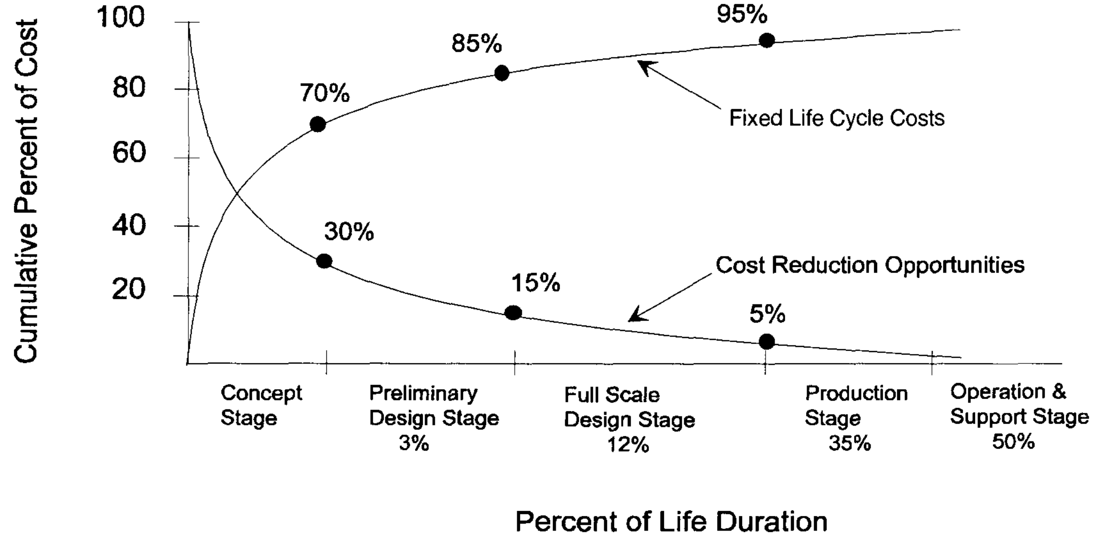

Figure 1.1.1 Life Cycle Cost Influences [2]

It was customary to make design decisions based on the acquisition cost of the product and not on the overall costs including operation and support. The British Aerospace Aircraft Group, Warton division, had been considering this issue in the early 1970's (Jones 1980[3]). They made a comparison between the relative cost of a product versus its effectiveness for a number the alternatives, which is shown in figure 1.1.2 (Jones 1980[3]). Then they compared the same alternatives using the relative life cycle cost and arrived at the shaded results also shown in figure 1.1.2. From these figures, it is important to realize that when doing a life cycle analysis and you intend to compare various options, the same cost elements must be used in each analysis. If different elements are used in the life cycle cost model, then a direct comparison between all the options would not be based on an equal scale. To be consistent and to make the analysis have some meaning, equivalent elements need to used in the comparison. For example, if the first life cycle cost model considered only four components in the operating and support of the product and a second model considered five components in the same phase, then the costs in the

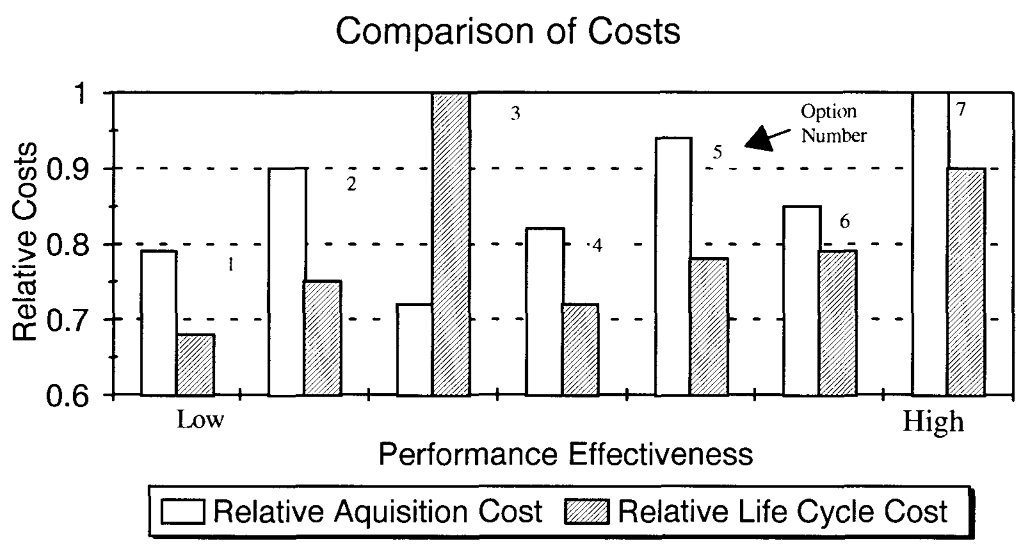

Figure 1.1.2. Relative Cost Rankings

first model may not be reflective of the true situation. Making comparisons in such circumstances would not be appropriate and possibly lead to an incorrect choice. This is a particular concern for an inexperienced user of life cycle costing for the purpose of evaluating various options.

As can be seen in figure 1.1.2, using the life cycle analysis can provide the means to evaluate the various options considered in view of the overall cost. Just comparing option 3 and 4 in the two graphs shows how expensive option 4 is when the life cycle costs are assessed. From the initial cost aspect, option 4 is the least expensive relative to all the other choices, yet the overall life cycle cost is the most expensive. This information should make it apparent how useful such analysis techniques could be.

Figure 1.1.3 show the distribution of direct life cycle costs for the a typical aircraft cycle. It is apparent from this diagram that almost 60 % of the cost incurred over the life cycle is in the support and maintenance area. Realizing that such a high percentage of the

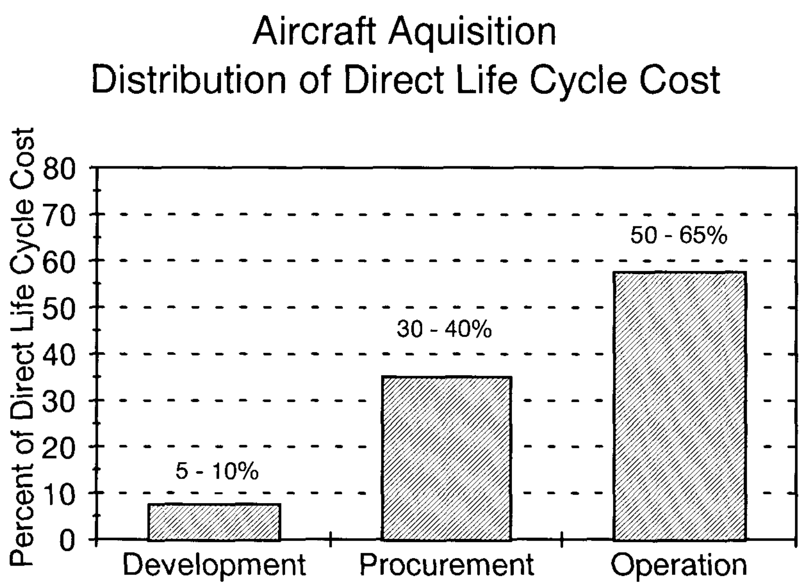

Figure 1.1.3 Distribution of Direct Life Cycle Cost

costs occur in the support area, life cycle cost analysis has proved to be very helpful in the aerospace industry. If life cycle cost consideration are not taken into account during design then the cost incurred over the life of the product may exceed the means of the owners.

Along with performing a life cycle cost analysis, a sensitivity analysis should also be completed of all the option available. Huie et al[4], gave the example of three suppliers' proposals which are as follows:

	Suppliers		
	A	B	C
Development	1.00	1.20	1.50
Procurement	1.00	1.20	1.30
Operating & Support	1.00	0.95	0.90
Life Cycle Cost	1.00	1.06	1.10

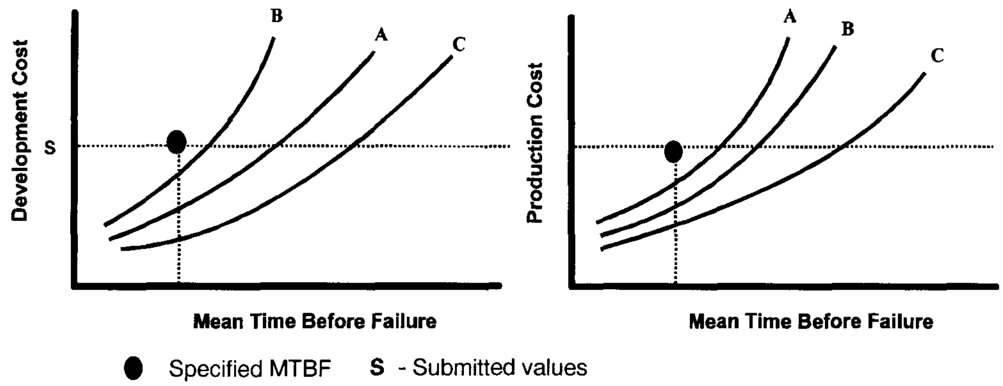

Figure 1.1.4 Comparison of Cost Functions

From the values given above, option A has the minimum life cycle cost. The suppliers were asked to provide results which indicate the sensitivity of these values to changes in the design parameters, specifically development and procurement costs. These are shown in figure 1.1.4. The point S on the figures represents the suppliers' initial submittal. So it can be seen that supplier C had designed his equipment to a much higher mean time before failure (MTBF) than the other two suppliers. If one was to use the same MTBF level for each of the suppliers, it is apparent that supplier C is now the most cost effective. Viewing the results from this perspective reverses the ranking order of the life cycle costs given in the table above. This indicates the importance and benefits of using a sensitivity analysis in the decision making process together with the life cycle analysis.

The importance and benefits that life cycle considerations have on a product have been shown. The next section will discuss how such consideration were implemented in the aerospace industry.

1.1.2 Implementation of Life Cycle Analysis

The early life cycle analysis were done using strictly parametric models. Data from previous designs were collected and cost estimating relationships developed from them. These models were of basic nature and usually only provided cost estimates that were within 30% of the actual (Jones, 1980)[3]. As these models were refined and subjective as well as statistical information were included in the model, the results improved to be within 10% of actual cost for detailed designs (Jones, 1980). All the estimates used in life cycle cost analysis are derived and extrapolated from previous designs, so the estimates can only be as good as the information used in the analysis. This causes problems for the designers, because they must have relevant data available to them to make the current estimates. A danger also exists when using the data base of information from old projects, since it is easy to extrapolate outside the statistical base which may yield results that are not possible or incorrect. It has been realized that it is almost always more cost effective to make improvements on existing technology rather than creating a completely new product. The research effort and testing that is required to design and develop an original product is more costly, but the maintenance associated with the new product in the first several years of service is considerably higher than that of a derived design (Grayson, 1980)[5]. Such an outlook on the design process would suggest that there should be little left to innovation of new designs. This is not actually true, since much can be done to improve existing designs with a higher reliability in the results, than can be achieved with a completely new design. However, when the current technology does not give the desired performance, then it is time for a new design with the incurred cost associated with it.

At the early stages of implementing life cycle cost analysis (LCCA), credibility of the results from such an analysis had to be established. What this type of analysis was trying to simulate in relation to existing logistics and maintenance policies had to be better understood to gain confidence in the analysis. There are generally two different types of LCCA studies. The first is to predict the likely budget levels for the cost of ownership for a future project. The second, is to quantify the effect of differing design aspects on the relative life cycle cost of the alternative aircraft configurations. Once the managers become more knowledgeable in LCCA and have a better understanding of the limits and the required extent of definition of the parameters used in the analysis, that credibility will evolve.

To implement a life cycle cost analysis, Jones 1980[3] has suggested to consider the following items.

1) Establish a cost breakdown structure and define terminology.
2) Utilization plan should be developed.
3) Maintenance and support concepts stated
4) Fiscal constraints stated
5) Cost model developed to suit current project
6) Review of information system available

Taking a structured and organized approach, as the one suggested above, would bring more consistent results to LCCA which in turn would increase the acceptance of the results. Through a conscious effort of consistency in the parameters used in the analysis, better comparisons between alternatives would be possible.

1.2 Nuclear Industry

The nuclear industry has considered the performance aspects from a quality management perspective,(Marguglio,1977)[6]. However, much of the information required for the quality management approach is very similar to that require to perform a life cycle analysis. These similarities will become evident when the information presented in this section is compared to the aerospace industry as well as the civil engineering industry.

The quality management approach necessitates that the desired requirements of the product be stated very clearly since it is these requirements that will determine the quality program that will be implemented. The requirements are typically obtained from existing codes, standards, and specifications as well as from the client. Experience gained by the designer in a particular field can also contribute to the requirements of the project.

The quality management approach in the design phase of development goes through a number of analysis depending on the importance of the item being considered. Marguglio 1977[6], suggests that techniques such as trade-off analysis, mission and environmental analysis, and quantitative reliability and maintainability apportionment can be used to establish the appropriate performance criteria. Once the performance criteria has been set, trade off analysis as well as yes-no analysis, (both will be explained in more detail later) can be used to determine if the desired performance levels can be achieved before commitments are made to the concept. A list of methods that could be used to determine the performance and design requirements are given below.

Techniques to Establish Design Requirements

1) Description of management system to control quality throughout the design process
2) Trade-off analysis to establish specific performance requirements
3) Mission and environmental analysis to establish specific performance requirements
4) System effectiveness quantitative analysis to establish specific performance requirements
5) Quantitative reliability and maintainability apportionment to establish specific performance requirements

6) Trade-off analysis to determine the design approach to meeting performance requirements
7) Yes-no analysis to determine the capabilities of meeting specific performance requirements
8) Analytical techniques to prevent non conformance to performance requirements or to assure conformance to them

The above outlined procedure does not have to be followed in the given order. This is arbitrary and it is up to the designer to decide on how to proceed. However, it must be kept in mind that much of this analysis can be done independently of each other, but the results from various analysis may be required by others working on another aspect. Therefore, good communication between groups that are dependent on each others outcomes should be established to minimize any re-evaluation of the work. All of the performance criteria established must be compatible with the given constraints of the project. Major constraints such as schedule and required funds must be considered in the entire evaluation of the performance requirements to ensure that the desired efforts are feasible. Different analysis may yield results that are not possible to achieve through current design capability. For example, a design approach chosen using the trade-off approach may not be capable of producing good designs based on the yes-no analysis.

1.2.1 Design Quality Plan

A key factor in such an approach is to outline a *design quality plan*. Such a plan is a compilation of all the components of a project with all related sub-components listed below and indented under the main component heading. In columns next to each item listed, the required design analysis is stated as well as the required design reviews and the level of quality required. The type of documents required (codes, standards and specifications) are also listed with the relevant sections. An example of a *design quality plan* is given in Table 1.2.1.

Table 1.2.1 Design Quality Plan

Item List	Required Design Analysis	Required Design Reviews	Quality Level	Required Documents			
				Codes	Standards	Specification	Other

Such a plan makes the designer aware of what is required for all of the components or items used in the project. It also makes the designer aware of quality issues early in the design phase. As the design progresses, items can be added to the quality plan and this shows that quality has been considered early in the design.

1.2.2 Mission, Performance and Environment Analysis

At the conceptual stage an evaluation of all expected uses and imposed conditions the product will be subject to must done so that the design does not prove to be inadequate under certain circumstances. A mission, performance and environmental analysis would assist the designer in dealing with these considerations. A table could be developed for this purpose with the expected uses classified under missions which make up the rows of the table. The columns would represent the various performance requirements and environmental conditions the product will be subjected to. An example is shown in Table 1.2.2.

Table 1.2.2 Performance and Environmental Conditions

Missions	Performance Requirements and Environmental Conditions			
	speed	altitude	temp	shock
Case 1				
Case 2				
Case 3				

The use of such a table would help the designers to formally state the requirements that must be met for the project. If all of the missions stated are to be designed for, the most stringent performance requirements under each condition would be used as the design standard that must be achieved.

1.2.3 System Effectiveness Analysis

System effectiveness analysis is another type of trade-off analysis which considers the three phases of the product mission. These three phases are availability, dependability, and capability. It seems obvious that one would want the product to be available when it is required to perform its mission, since that is the reason for its existence. Once the product is put to use, the product should perform dependably without failure. However, if the product does have a failure, it should be easy to repair so that such occurrences will have a minimum impact on the mission performance. Capability of the product to perform the objectives to the desired level of performance during the mission is the last phase of the effectiveness analysis. Each of these phases plays an equally important role in the effectiveness of the product. Comparisons between various alternatives can be compared with respect to these three phases to arrive at the best possible choice for the application.

Reliability and maintainability aspects of the product are very closely related to the effectiveness of the product. Marguglio[6] suggests to develop a functional block diagram of the system down to the lowest level that is considered appropriate, i.e. component level. Then a mathematical model is developed that describes the reliability relationships between the elemental blocks. The quantitative reliability requirements are then distributed to each of the functional blocks in consideration of complexity of the functional element and the criticality of the element. Other factors such as the degree of redundancy and the maintainability of the element, all influence the reliability associated with each of the elements in the block diagram. Much of these values must be assigned early on in the design process when many aspects of the design have not yet been decided, and hence, assumptions must be made. As the design matures, these mathematical functions can be updated and refined. Some data that will be required to assign reliability values to the elements will not be available and for this reason this type of analysis can only be considered a rough estimate of the overall reliability of the product. Breaking the product up into the various block elements and assigning the reliability values to each of these smaller elements and then summing these elemental reliability up to get the overall reliability of the complete project is thought to be the best way of estimating this overall value. If it were not broken down into smaller components, the estimate would have a lot more uncertainty associated with its value than the broken down model. Using such an analysis technique, again shows the reviewers or the client that due care and attention has been given to assessing the performance of the product during the design if something does go wrong during the service life of the product.

1.2.4 Trade-off Analysis

Using a trade-off analysis to evaluate the performance requirements of the product as well as determining which design to use once the requirements have been determined, is great benefit to the designer in helping him make his choices. The typical steps in a trade off analysis are shown in figure 1.1.5.

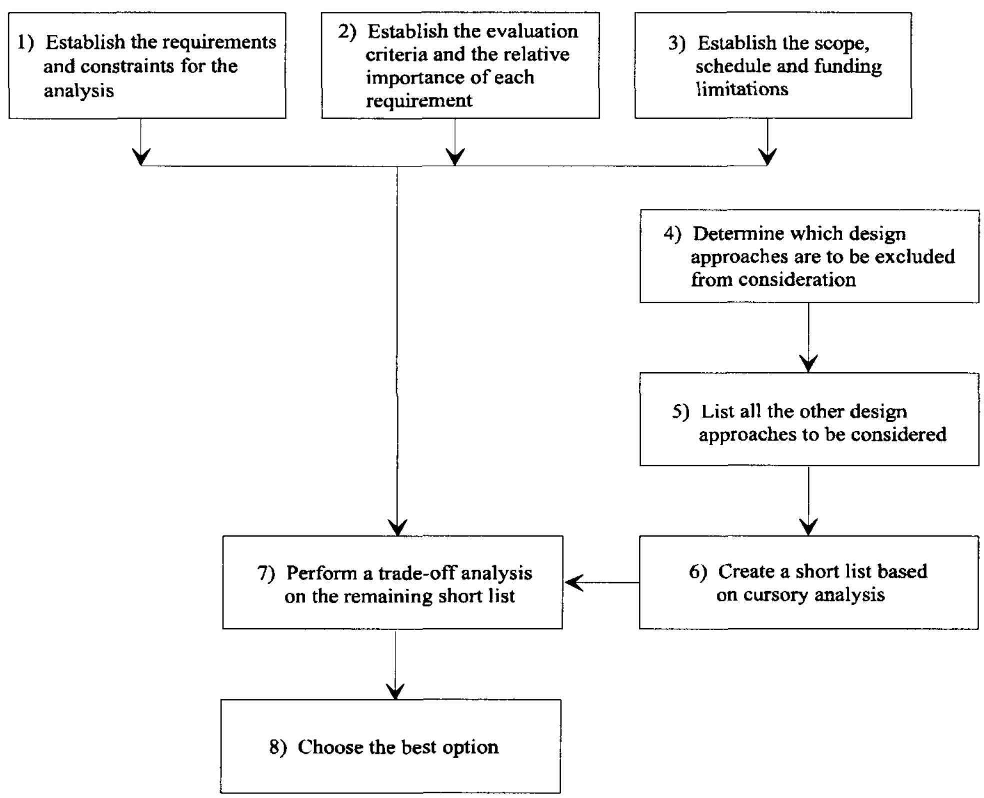

Figure 1.1.5 Steps in a Trade-off Analysis

The most difficult and important steps are the first and second. The requirements and the relative importance of each, could have a large influence on which design is chosen. A sensitivity analysis would be worth considering in this type of trade-off analysis since it would show how a change in the requirements may change the choice of design.

1.2.5 Yes - No Analysis

A Yes-No analysis has the primary goal of determining where adequate technology does not exist to meet the current design requirements. The analysis is applied to a project work break down structure. That is, the project is separated into its various systems, with each system further subdivide into sub-systems, and sub-systems into modules etc. For each of these levels, an evaluation is done to ascertain if it is possible, with current technology, to meet the requirements on schedule and on budget. If the answer is no, then a "no" is assigned to the current element level, say level 4, and all levels above the current level that are connected to level 4 will also have a "no" assigned to them. This will show where the design needs further development and assessment to see if the requirements can be met under the current constraints. Figure 1.2.1 illustrates the use of a Yes-No structure.

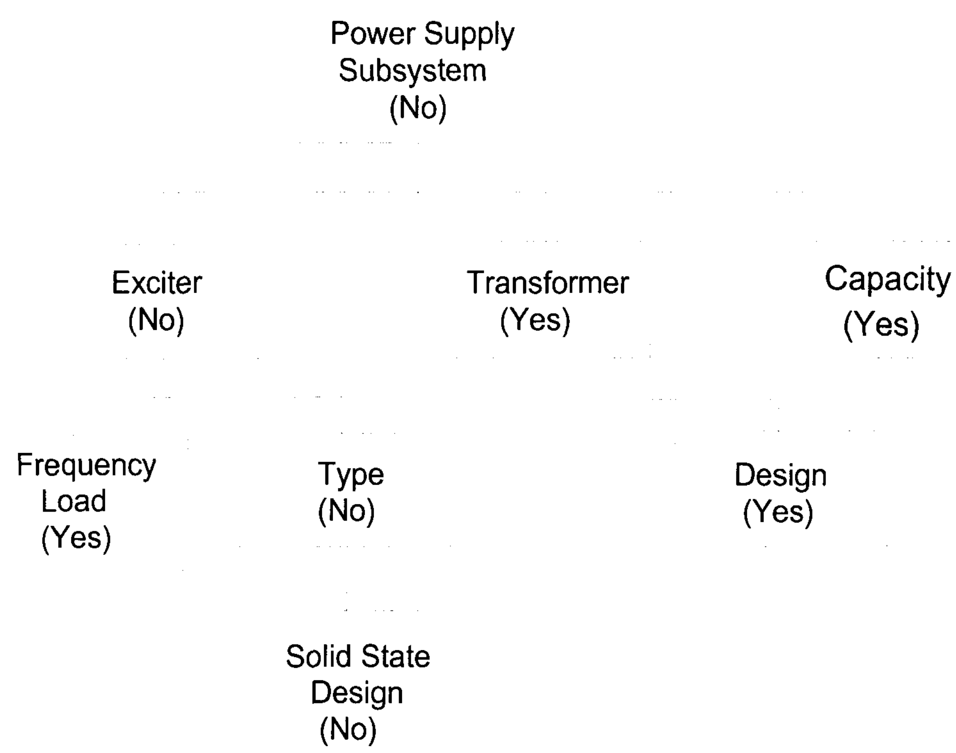

Figure 1.2.1 Yes - No Network Analysis

Figure 1.2.1 indicates the Yes-No structure for a power supply subsystem. From the figure it can be seen that it is the solid state design of the exciter which is the reason that the power supply subsystem cannot be completed. All levels that are dependent on this component have been assigned a "No" and until the solid state design issue is resolved, the subsystem cannot be completed. The designer must now decide what is required to resolve this and if the solution is not feasible using available technology, research and development may be one avenue to obtain a solution.

Once the design parameters have been determined, a maintenance task analysis should be performed which would determine the type and form of maintenance required for the design. The following benefits would result from such an analysis:

1) Checklist of maintenance tasks for which maintenance procedures are required
2) Fault detection and correction verification criteria to be incorporated in operating and maintenance procedures
3) Special tools, equipment, personnel skills, and procedures data used to evaluate compliance with design standards and to identify potential cost reduction design improvements
4) Checklist of special tools, equipment, personnel skills, procedures and maintenance aids used as input for future estimating and budgeting and for scheduling the design/procurement/fabrication of the item on the checklist
5) Safety precautions data to be incorporated in operating and maintenance procedures
6) Maintenance and man hour estimates used for future estimating and budgeting and incorporation in manpower or staffing plans
7) Calendar or elapsed maintenance time estimates used to evaluate the degree of compliance with mean time to restore and turn-around requirements
8) Checklist of maintenance tasks used for the identification of required spare and replacement parts.

With such a maintenance task analysis, much of the thought that goes into the maintenance aspect of the design is then formalized and documented. If nothing else, the designer has been forced to evaluate all maintenance aspects of the design so that the estimates of the overall performance and costs can be done.

Once the design requirements have been established and it has been determined that the design can proceed, methods of evaluating the development of the design must be considered. It is at this stage that the design review comes into play. The complexity of the design will determine how much design review will be required. Marguglio[6] has suggested that more progressive design reviews should be implemented instead of one final design review. If there is only one final design review, there is a larger possibility that some changes would require a large amount of reworked, which could have otherwise been dealt with earlier in the design. A progressive design review would minimize the amount of rework since the choices made by the designer would be reviewed as the design progressed and any problems would be caught at a much earlier stage in the design process. The following benefits could be realized if such a process were implemented:

1) Fosters a more cooperative atmosphere
2) Allows evaluators to maintain understanding of design and decision trade-offs
3) Provides a better opportunity for designers to understand all aspects of the design
4) Increases chances of selling needed design improvements
5) Reduces cost of making design improvements
6) Reduces adverse schedule impact of design improvements
7) Allows sufficient time for review of design improvements
8) Precludes exertion of schedule pressure on the evaluation organization

Going through such a design review procedure and documenting the results of each review along with recommendations, provides the records to show that effort has been expended towards achieving the requirements. This can also be used to indicate to the client that a logical and rational approach has been applied to arrive at the final design. A checklist procedure for the various design aspects should be developed and documented so that the procedure is of a formal nature rather than informal. A formal approach would yield better results since there is a less likely chance that some reviews would be missed. A breakdown of the various design aspects could be classified under the following headings:

1) Geometry
2) Kinematics
3) Forces
4) Energy
5) Material
6) Safety
7) Ergonomics
8) Production
8) Quality Control
9) Assembly
10) Transport
11) Operation
12) Maintenance
13) Costs
14) Schedules

Under each of these headings, a check list procedure should be developed which is appropriate for the current project. Figure 1.2.2 shows a very general outline that could be applied for the checking procedure.

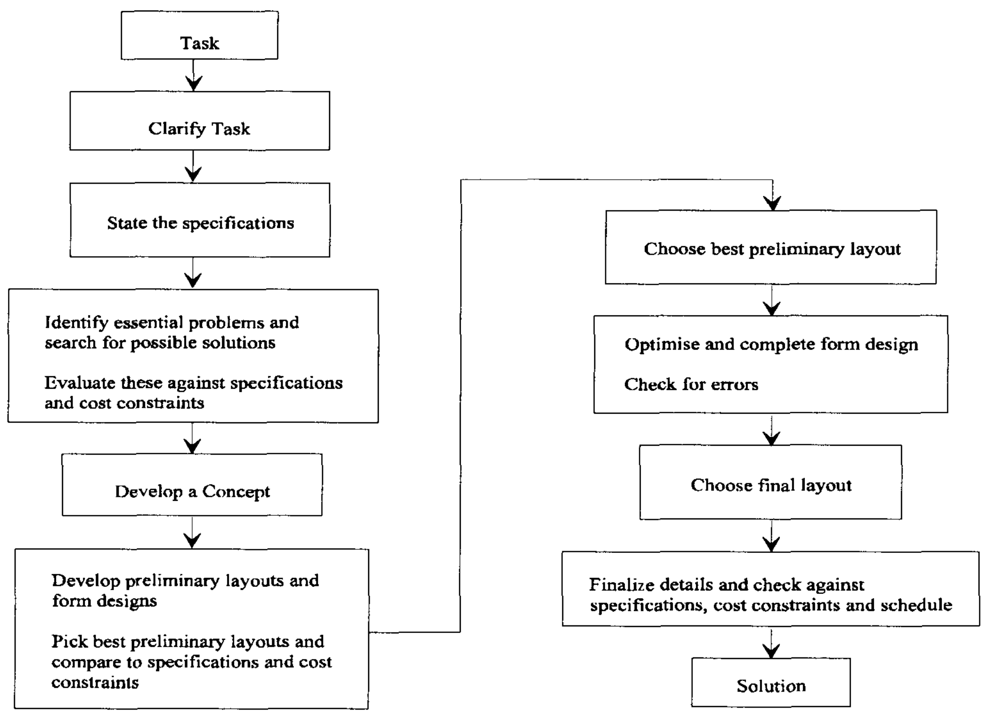

Figure 1.2.2 Proposed General Design Check Procedure

1.2.6 Component Qualification

As a means of achieving the design objectives, the nuclear industry has used component qualification to ensure that the product will perform to the defined requirements. Qualification is defined here as the capability of the component to be manufactured according to the specifications and requirements. Also, the component must have the capability to perform its function under the most adverse expected working conditions. To obtain the component qualification, tests must be performed or models constructed and then correlated with actual data. The importance of using appropriate testing methods so that the results are representative of what will be experienced in actual practice must be realized. In many cases it is not feasible to construct full scale models of components and test them, so scaled models or simply portions of the component are tested. Caution must be exercised in this area since it is not usually known if the test data correlates with the actual performance in practice if the product being tested is new. The difficulties with testing procedures is considered in more detail in Chapter 2. The main benefit realized by implementing a qualification testing procedure is that confidence is gained in the component prior to commitment of resources to the product. This also provides some reassurance that the project schedule and financial constraints can also be met using the proposed component.

1.2.7 Feedback Mechanism

It has also been realized that a mechanism must be put into place to monitor the performance of the product after it is completed and convey this information back to the designer. This not only gives an indication of where the design could use improvement, but provides information on how the changes used in the current project have worked. A *closed loop corrective action system*[6] could be developed to address this feedback requirement. This is shown in Figure 1.2.2.

Feedback mechanisms are developed for such a process in order to have information come in, in a structured format for compilation and evaluation. The structure of these mechanisms for documenting the information will depend on the type of information that is being tabulated, which in turn, depends on the type of component. These have to be developed individually for the system that one is dealing with. However, once such a

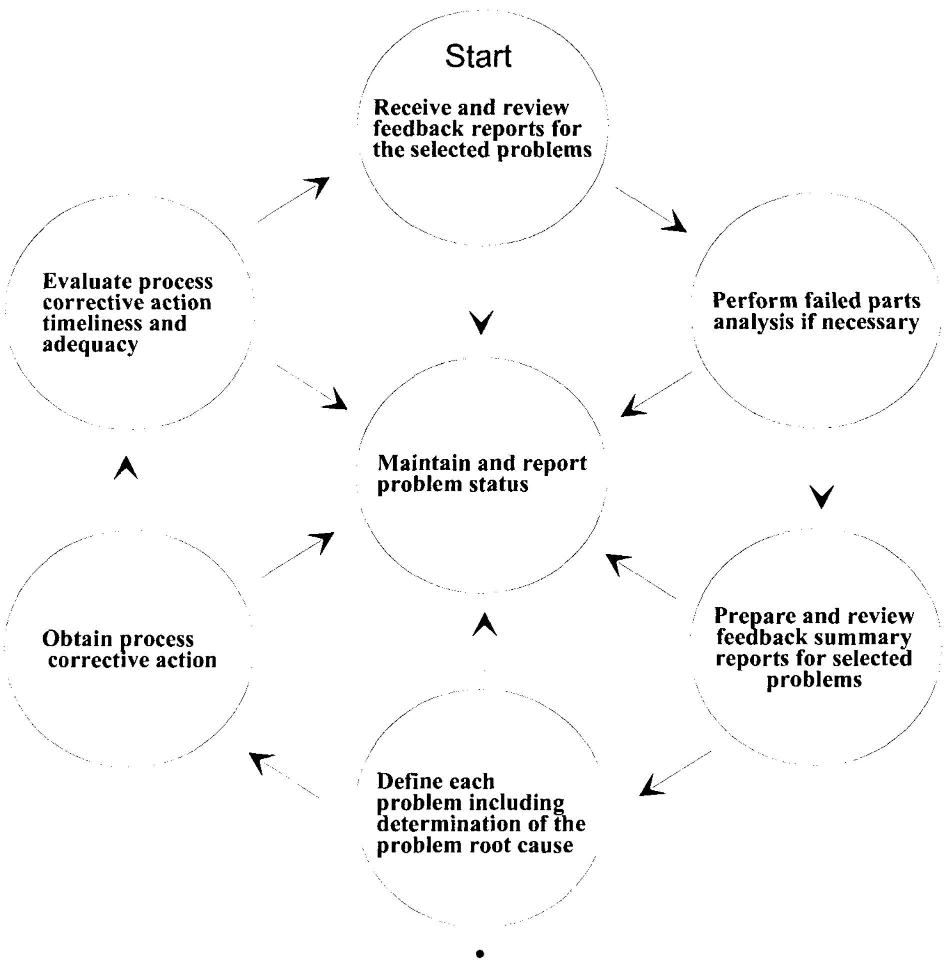

Figure 1.2.3 Closed Loop Corrective Action System

mechanism is put into place and the maintenance and inspection personnel provide this information, action can be taken to rectify the problems. A data base for the particular project can also be compiled which would assist the designers in accessing the information in a rational and efficient way to use in future designs.

1.3 Structural Engineering

The field of civil engineering has not considered life cycle evaluations as being important to the same extent as other industries such as the nuclear and aerospace industry have. The aerospace industry was forced into using life cycle analysis to control the costs of their products and production. These constraints were imposed by the largest client of the industry, the government. The nuclear industry was drawn into using life cycle analysis by their concerns over quality and performance in their structures. The service lives of nuclear power generation stations were foreseen to be long term projects and hence performance under adverse working conditions had to be dealt with. It has only become a concern to the participants in the civil engineering industry, more specifically in the structural engineering discipline, in the last 10 years or so. This attention to life cycle considerations has been spurred by the poor performance of structures in the last 40 years. The questions have been raised as to what can and should be done to improve the performance of structures. Life cycle analysis would make the designer more aware of the factors influencing the performance of a structure, but do we have enough information available to make the required decisions to improve the service life performance of structures. In the following sections a summary of suggested methods of dealing with design life issues are presented as relating to structural engineering.

Stillman[7] has suggested a rational and quite structured approach where the designer first develops a building profile of the structure. Such a profile starts with determining the required life of the structure. Table 1.3.1 could be used to make this choice. Further information, such as the building use and what loads, agencies, and climatic conditions the structure will be exposed to, should also be determined as indicated in Table 1.3.2.

Table 1.3.1 Categories of Required Life (after Stillman, 1990).

Class	Life Span	Examples
transient	up to 1 year	fair structures, special events
temporary	1 - 10 years	site offices, exhibition structures
short life	10 - 30 years	trailers, temporary classrooms
medium life	30 - 60 years	commercial, industrial buildings
normal life	60 - 120 years	public sector structures, military bldgs.
long life	more than 120 years	civic and other high quality buildings

Table 1.3.2 Building Use and Service Environment

Building Use	Examples of Service Environment Exposure
commercial	impact loads of light machinery, storage loads, transportation usage
industrial	vibrations, processing chemicals, humidity, heat generated by equipment
residential	occupancy load, climatic conditions, public traffic
shelter	impact loads, extreme climatic conditions
military	combat / peace time conditions

It is only after determining the required life and the building use that materials and conceptual forms can be chosen which may meet the design requirements. Classifying the components of the structure, with respect to the duration of their lives and the required maintenance, will assist the designer in making choices that will meet the objectives. An example of such a classification is given in Table 1.3.3 and Table 1.3.4.

It should be stressed that a good understanding of the properties and limitations of the materials being considered is necessary to reduce effects of poor detailing on the design life of the structure. A further classification considering the failure mode can be made. All of this information could be stored on a design life data sheet. Table 1.3.5

indicates the failure modes, and Table 6 is an example of a design life data sheet.

Table 1.3.3 Classification of Components (modified Stillman, 1990).

Class	Description	Examples
replaceable	easily exchanged building components or equipment	floor finishes, mechanical & electrical components
maintainable	lasts with treatment for a lifetime of the building	doors and windows, handrails, wall coverings, wall paper, paint
life long	lasts the life of the building	foundations, precast cladding panels

Table 1.3.4 Further Definitions of Maintenance (modified Stillman, 1990).

Maintenance	Description	Examples
repairs only	as required	broken windows, damaged doors
scheduled maintenance / repairs	at regular intervals	5 yearly repainting of joinery
condition based maintenance and repairs	to follow regular inspections	contract maintenance of elevators

Table 1.3.5 Classification of Failure Modes (Stillman, 1990).

Class	Failure Mode
I	danger to life
II	danger to health
III	costly repair
IV	frequent repair repeat
V	interruption of building use
VI	no exceptional problems

Table 1.3.6 Example of a Design Life Data Sheet (Stillman, 1990).

Data	building category *medium life* (Table 1.3.1) to be built on exposed site in Vancouver	
external finishes	roof membrane	
	materials	mastic asphalt
		replace every 15 years
	failure mode (table 1.3.5)	VI: no exceptional problems

The designer now has the task of deciding what components and forms of construction will be suitable to achieve the anticipated performance as stated in the data sheet. Such an approach is used during the conceptual phase of the design process. A flow chart outlining the procedure above is shown in figure 1.3.1.

To deal with the problem of deciding which design is the most economical in achieving the desired objectives, some form of life cycle cost analysis must be done. The following two approaches are proposed which could be used for such an evaluation. The first is the *Modified Structures Appraisal Approach,* introduced by Webber[8] and expanded by Tam[9] for the special case of highway bridges. The latter included a discounted cash flow analysis, providing a computer aided framework within which through-life costs can be easily examined in regard of its corrosion protection. Adopting such an *Cost Analysis* (CA) approach permits sound investment decisions based on as many fact as available. One can easily find in Tam's computer simulation, which level of initial standard is needed or justified. The steps for this approach are shown in Figure 1.3.2.

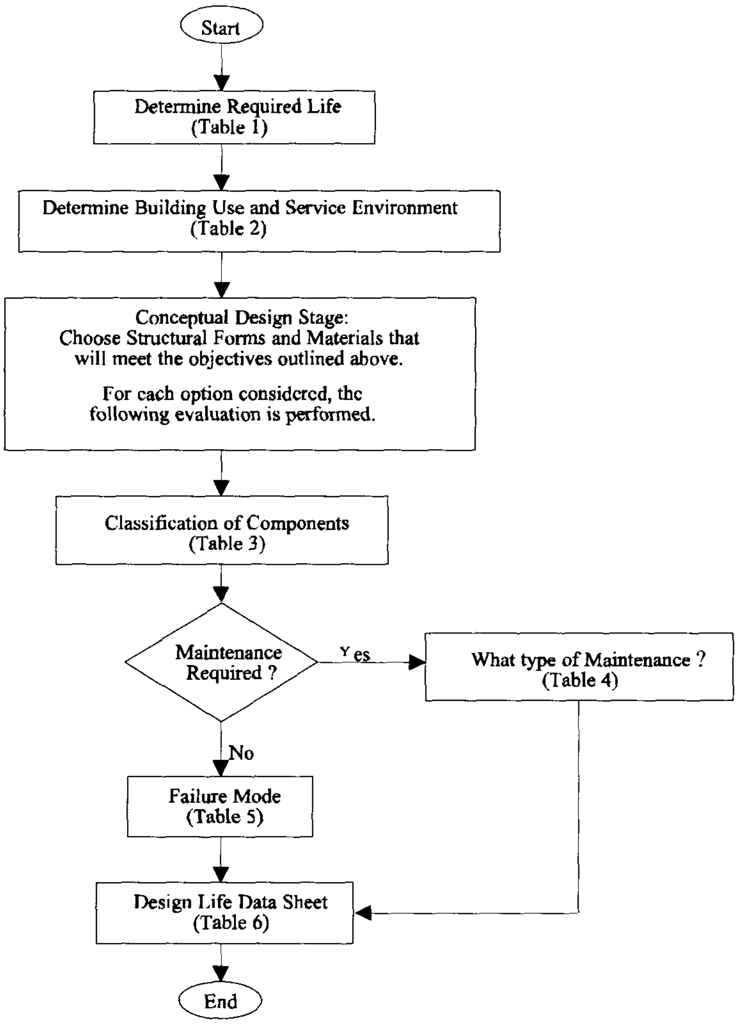

Figure 1.3.1 Flow Chart for Use with Tables 1.3.1 - 6

The first two steps can be handled using the procedure outlined earlier. The third step, how to identify the costs and benefits of each option, can present some problems for the designer where insufficient repair cost information is available (which is most of the time). The fourth step is easily dealt with using common engineering economic principles. The fifth step, how to evaluate uncertainties, can be a judgmental consideration that the designer must deal with, because there is usually inadequate data available for him to predict with much accuracy the benefits of higher initial expenditure with reduced maintenance over the long term. These uncertainties can possibly be reduced if a sensitivity analysis were used to get a better estimate of the long term costs. Another approach utilizes probabilistic distributions or expert systems based on fuzzy logic (Tam[8]). The designer must communicate these parameters to the client and then reach a consensus on what to use for the given situation.

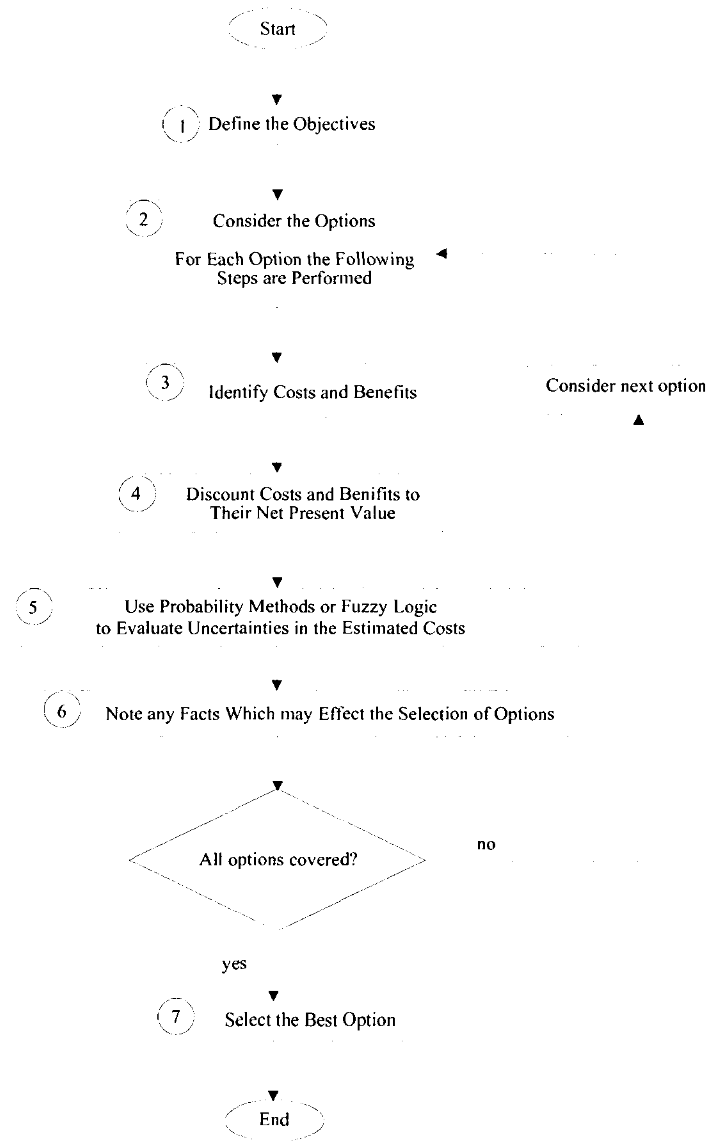

Figure 1.3.2 Flow Chart of the Structures Appraisal Approach

Another proposed approach is based on the *Performance Approach* by White[10]. This method starts with the development of a particular building performance profile which is appropriate for the current objectives. It includes defining the clients strategy for maintenance and evaluates the seriousness of premature failure of any element to the clients operations. Such a profile could take the form of Table 1.3.7.

During the next step the design team prepares *System Performance Profile* using a similar format to that shown in Table 1.3.7. The extent of each system profile will depend upon its importance to the building and the impact of premature failure. This is brought to the attention of the client and a consensus is reached to form the basis of detailed design development. Then the design team selects the materials and systems with the appropriate performance characteristics and anticipated life. When all the information on maintenance, repair, and part replacement as available is given, costs-in-use can be evaluated and comparisons made between the various options chosen.

The necessary information could be obtained from the following sources:

- manufacturers' and suppliers' technical literature,
- published test results from recognized laboratories,
- feedback from existing buildings,
- tendering on performance specifications, with tender's responding by supplying full operating and maintenance details and the anticipated life expectancies related to the offer,
- a building performance and cost-in-use data base.

In this approach the system and material performance profiles and cost-in-use forecasts from various design stages become part of the normal operating and maintenance manual.

Table 1.3.7 Example of a Building Performance Profile (White[10])

Building System Detail	Criticality	Target Life Before Replacement [in years]					
		>5	5 - 10	10 - 20	20 - 40	40 - 100	<100
Foundations	A	---------	---------	---------	---------	---------	---------
Structure	A	---------	---------	---------	---------	---------	---------
Exterior Walls	A	---------	---------	---------	---------	---------	---------
Exterior Cladding	B	---------	---------	---------	---------		
Curtain Walling	B	---------	---------	---------	---------		
Windows	B	---------	---------	---------	---------		
Roof Covering	A	---------	---------	---------			
R.W. Goods	B	---------	---------	---------			
Internal Partitions	B	---------	---------	---------	---------		
Demountable Partitions	B	---------	---------				
Doors and Iron work	C	---------	---------	---------			
Finishes Generally	C	---------	---------	---------			
Raised Floor	A	---------	---------	---------	---------		
Floor Covering	B	---------	---------				
Suspended Ceilings	B	---------	---------	---------			
Fittings / Furnishings	C	---------					
HVAC Plant	B	---------	---------	---------			
HVAC Ducts / Pipes	B	---------	---------	---------			
Water installations	B	---------	---------	---------	---------		
Public Health Services	B	---------	---------	---------	---------		
Drainage	B						
Sanitary Fittings	B	---------	---------	---------			
Electrical Plant	A	---------	---------	---------	---------		
Electrical installations	A	---------	---------	---------	---------		
Lighting	B	---------					
Internal Decorations	C	---------	---------				
External Decorations	C	---------					
External Works	D						
Paved Areas	C	---------	---------	---------	---------		
Road Surfacing	C	---------	---------				

The rating system for criticality is defined as:

A = *Highly critical:* failure causing the use of the facility to stop during repairs.

B = *Critical:* reduce the working efficiency, repairs done outside of normal hours.

C = *Not critical:* requires remedial work but not immediately necessary.

D = *Not effecting the structure.*

A specialized profile with the information appropriate to facilities managers can be made available to future tenants. A number of apparent benefits result from such an approach:

- Clients are provided with the means to convey to the designer the performance required or state their needs so the designer can respond.
- Designers can ensure that the clients understand the limits of expected performance at a certain cost, and can respond to the clients requirements.
- Designers and manufacturers can select and provide materials appropriate to meet the clients' needs.
- Designers can demonstrate that they have exercised skill and care in the selection of materials.
- Facilities managers and maintenance engineers can be briefed on the anticipated running costs and the re-investment pattern likely to be required during the life of the structure.

The durability of a structure or component is what a designer would ideally like to be able to predict. However, this is where much information would be required to predict with any certainty the durability of a material in a given environment. The complexities of this issue will be discussed further under the heading *Testing* , in Chapter 2 on page 45. Currently the durability of a structure over its service life is ensured through a prescriptive approach used in the building codes. For example, CSA A23.1-M90 specifies minimum cement contents, maximum water to cement ratios, and minimum concrete covers for various aggressive agents. Using such standards would help to ensure that a reasonable durable product will result. However, these standards do not quantify the length of time that the structure will perform without excessive maintenance costs. We know that all structures deteriorate over time and the loads imposed on structures usually increase during the structures service life. If we consider the resistance of a structure, R, as decreasing over time and the loads on a structure, L, as increasing over time, and that both R and L are normally distributed we get curves shown in figure 1.3.3[11]. As the structure ages, the overlapping area between the two curves increases which eventually will result in failure. The rate at which these two curves merge is a function of many factors, but as mentioned earlier the exact rates cannot be easily quantified at this time. It will not be until more comprehensive field performance data is available, that more quantitative methods and more precise predictive relationships will be developed.

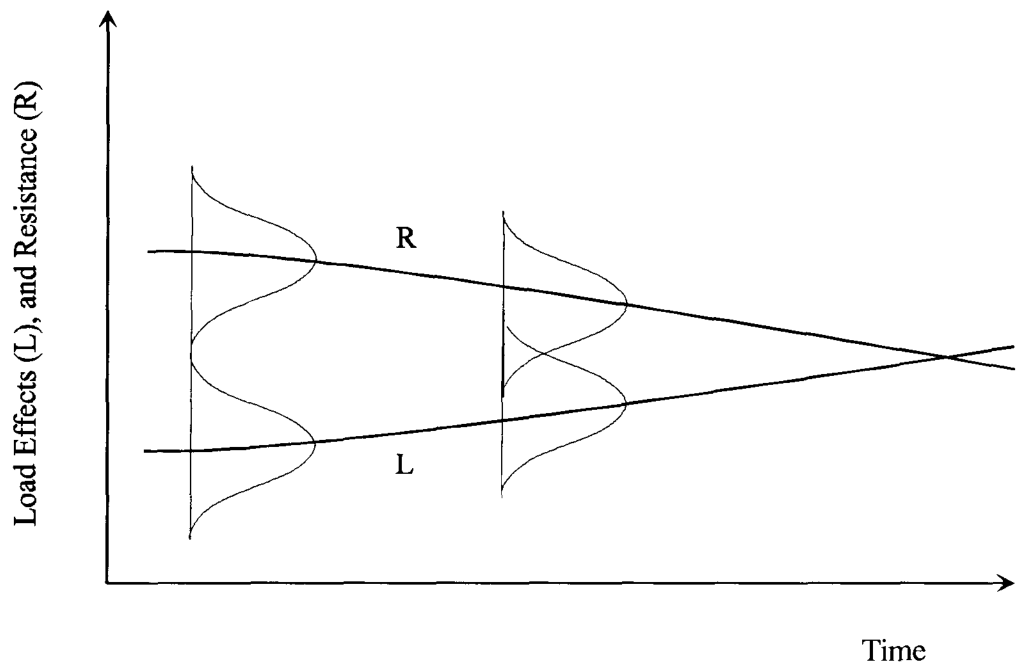

Figure 1.3.3 Load-Resistance verses Time

However, the seasoned engineer will be able to qualitatively provide information through his own experience. Engineers practicing in one area for any extended period of time have a very good feel for what seems to be required to achieve the objectives. What will work in one location and climate may not be appropriate for another, and this is what local engineers can contribute to the design.

Obtaining maintenance cost information can present a problem to the designer. To determine what and how much information is available, two property management firms were contacted. Since it is their business to manage and maintain properties, they have records of all expenditures for each complex which they are responsible for. Both firms indicated that they have not made any formal attempt at compiling or sorting the cost data. Through their experience they know that some features are costly to maintain such as pools and water fountains. They have not considered performance aspects of the various building materials since they are not usually involved in the design and construction stages of the development where such choices must be made. Property management firms would certainly be one source of cost data which may prove to be helpful for the designers. A development company was contacted which builds and maintains only commercial use, reinforced masonry buildings. These buildings consisted of office/retail space in the front and warehouse storage space in the rear. The same development company indicated that they have complete construction and maintenance cost information for all of their buildings, but they have never used any of it for design purposes. They did indicate that, as common practice, they put 5% per year of the structures original cost into a maintenance fund for that structure. They have found this amount to be adequate to cover maintenance costs incurred during the service life of the structure, such as replacing heating and air-conditioning roof top units, re-roofing, painting, and regular maintenance. All the structures that the development company maintains are in one city and hence these costs could vary if buildings were in a different climate and exposed to different agencies.

1.4 Quality Control and Quality Assurance

Quality control has played a large role in the manufacturing sector since it was first implemented in the United States in the early 1950's. As methods evolved, the results from implementing quality control has yielded better products with higher customer satisfaction. The focus of such quality control procedures was mainly in the manufacturing arena, since such processes usually have large production runs where statistical methods could be applied. Much quality control was in the form of inspection for defects, but recently companies have become aware of the need to prevent defects, and this is where true quality control is becoming a reality. To determine after a production run which of the products have met the quality standard is important, but trying to prevent and improve the production process to eliminate the need for the inspection at the end of the run is the true goal of quality control. This leads to a definition of what quality control and quality assurance really is:

> *Quality control is a diagnostic system to discover problems in work procedures and output. Once steps are taken to improve or eliminate these problems and checks are put into place to assure that the problems have been addressed, quality assurance has been established.*

This discussion appears to be very relevant to any manufacturing process where repetition is involved in the production of a product. However, many of these principles could be applied to low production items and one-of-a-kind products, such as civil engineering structures. Most buildings that are designed and constructed are one-of-a-kind items, though they may be very similar one another, they are considered single entities. The approach of applying quality control and quality assurance to such a project takes much the same form as the approach suggested by Stillman in creating a building profile of the various components of the structure (section 1.3). The establishment of a quality standard for the various aspects of design and construction, right through the support phase to the end of the structures envisioned life is required. For designers dealing with particular types of projects, the quality standards would only have to be modified to suit the current project. If this is a new type of project, which they have not done before, a new standard would have to be developed to ensure the quality of the design and construction.

1.4.1 Development of Quality Control Standard

The creation of a quality control standard could be considered in two levels, the *system approach* and the *project approach*, as suggested by Mizuno[12]. The system approach involves establishing work standards for every step of the way, from design to the end of the products life. This includes deciding on the quality characteristics, stipulating the quality indices, and establishing standard quality. Also, an explanation of how to check for abnormalities, how to trace their causes, and how to correct them should be stated. The project approach concentrates on specific quality problems, determining the priority problems and correcting them. One approach is not independent of the other and it is only through the use of both, that a sound and effective quality control program can be achieved. To devise a quality control program, Mizuno[11] suggests the following six questions must be answered for each component and step in the project life.

1) Why do you need to do this?
2) What are you going to do it with?
3) Where will you do this?

4) When must you perform the activities?

5) Who is responsible?

6) How will you carry out the tasks?

Addressing these six questions for each aspect of the project basically formalizes the quality control commitment. Going through the process of answering these questions for each of the design aspects of the project, makes the designer and all those involved in the project aware of the requirements that are trying to be met. New aspects that have not been encountered before in design will have higher quality control standards applied to them since they will be subject to higher uncertainty. This will be outlined in the quality control standard for the project, which is made available to the personnel working on the project so that the right amount of effort and time is allocated to the various design aspects. Many informal quality control activities are implemented in design offices, such as engineering design calculation checks by a second designer, review of conceptual proposals to determine which is the most suitable for the current need etc. Such informal, yet required processes, would be incorporated into the formal company quality control plan, easing the transition in implementing a total quality control plan. Quality control information could be included in the design life data sheet proposed by Stillman in table 1.3.6 of the previous section and repeated here. The form of the data sheet incorporating the quality control concerns could be as shown in table 1.4.1.

The quality standard designation comes from the quality control plan for the project. Once this has been stated in the design life data sheet, the designer not only knows what conditions and expected life he must design for, but also he is made aware of what controls must be implemented at this design and construction stage to ensure that this aspect of design is carried out correctly.

Table 1.4.1 Modified Example of a Design Life Data Sheet.

Data	building category *medium life* (Table 1) to be built on exposed site in Vancouver	
external finishes	roof membrane	
	materials	mastic asphalt
		replace after 15 years
	failure mode (table 4)	failure mode (table 4) F: no exceptional problems
quality control	level of inspection	quality standard X.X.X

In developing and monitoring a quality control program, the following six questions must be answered to ensure that the program achieves the desired goals.

1) Why do you need control?
2) What are the control items?
3) Who is responsible?
4) When must control be carried out?
5) Where is control required?
6) How will control be performed?

For each of the design aspects these considerations must be carried out to arrive at the appropriate quality control plan for the project. The documentation that must be a part of the quality control effort in critical to ensuring that the appropriate checks were done. A complex and lengthy process would only hinder a successful quality plan since this would only take away valuable time from the design work of the project. Efficient and effective forms for the documentation of the quality control effort are key to a useful and successful plan. Taylor[13] has suggested the use of flow tags, stamps, labels, or other devices which are appropriate for the current project, in order to show that the control measures have been applied where called for. In the construction phase of development of a project, many human factors play a large role in the final quality of the project. The quality control plan would address these issues at the time of its development and hence, the level of inspection and type of quality enforcement would be decided at that time.

There are areas on large projects that can cause problems in implementing quality control where many groups of people are involved, such as construction projects. These problems arise when quality issues must be transferred across the interface that links the various groups to the project. This is where a formalized quality control standard is important so that the various parties can be informed consistently with what is required in the project. If no such quality standard exists, it will be difficult to ensure the desired level of conformance of the work has been achieved by all parties involved. Communication of requirements in construction projects is normally accomplished through the use of specifications given in contract documents so that contractors know before the work begins the level of performance expected as well as the measures used to control their work. Critical elements of the project should be brought to the attention of the contractors so they can exercise the appropriate amount of time effort to achieve the desired goals or perhaps suggest other options to achieve the same end product.

The development of a quality control plan would benefit from the input of the groups involved in the project. Such an approach has been implemented in many factories, especially in Japan, and has been known as the quality circle. This is an action team, composed of members of management, workers, and sometimes union representatives, that meet regularly with a group facilitator to work on quality and productivity matters. Such a program provides feedback and possible solutions to issues from the people that are directly involved in the various aspects of design and construction of projects. A level of cooperation is developed amongst the various parties, which can only help in improving the end product.

With the current trend of rapidly evolving technologies, the quality standards must take this issue into consideration by leaving some flexibility in the requirements where appropriate. This stems from situations where new products are developed, which have never been constructed or installed before, and there are always unexpected difficulties that arise during this process. The quality assurance standard, no matter how much thought goes into its preparation, will need to be updated once the construction or installation is complete. In these situations, contractors or groups with experience in the appropriate areas should be consulted during the development of the design standard to come up with reasonable requirements that can be achieved with the current level of technology.

There are many quality assurance standards in existence for the various disciplines, and most are tailored to production items. Taylor[12] has adapted the CSA Z299.1-1978 (which has been replaced by CAN-ISO 9000 series) quality control standard to deal with design and construction issues. The International Standards Organization (ISO) 9000 standard is now recognized and respected internationally as the goal that should be achieved in implementing a quality program. All these standards are guidelines for the development of quality assurance programs and in the case of one-of-a-kind projects, modifications to suit the current needs will have to be done to allow the quality system to yield the desired end result. An example of a quality control frame work for structural design suggested by Tsuyuki 1990[14], is given in Appendix 1.

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CHAPTER 2

DESIGN LIFE CONSIDERATIONS

The life cycle analysis considered earlier is not a separate evaluation from design life considerations. Design life issues deal specifically with the evaluation and prediction of component lives as well as the life expectancy of entire products. This may appear to be a simple task on the outset, however, a closer look at the issues will indicate that this is a complicated undertaking. The difficulty in dealing with the design life of a component or product comes from the numerous variables and influences that play a role in the deterioration and wear and tear of a product. The design life issue is a part of the life cycle considerations, since in order to estimate the life cycle cost of a product the expected service life of the various components needs to be known (or estimated). This leads to the realization that until some performance data is known, no estimates can be made. The ultimate goal of any designer is to be able to predict the service life of a component or product over a long time frame with great accuracy. A vast amount of information needs to be available in a usable format to accomplish such a task. This is a focal point that must be addressed to achieve the level of performance desired and demanded in many disciplines. Research institutes such as universities and private laboratories have devised a number of testing techniques to provide this information, but there are many difficulties in extracting accurate results. This will be discussed later in more detail. Another issue affecting the performance of products, is the type or types of materials that are used to achieve the desired goals. Again, research institutions play a dominant role in developing new materials to achieve better and more economical designs.

The performance of these new and improved materials must be tested in many different environments over extended periods of time before they can be accepted as viable alternatives.

2.1 Predictions

Under this heading, the material and testing issues will be dealt with. Each of these two issues are key to the prediction of the service life of a product but difficulties arise in obtaining accurate information from them.

2.1.1 Materials

Much information is available about conventional material properties such as the yield point, elastic modulus, density, etc. These attributes are important in the design process, but the factors effecting the service life performance of a material depends on the agents acting on them. The type of agents acting on a material can be broken up into two categories, environmental and non-environmental agents.

Environmental Agents

Environmental agents may affect the long term properties of the material through corrosion, deterioration, rotting, etc. Having the knowledge of the chemical and physical properties of the material, rational decisions can be made on what agencies will be critical to the performance of the material. The behavior of conventional materials under various environments is well known because these materials have been in use for quite some years. Data accumulated over this period of use provide much of the information on the behavior of the material under these various circumstances and hence, prediction of the material's usefulness for a given application can be evaluated with a higher degree of accuracy than for a new material with no data history. Some main environmental agencies can be categorized as acting externally, internally or from below ground. Jubb[1] has suggested the main agencies in table 2.1.1 as contributing to material degradation.

Table 2.1.1 Main Environmental Agencies

	External	Internal	Underground
Heat	Solar(thermal) radiation, Radiant loss	Internal heating, Solar gain, Lighting equipment	
UV	Solar radiation	-	-
Water	Precipitation (solid/liquid), Humidity	Processes, Cleaning, Spillage,	Soil water
Chemical	Oxygen (ozone), Carbon dioxide, Industrial pollution, Marine atmosphere	Processes, Cleaning, spillage	Variable pH, Variable chemical content, Pollution
Wind	Wind loads	Wind loads	-

The information in table 2.1.1 is well known and many codes give consideration to such environmental effects. For example, the concrete codes require minimum concrete cover of the steel reinforcing bars for various exposure conditions. Where this type of information is known and documented, little else must be done by the designer to obtain predictable results. Information on other agents, such as ultra violet (UV) radiation, is scarcely available since a long period of recording must be implemented to get a sense of the amount of radiation to expect in a given area. This is also a the type of information that is almost totally dependent on the location of measuring. One location cannot be monitored and the results used or inferences made for another location a large distance away. The enormous amount of work and time required to accumulate this information explains why this type of information is not readily available.

Non-environmental Agencies

The non-environmental agencies encompass all the other factors that could contribute to the deterioration of the material. These are generally the stresses imposed on the materials by the users during the use of the product or structure. Stresses induced through permanent loading, fatigue loading, impacts, abrasions and chemical effects are some examples. It should be remembered that it is difficult to identify and tabulate all of the agencies that will affect the materials throughout the life of the structure. Identifying the main agents and making design decisions to deal with these agents is presently the best one can do. Much of the identification of these agents comes from experience, which could be obtained from senior design personnel.

Every material has its own strengths and vulnerabilities which must be clearly understood by the designers as well as the constructors. If designers specify materials which they are not very familiar with, unexpected problems are most likely to occur. An example of such a situation is the use of masonry in place of reinforced concrete. This substitution can be used in many situations, however, the behavior of masonry under seismic conditions differs from reinforced concrete. Concrete with appropriate reinforcement can have a high ductility capacity while this can hardly be achieved with reinforced masonry. Another example where a good knowledge of materials is critical is when special heat treated steels are used for their increased strength. They might need to be welded on site which could cause problems. The properties of the steel around the welded area changes to a different state, usually with a reduction in strength, and hence the properties used in the design must reflect this. A thorough understanding of the materials that are being used in the design and construction are very important to obtaining the desired end results.

2.1.2 Testing

The testing of material properties has resulted in the advancement of material performance as well as a better understanding of the material itself. The materials discipline in engineering has evolved developing stronger, tougher, and lighter materials as well as materials with special properties. Along the development process, tests have been devised to assist the designers in comparing various materials in a standardized way, so that the best alternative could be chosen. These test can be categorized into two types, predictive tests and indicative tests.

Predictive tests are those where the rate of reaction of a material to a given agent is controlled by the laws of thermodynamic. These types of tests give results that could be extrapolated to longer periods of time and as well as using accelerated test conditions to predict the performance under normal service life conditions. Processes that fall under this type of category are chemical reactions, thermal degradation as well as some physical changes. The rates of reaction are not usually what is of value to the designer, but how the mechanical properties change in the material is of importance. This means what normally is desired, is the rate of change of the mechanical properties of the material against the time exposure to the agents. Many accelerated testing techniques are used to determine the minimum time before failure. This is usually accomplished by using the worst case scenario of conditions that are detrimental to the material and letting these conditions act on the material for a predetermined amount of time. Testing of this type will only be of value if it can be verified that the accelerated conditions do not produce reactions that are different from the normal service conditions. These concerns are mostly the responsibility of the material engineer, since he is the one who determines the method of testing and get results that will be of use to designers. The level of stress acting on a material can affect the rate of degradation and this must also be considered in the testing process. If one knows that the material will be subjected to high stress levels, then the tests should be conducted in a manner that encompasses this condition.

Indicative tests are those which monitor particular properties of a material and when combined with a prior knowledge of it, gives information on how the material will behave in practice. For example, the water to cement ratio in reinforced concrete is an indicator of what the permeability of the concrete will be after it has set. All indicative type tests are devised for each material since they all have different properties and attributes. Another form of an indicative test is a performance type test. Freezing and thawing, fatigue, abrasion, and impact resistance are a few examples. When using these types of tests it should be kept in mind of what the objects are. One is trying to reproduce as accurately as possible the service conditions that will be encountered in practice. Also, a test that is appropriate for one material may not be appropriate for another material that has very different characteristics. There is knowledge and skill required to determine what the appropriate test are for particular material, and many of these requirements have been determined and set out in testing standards. If accuracy of the results is dependent on first of all the test procedure, as well as the manner in which it was carried out. Correlation of the test results with actual in service performance will provide the necessary feedback that will indicate the validity of the testing procedure.

There are benefits from a well structured testing program for all parties involved in a construction project. The designer can evaluate various options with a more certain end result. The producers could market their products more effectively if they could show the performance to those who will be specifying them, i.e. designers. These performance statistics could be backed up with warrantees and guarantees by the manufacturer. The client will be satisfied that he has obtained the best product for his investment.

2.2 Desired Information

As has been stated above, much information must be available to the designers to make appropriate choices during the development of the project. It is of prime concern what information is required to make these choices as well as determining how to obtain this information. Currently there are numerous standardized testing procedures for various purposes, but it is questionable if these are suitable to the needs of design life considerations. There is information available for materials that have been used in design for many decades. Such materials are structural steel, timber, and reinforced concrete. Other materials that have worked their way into common civil engineering use are fiber glass composites, aluminum, and plastics. As the unproven materials get used in projects, actual performance information becomes available. Testing procedures can be developed to more accurately predict the materials response to various service environments. For new and innovative materials, the risks are much higher in implementing them since their actual performance characteristics may not be yet defined. There are potentially high performance gains to be realized with new materials but the potential of premature failure may also be higher. As there is more demand for long term performance statistics, new or better testing techniques may be developed.

There is obviously a large amount of information that needs to be compiled into a easy to use knowledge base. There is still room for much development in this area with current technology continuously evolving in an attempt to meet the demands of the integration of large information databases with analysis tools. Since much of this information must be compiled from many disciplines, a universal format must be developed to deal with these issues. Feedback of information from the maintenance and support aspect of a project, is critical to developing better designs as well as choosing the appropriate materials for the application.

The National Materials Advisory Board[2] has published recommendations for a unified life cycle engineering approach. It has outlined that technology must be developed to incorporate the materials statistics into the design process. An integration of the human designer and materials information with analysis tools has been suggested to produce better performing structures in a more cost effective way. Such a development environment is illustrated in the Figure 2.1.1.

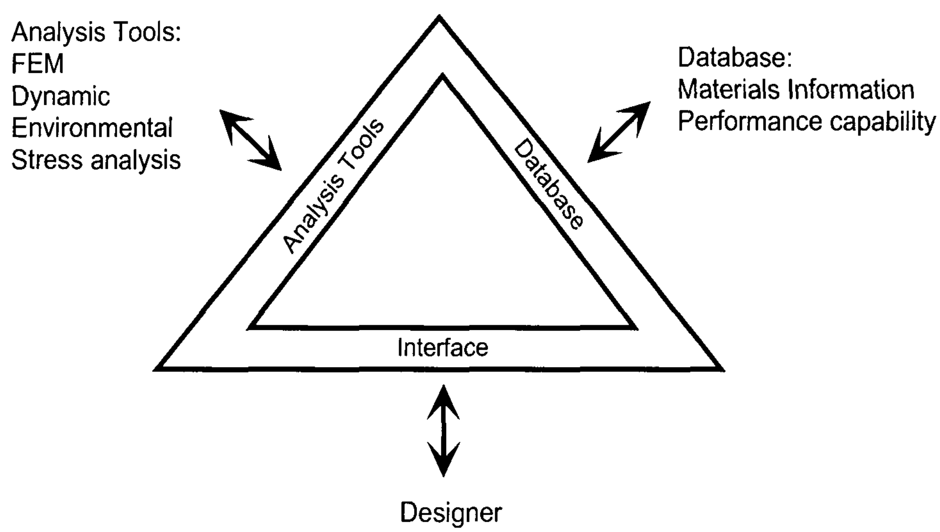

Figure 2.1.1 Desired Integrated Design Environment

It should be mentioned that design life issues are not the concern of one single discipline, but encompass knowledge from numerous fields. To be able to identify possible problems with material choices for specific applications, one must be knowledgeable in the agencies that are expected to act on the material as well as the material characteristics. A much broader band of knowledge must be at the disposal of the designer.

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CHAPTER 3

STAGES OF DEVELOPMENT AND THEIR INFLUENCE ON DESIGN LIFE

In this chapter the influences of decisions made at the various stages of development, on design life, are considered. The life span of a structure is considered at the typical stages of progression for a civil engineering structure, i.e. conceptual design, final design, construction, and maintenance and repair, with the various influences identified and discussed at each of these stages. The methods used in other industries mentioned in chapter 1 will be considered where appropriate for their suitability in civil engineering structures. This chapter will propose methods using available technology and theory. Further research and required development will be suggested.

3.1 Conceptual Design Stage

The conceptual design stage plays a crucial role in the design life of a structure, since at this point all the decisions are made about the materials and structural schemes. The client's participation at this stage is important because he/she determines the building requirements and provides the necessary resources, i.e. the financing, to make the project happen. Usually the client does not specify a design life in terms of the number of years that the structure will be used, but rather, requires that the structure survives long enough to get a predetermined return on the investment. The time frame is largely dependent on the client; for example, a developer who wants to sell the structure after only a few years will not be concerned with long life considerations. If the client is an owner/operator and intends to maintain the structure for most of the design life, then there will be a greater concern regarding the quality and durability of the structure. The initial amount of investment that the client has to work with will also dictate the options that can be used in design. If there is a limited amount of initial capital, then the client may prefer an option with lower initial investment and with higher maintenance throughout the life of the structure, with the maintenance costs countered by the revenue produced from operating the business. To assist the client in conveying his/her requirements to the designer, a building profile can be developed, as outlined in Section 1.3 in Tables 1.3.1 to 1.3.6 which are repeated here for clarity.

Table 3.3.1 Categories of Required Life (after Stillman, 1990).

Class	Life Span	Examples
transient	up to 1 year	fair structures, special events
temporary	1 - 10 years	site offices, exhibition structures
short life	10 - 30 years	trailers, temporary classrooms
medium life	30 - 60 years	commercial, industrial buildings
normal life	60 - 120 years	public sector structures, military bldgs.
long life	more than 120 years	civic and other high quality buildings

Table 3.3.2 Building Use and Service Environment

Building Use	Examples of Service Environment Exposure
commercial	impact loads of light machinery, storage loads, transportation usage
industrial	vibrations, processing chemicals, humidity, heat generated by equipment
residential	occupancy load, climatic conditions, public traffic
shelter	impact loads, extreme climatic conditions
military	combat / peace time conditions

Table 3.3.3 Classification of Components (modified Stillman, 1990).

Class	Description	Examples
replaceable	easily exchanged building components or equipment	floor finishes, mechanical & electrical components
maintenance	lasts with treatment for a lifetime of the building	doors and windows, handrails, wall coverings, wall paper, paint
life long	lasts the life of the building	foundations, precast cladding panels

Table 3.3.4 Further Definitions of Maintenance (modified Stillman, 1990).

Maintenance	Description	Examples
repairs only	as required	broken windows, damaged doors
scheduled maintenance / repairs	at regular intervals	5 yearly repainting of joinery
condition based maintenance and repairs	to follow regular inspections	contract maintenance of elevators

Table 3.3.5 Classification of failure modes (Stillman, 1990).

Class	Failure Mode
I	danger to life
II	danger to health
III	costly repair
IV	frequent repair repeat
V	interruption of building use
VI	no exceptional problems

Table 3.3.6 Example of a Design Life Data Sheet (Stillman, 1990).

Data	building category *medium life* (Table 3.3.1) to be built on exposed site in Vancouver	
external finishes	roof membrane	
	materials	mastic asphalt
		replace after 15 years
	failure mode (table 3.3.5)	VI: no exceptional problems

Once the designer has obtained the information for the first two tables, Tables 3.3.1 - 3.3.2, he can indicate some structural schemes that would achieve the desired function. For each of these structural schemes, the classification and maintenance of the components as well as the failure mode for each of the components would be indicated as shown in Tables 3.3.3 to 3.3.5. For each of the components a design life data sheet would be compiled containing all the relevant information as indicated in Table 3.3.6. With this information in hand the designer has a very clear description of what is expected and required for each of the schemes that were considered.

The large influence that decisions made at the conceptual stage have on the overall life cycle costs was indicated in chapter 1 in Figure 1.1.1. This stems from the fact that once a structural scheme is chosen, there are many characteristics immediately fixed with this choice which are dependent on the materials chosen and the form of the structure. For example, if a structural steel frame type scheme was chosen then connection details will be an important issue which would not be an issue if a reinforced concrete option was chosen. Each option that uses different materials will have different attributes that will be key in achieving the desired results.

Now the designer must deal with the task of choosing the most economical scheme which is still within the financial constraints of the client. What will appear as the best option will not necessarily be chosen, since, as mentioned earlier, the type of client dictates what can be accommodated in the design of the structure. To assist the designer in making economic decisions the modified structures appraisal approach outlined in section 1.3 Figure 1.3.2 could be used. This simply incorporates a discount cost analysis into the evaluation of each scheme considered earlier in the conceptual stage. Estimating the future maintenance costs and other unexpected expenses presents some difficulty for the designer at this stage. As mentioned earlier, property management company's could be a good source for such cost information. This would take some effort to obtain and compile the cost data in an attempt to determine where the design could have been improved to reduce maintenance costs. Most designers rely on the design codes for guidance in detailing the design and generating a structure that will be durable with minimal expense for upkeep. It must be remembered that codes represent the minimum standard that should be carried out in design to produce acceptable results. Since these are general guide lines they will not encompass all situations and this is where the building profile can come in very handy. If the designer has made an effort to determine the type of agencies that the structure will be exposed to, he can take appropriate action and provide appropriate details to achieve the requirements set out by the client.

After a discount cost analysis has been completed some form of sensitivity analysis should be done on the various costs, especially the estimated future costs to see how the outcome would change with small changes in these predicted costs. Such an analysis would give indications of which items are sensitive to cost changes, which perhaps would direct the designer to further investigation of these components to get more accurate information. Such an analysis would also indicate to the designer which components of the structure need to closely monitored during construction so that the specified level of performance is achieved and the estimated costs will not be exceeded. After these analysis have been performed, the option seen as best for the given circumstances and constraints can be chosen. The next stage is the final design stage.

3.2 Final Design Stage

Once the final design stage has been reached, approximately 85% of the costs of the structure have been fixed. The structural scheme has been decided, the materials that will be used have been decided and now the final details of the structure must be completed for the structure to be constructed. All of the information compiled at the conceptual stage about the option chosen will now be assessed in more detail to ensure that appropriate details are used in the design. It is obvious that the experience of the designer will have a large influence on the design details that will be used. The designers understanding of the materials being used in the design also plays a crucial role in achieving a good robust design. Senior design personnel can contribute significantly to the design by reviewing the design as it progresses and providing feedback for improvements. This provides two functions to the designer working on the project. Firstly, the designer is given suggestions for design improvement which they would otherwise not receive and secondly, the knowledge from senior design staff is passed on to the junior engineers. Such an environment will assist in the quality control of designs and continue the flow of knowledge gained over the years by older designers.

Much attention has been given to the extension of service life through the concept of replaceability of components (Schlaich and Potzl, 1990[1]). Elements that have a limited life should be made accessible for replacement and repair so that the overall structural lifetime is not limited to the life a few singular elements. However, replacement is not always the answer to design life problems and such an approach should not replace quality design and construction. If an optimization of design was to be carried out, one must expect the replaceability option to be more expensive than a more robust design. However, there are always some components that have a very limited life. The overall design must take this into account and accommodate the replacement of those components (Davies, 1990[2]).

The main objective of designers should be to produce an economical and practical design that provides the features the client has requested. An experienced designer can usually achieve good results most of the time, however, when dealing with complex projects group decisions between all parties involved seem to achieve these goals more efficiently. Such an effort has been called *partnering*. It entails forming a design team which includes representatives from the client, designer, and contractor at the conceptual stage of the design. The project becomes a true team effort with all parties knowing exactly what is required of them since they have had input into the project right from the start. The contractors contribution to the practicality of the design can be considerable. He can contribute many ideas and proven methods for achieving an efficient design which the designer may not be aware of. With this type of cooperation, the design and construction aspect of the project will have a better chance of being realized. If the contractor is involved in the design, he will be well aware of what elements of the construction are critical to making the project work and he can then exercise the care need to achieve this goal.

The loads used in the analysis are usually obtained from a building code or, in special cases, defined by the client. If the structure undergoes a change of use, the serviceability conditions may also change. Generally the loads increase with longer life structures, which could cause faster deterioration or higher maintenance costs (Chan, 1990[3]). However, it is not well documented by how much the loading conditions change over time. Structural collapse occurs rather seldom since there has been much development in the area concerning ultimate strengths of materials and the codes have reflected this effort. Serviceability failure, however, happens much more frequently and can be as expensive as structural collapse, but has not received the same attention in research and development. This is due to the high expense in collecting and obtaining the load data as well as the unsuitability for laboratory experimentation amongst other reasons. Developing a service load spectrum, which the structure will be subjected to over its design life, may be one option. Further research in this area will help to quantify the effects which loads have on the design life of a structure.

3.3 Construction Stage

The construction phase and its level of quality has a very large contribution to the design life of a structure. This is mostly due to the large amount of human involvement in the construction process. It is the responsibility of the contractor to manage the human resources in a way that will minimize or offset the effects of human error. Some examples of possible problems are: reinforcement not correctly placed or offset during the placement of the concrete, bolted connections not tightened properly, and inadequate preparation of surfaces before coatings are applied, (Woodd, 1990[4]). These errors are not always a result of carelessness, but ignorance and practical difficulties also contribute. The designer should recognize these human factors and site practicalities and consider them in the design process, as the codes address this issue only partially for the safety aspects. It is clear that a bad design and/or bad workmanship would reduce the chance of achieving a long life structure, however, good workmanship can mitigate poor design and bad workmanship can destroy a good design.

Workmanship contributes significantly to the design life of a structure. Good workmanship encompasses many factors (Woodd, 1990[3]). To use clear, sensible and understandable requirements is a good start. More time could then be given to complete the job properly rather than trying to understand what is being required. Sufficient communication between all parties is critical, so that everyone knows what they are supposed to be doing and why. Misinterpretations can be avoided and the concerns of the various parties will be conveyed and realized by all involved. Adequate tools and equipment should be available to achieve the desired results and the timing of the work should be appropriate to the given climatic conditions when this is important to the type of construction. Also the time constraints of the construction should be reasonable since a rushed job usually results in a lower quality product. There is always the issue of instilling good motivation when dealing with the human element, which most of the time is not achieved with money alone. Supervision plays a large role in this area. A key factor in achieving good workmanship is sufficient training and experience. Although it appears to have been stressed in recent times, the training effort has not always been directly applicable to improving the work. Experienced contractors and engineers report, that the training efforts may not always have addressed the focal areas.

Further development is needed in the field of quality assurance and quality control (QA/QC) programs that focus on the construction/fabrication issues (Stiemer and Zhou, 1993[5]). Defects committed during the construction of a building shell and interior facilities resulted in costs of between 4% and 12% (average 8%) of the structures construction cost (Jungwirth 1991[6]). An investigation was done to determine what the causes of the defects were, which are summarized below.

46% were a result of incorrect execution, which could be further classified into:

- 30% a result of lack of care
- 8% a result of lack of information
- 4% a result of lack of competence

4% a result of lack of knowledge

30% were a result of failures in the development and design

8% were a result of lack of clear data

8% were a result of material faults

6% were because the task was impossible to execute

2% were a result of other causes

One can see from the values given above, 60% of the causes stem from direct human efforts, that is, lack of care and failures in the development and design. These results again reinforce what has already been stated, that the conceptual and design stage as well as the construction stage play a large role in the design life and durability of a structure. To reduce these defects, a quality assurance system should be implemented. Considering the average 8% of construction costs for repair and viewing figure 3.3.1, one can see that an increase in quality assurance expenses by 2% of construction cost will reduce the cost of repairs to approximately 4% from the previous 8%. This resulted in a total cost for repair and quality assurance of 6% of construction cost, which is a savings of 2% over the case of virtually no quality assurance system being implemented.

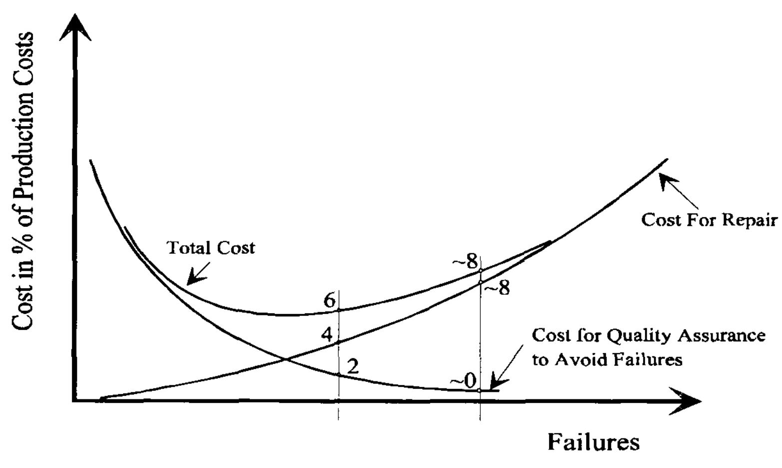

Figure 3.3.1. Relationships between Cost, Failures and Quality Assurance

It can also be observed form figure 3.3.1 that there is a balance between the cost of the quality assurance procedure and the cost of repair. The intersection of these two curves will give the optimal solution for the given situation, which results in the lowest total cost.

Difficulties exist in monitoring every aspect of work being carried out on a construction project. Therefore, a system of random spot checks and hold points seems to be more practical and such methods are usually implemented. This can ensure that the work is being done to the specified standard. Well trained and qualified personnel will be able to achieve the desired goals within such a framework, but such resources are not always readily available. The result is that in most cases there is no assurance system at all implemented. While various QA/QC procedures have been developed for repetitive production items, the typical on-site work is much less standardized than the environment of a factory or production plant. If better quality control and quality assurance procedures were developed for on-site monitoring, such as those mentioned in chapter 1, section 1.4, the design life of a structure would be easier to predict. A rigorous and adaptable standard such as the ISO 9000 series (CSA 1991[7]), would be very advantageous in dealing with such concerns.

Much of the contractors' contribution to the design life of a structure can be summarized as follows, (Woodd, 1990[3]):

- It is the contractors responsibility to set up a framework for providing managers, supervisors and operatives with both training and experience.
- Conveying practicality into the design detailing could achieve a better quality of work, since these ideas come from the contractors personal experience.
- The contractor should also ensure that there is adequate construction time allocated, since a rushed job usually does not achieve the desired quality of work, which in turn

would reduce the design life of the structure.

- A conscientious contractor should only take on work that he is competent and resourced to plan and supervise.
- The contractor should use self-imposed discipline, such as quality assurance and quality control procedures, where appropriate.

These issues need to be considered carefully when selecting a contractor in a situation where the design life of a structure is important. In particular the reluctance to adopt quality assurance and control standards in the construction industry is difficult to understand, because experience has shown, that usually the efficiency and economy of any operation could be improved by these measures.

3.4 Maintenance and Repair Stage

The maintenance and repair phase of the design life is the period after construction when the building is put into service. It is necessary to decide on the strategies to be adopted to maintain the structure in service already during the conceptual and final design stages. There is a large range of approaches that could be taken depending on the facility's use. Some options are shown in Figure 3.4.1.

If the facility has a very long desired life, one possible strategy may be to

1. let the structure deteriorate to a certain level and then ,
2. proceed with the maintenance and repair necessary to bring the structure back up to its original new condition.

This could be repeated almost indefinitely. All the various materials and components would have their own rates of deterioration. Hence, the interval of servicing depends on those rates.

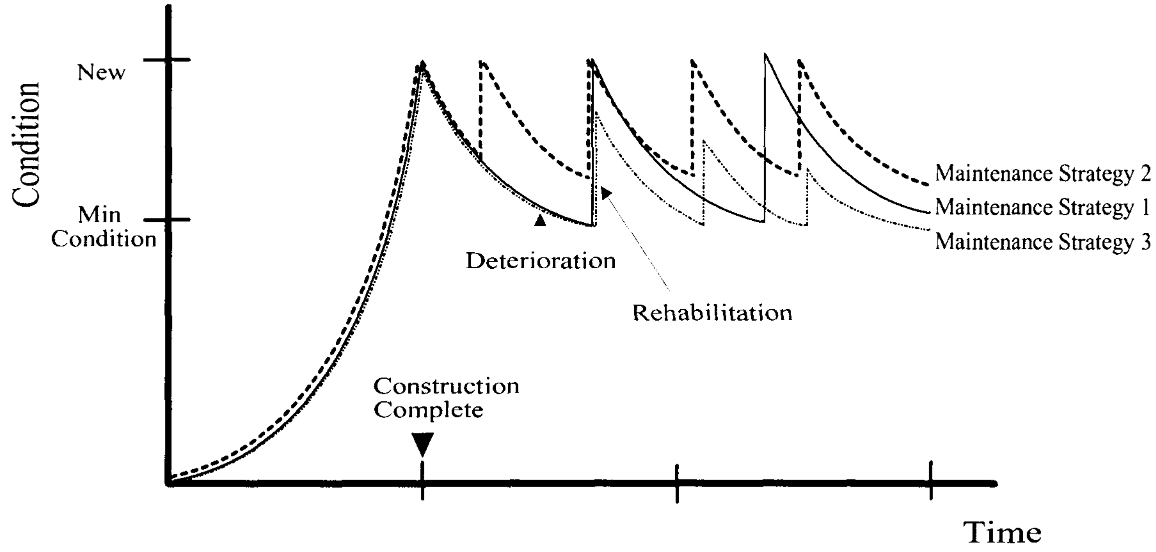

Figure 3.4.1 Deterioration of a Structure of Various Repair Strategies

Other variations are as indicated in Figure 3.4.1. As the construction proceeds, the condition of the structure increases to the level of the *new condition*. From there on the overall structure will deteriorate at a rate which is dependent on the types of materials that

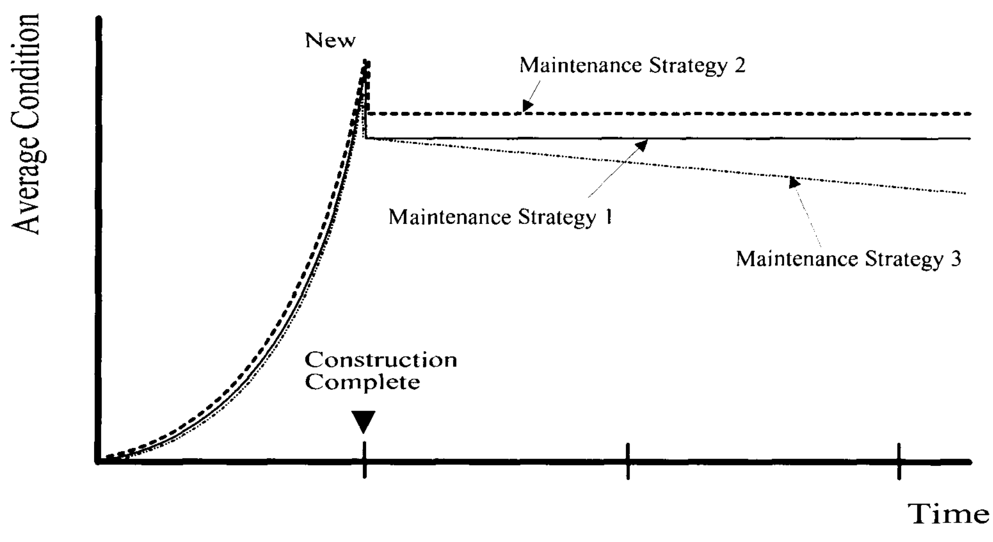

Figure 3.4.2 Average Overall Condition of a Particular Structure for three Different Repair Strategies as shown in Figure 3.4.1.

were used in the design, and the type of agencies that the building was exposed to. In Figure 3.4.1, only three different maintenance strategies were indicated for one particular structure. Figure 3.4.2 shows the average condition that the overall building will be in if the maintenance strategies indicated in Figure 3.4.1 are used.

The costs associated with such maintenance schedules will again depend on the materials used in the original construction. Such data would be of great use in creating a cost-in-use data base. At the maintenance and repair stages, some components may need to be replaced completely or perhaps just routine maintenance performed. It would be desirable for a designer to have this information at hand during the design stage. This would enable him/her to better predict the maintenance needed. The client would get a better indication as to what financial resources will be required over the life of the structure. This may lead to an optimized financing scheme which could result in lower costs for the owner.

The maintenance and repair strategies will also be of interest to the client when considering the value of a structure. Many parameters influence the value of a structure, besides the integrity of its components, such as the appearance of the structure, the adaptability for change of use and the ability to accommodate improvements in technology such as new ventilation systems and high technological equipment, etc. All of these parameters should be considered at the design stages and discussed with the client to aid him/her in the decision making process. The value of a structure changes typically with age as shown in Figure 3.4.3.

As indicated on the diagram the quality and hence, durability and robustness of the structure, will influence the slope of the value curve. The higher the quality of the construction and the design of the building, the higher the residual value will be over time. Parameters such as the *ability of the structure to accommodate changes of use* or

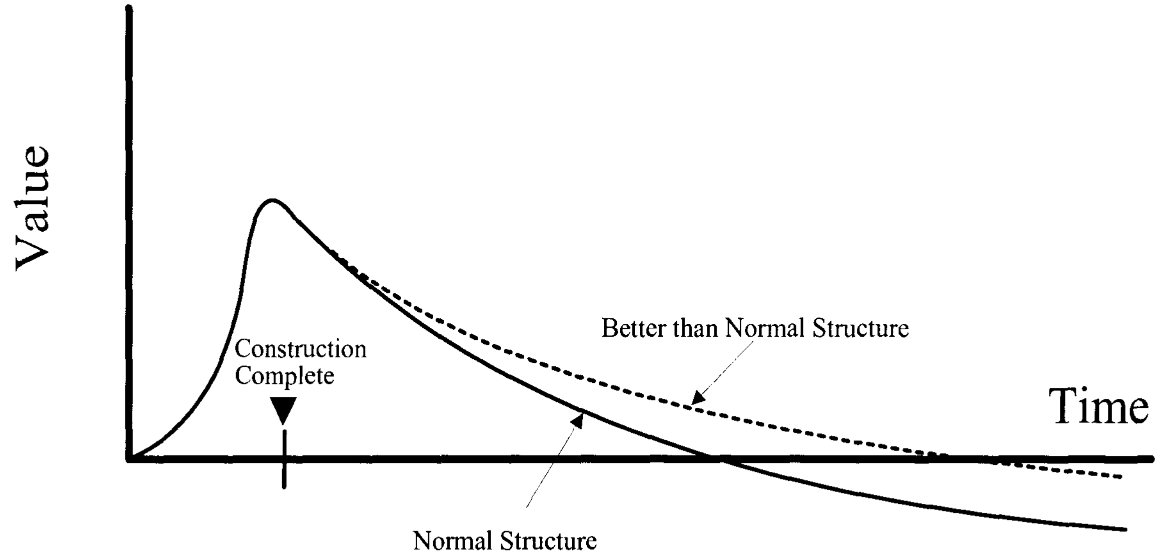

Figure 3.4.3 Value of a Structure over Time

upgrading of components to a newer technology also contribute to the slope of this curve (Burns, 1990[8]). Outside markets influence the value of the property. Changes in demand for another type of structure will also effect the slope of the curve. However, these issues are not directly related to the actual design life of a structure and hence will not be discussed further here.

It needs to be stressed, that at some point in time the value of the structure will take on a negative value. This does not necessarily indicate that the structure's condition has reached a critical level, but in many instances the structure can no longer accommodate a change to another use and the original use no longer exists. The value becomes negative when the upgrading efforts cost more than the demolition and reconstruction of an entirely new structure. This is a state which most clients would like to defer as far as possible in order to get the largest return on their money. As mentioned earlier, this could happen at any time in the design life of the structure, but if this occurs early in the expected life span, it is usually a result of changing market forces. Some thought should be given to such forces at the design stage but this would be in the form of pure speculation.

If the design life approach was implemented and adequate information was available to the designer then some form of optimization of the maintenance and repair stage would be possible (Tam, 1993[9]). In most cases the goal would be to minimize the cost while maintaining a specified average condition for the structure. The information needed to perform such an optimization is the same as that expressed earlier in the design stage, i.e. material statistics and performance data, as well as, cost-in-use data. A database containing the information needed to satisfy several disciplines involved in the design and construction of structures should be developed. The gathering and accumulating of information for the database is an enormous task, however, the pooling of currently available information would be a big step towards a more productive design environment.

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CHAPTER 4

SUGGESTED FORM OF A NUMERICAL MODEL

In this chapter a suggested model and layout for the implementation of life cycle analysis is presented. The model is a combination of the approaches outlined in previous chapters with modifications made where it was thought appropriate to improve implementation and practicality. Since much of the task is to have information and forms available to compile the design life data, which will become apparent from this example, a database would appear to be the development environment of choice. The implementation of such an analysis procedure should be very simple for the user to interact with and it should also provide the flexibility of allowing the addition and modification of the information in the knowledge base with minimum effort. To make such an analysis efficient and practical, further development needs to be done in compiling a comprehensive knowledge base. Such a knowledge base is critical since the effectiveness of a life cycle analysis hinges on the amount of available numerical information with regards to deterioration rates and performance levels under various service environments. Cost functions for the maintenance of the various components must also be included in the knowledge base so that a discount cash flow analysis can be used to evaluate the options and determine the most cost effective strategy. To obtain the most effective and efficient maintenance strategy an optimization algorithm needs to be developed that can be used in conjunction with the Life Cycle Cost Analysis (LCCA). The development of the knowledge base would require a substantial effort from many organizations to compile the information that would be required to perform a life cycle analysis as outlined below. An available knowledge base was not found and the time constraints on the research project would not be sufficient to develop one. It is for this reason that the following is presented as a framework of how this analysis could be implemented once a knowledge base has been developed for the use in structural design.

The flow chart in Figure 4.1 indicates how the Life Cycle Analysis would proceed. The procedure would start with the designer indicating the type of structure to be designed. In the example given it is assumed that a building is to be designed, but the model would be able to accommodate other common civil engineering structures such as bridges, liquid retaining structures, and parking structures. The initial screen the user would see could take the form of figure 4.2.

The user would select the type of structure that is to be designed and then move to the next stage of indicating the required life of the structure and the service environment that it will be exposed to. The required life of the structure would be the amount of time that the client would like the structure to remain in service. These would be indicated in general terms as shown in Figure 4.3. Also in this figure, the types of service environments that the building will be exposed to should be indicated. These parameters would be stored and used later on in the analysis.

The next step in the analysis is to break the structure down into its various components so that *design life data sheets* can be compiled for each component. The next sequence of steps will be repeated for each component as indicated in the flow chart in Figure 4.1. The designer chooses a component, and in this example it is the foundation for the building. Figure 4.4 shows the dialog box for making such a choice. The next step would be to get further information about this component in terms of the type of maintenance required and the failure mode(s) of the component. These could be classified as shown in Figure 4.5.

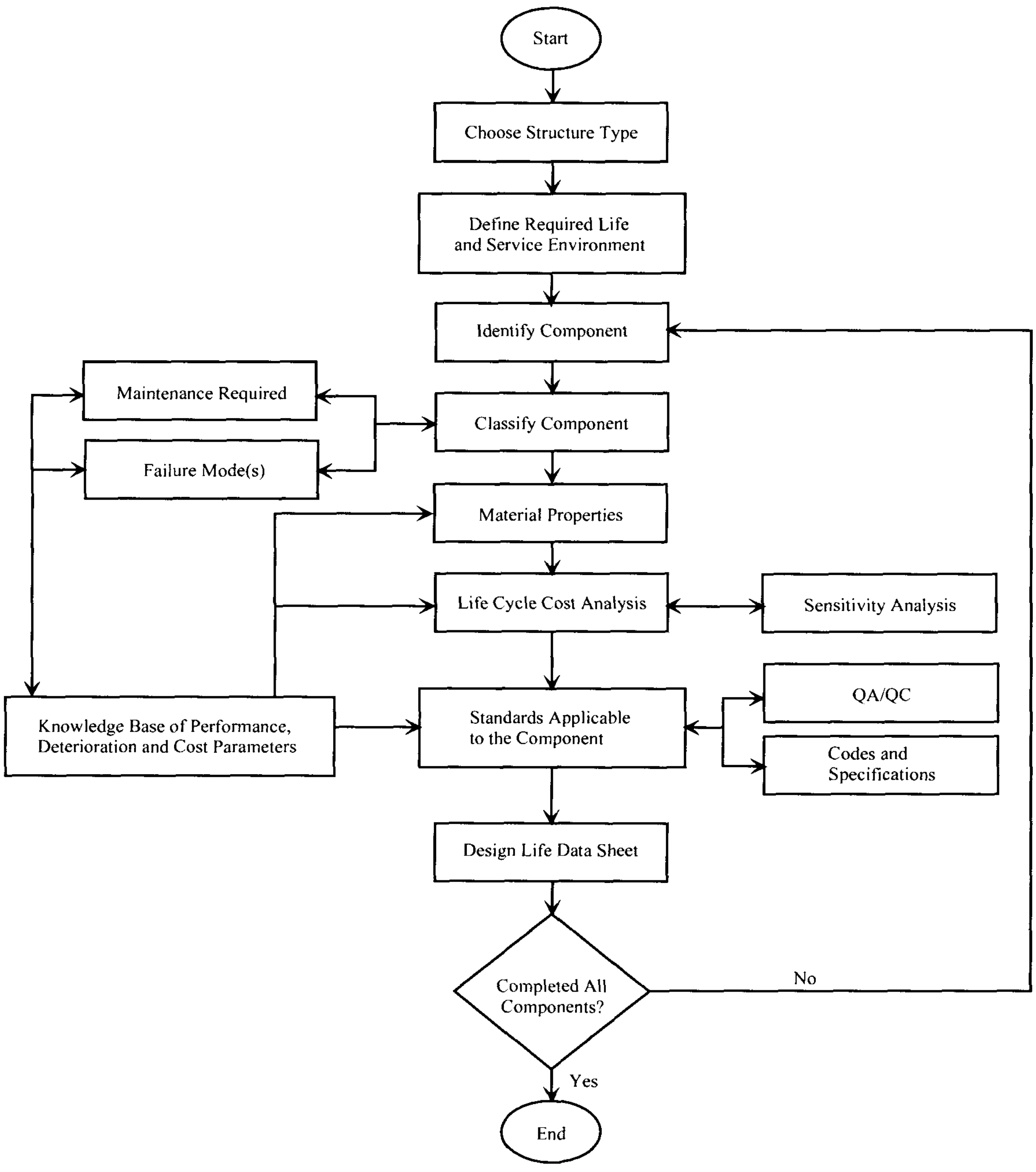

Figure 4.1 Suggested Procedure for a Numerical Life Cycle Model

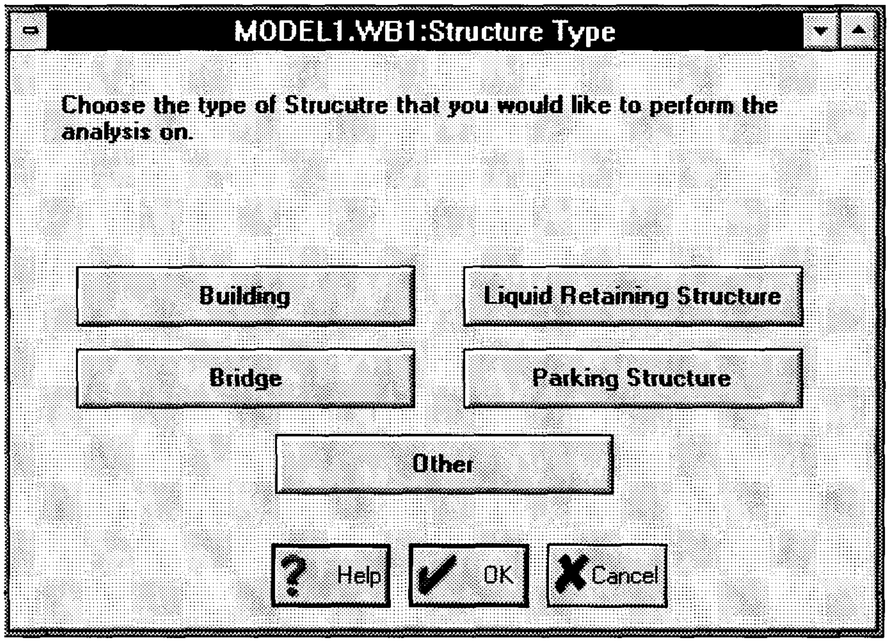

Figure 4.2 Selection of Structure Type

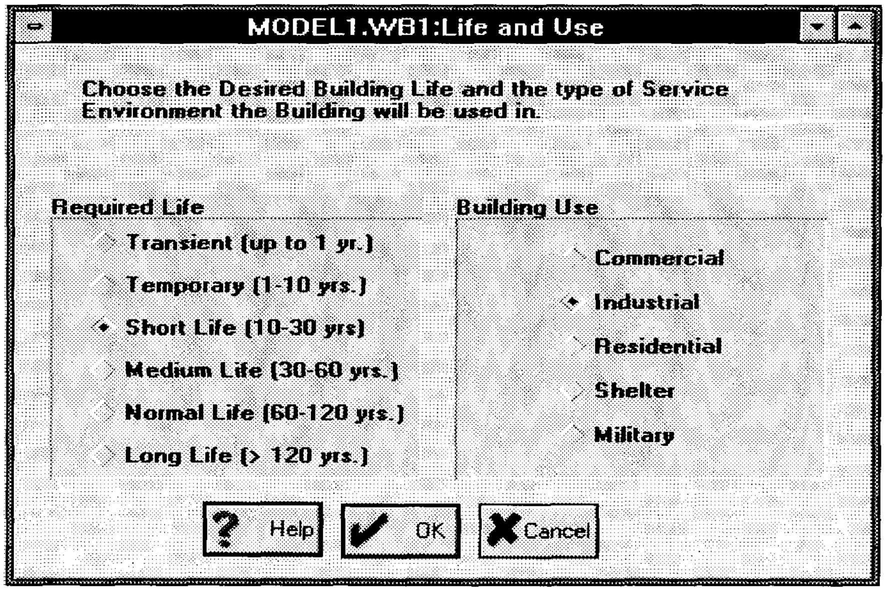

Figure 4.3 Required Life and Service Environment

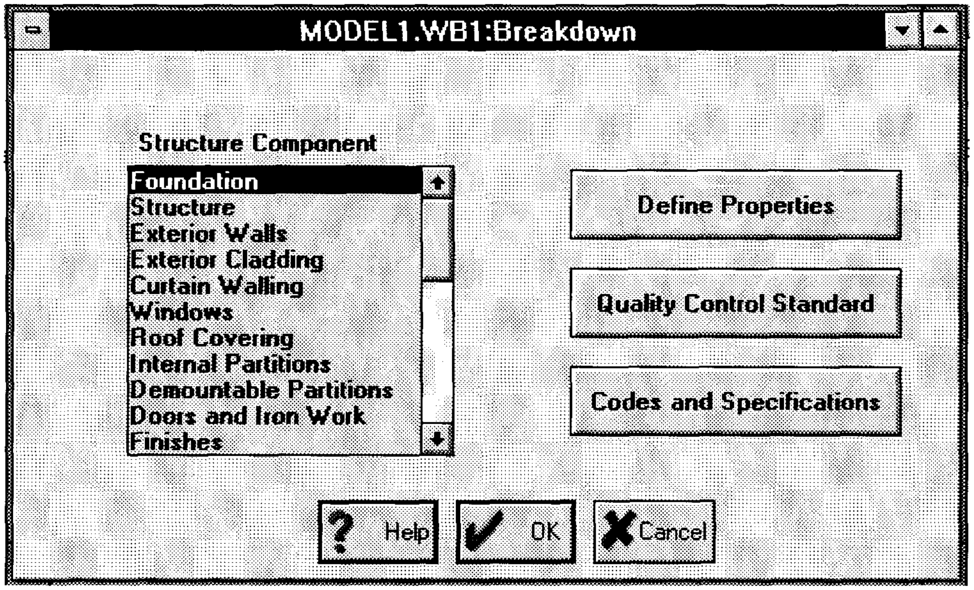

Figure 4.4 Identify the component

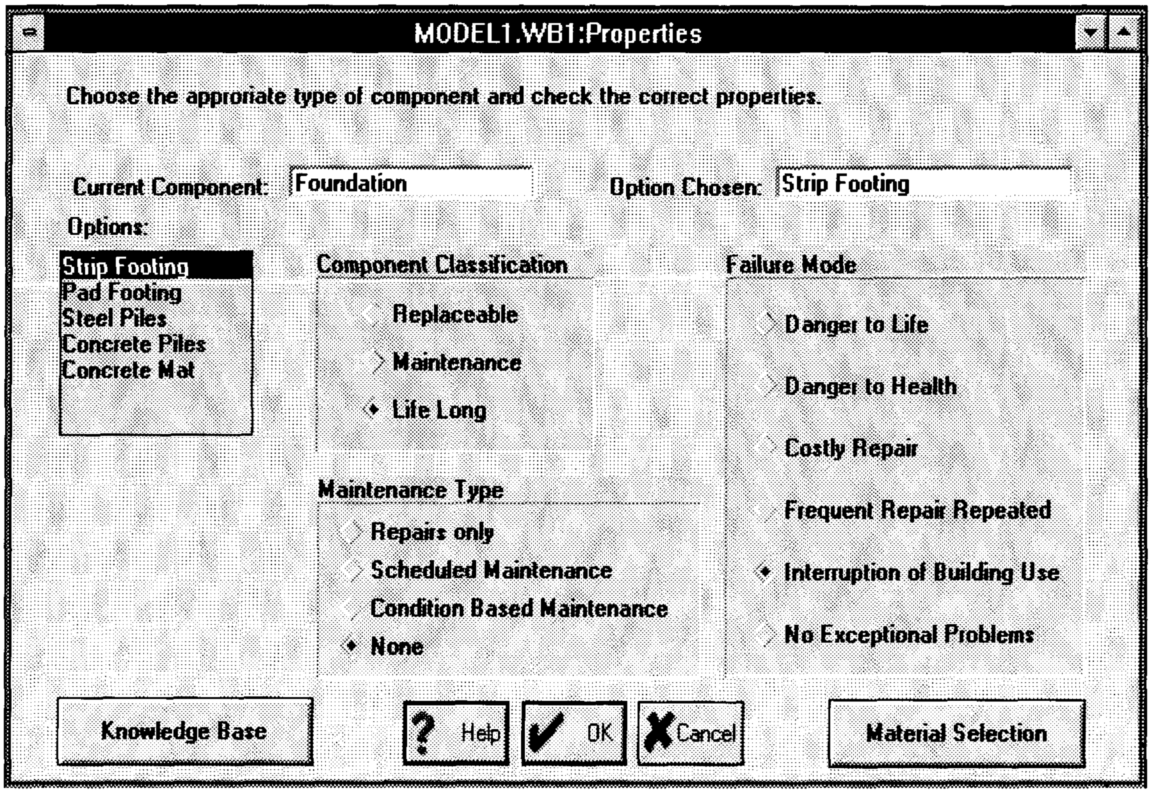

Figure 4.5 Component Type, Maintenance and Failure Modes

The knowledge base is accessible at the stage in Figure 4.5 so the designer can make the right decisions if there is any uncertainty about the component characteristics. The next step in the analysis is to define the material properties, i.e. the material strengths, modulus, etc. and other parameters that will be required in the design. In this example we have chosen a strip footing and hence concrete would be the material used in this case. To define the concrete parameters the user would press the Material Selection button shown in Figure 4.5 and the material selection menu shown in Figure 4.6 would then become available. The type of material would then be chosen and another dialog box would become visible where the designer could input the material parameters that will be used in the design. This is shown in Figure 4.7.

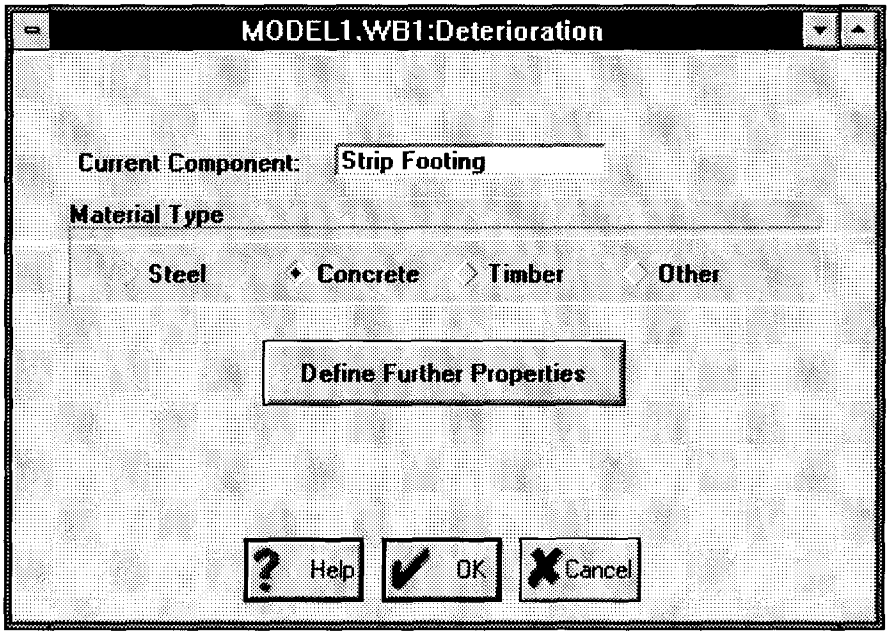

Figure 4.6 Material Type

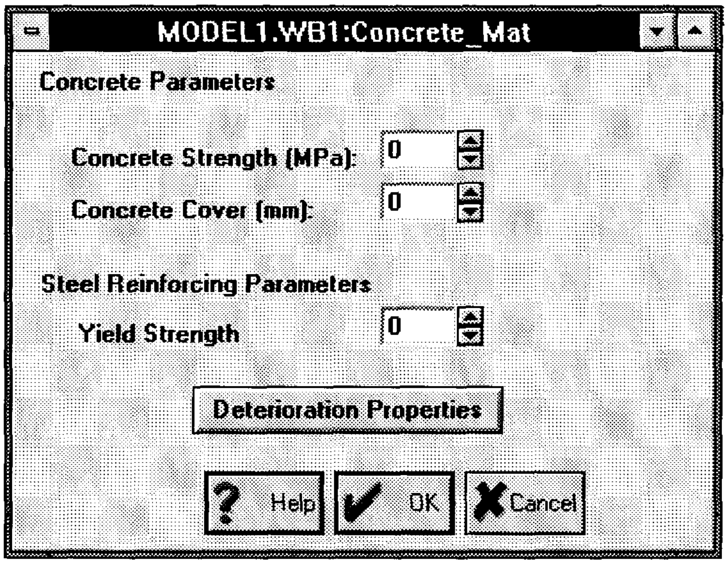

Figure 4.7 Material Properties

The next step in the procedure is to carry out a cost analysis. To implement a life cycle cost analysis, deterioration and cost functions for the given service environment need to be accessed from the knowledge base so that cost estimates can be calculated. It is at this stage that the optimization routine to determine the most cost effective maintenance schedule using a discount cash flow analysis is used. The discount cash flow analysis is based on typical engineering economic principles. The optimization routine would determine the optimum strategy considering the desired life of the structure and the expected life of the component. The life expectancy estimate for the component would be calculated based on the type of material being used for the component and the service environment that it is being used in. The optimization routine would then iterate through various permutations of maintenance schedules to arrive at the minimum cost solution. Tam 1993[1], has implemented an optimization routine for the maintenance of coatings on steel bridges which could possibly be adapted for the current situation. If the component can be made out of more than one material then the life cycle cost estimates for the other materials option should be calculated at this stage so that the most cost effective option will be determined. Once a decision has been made as to which option is to be chosen, those that were not selected would be discarded and the best choice saved to be included in the design life data sheet. A suggested form of the cost optimization could be as shown in Figure 4.8.

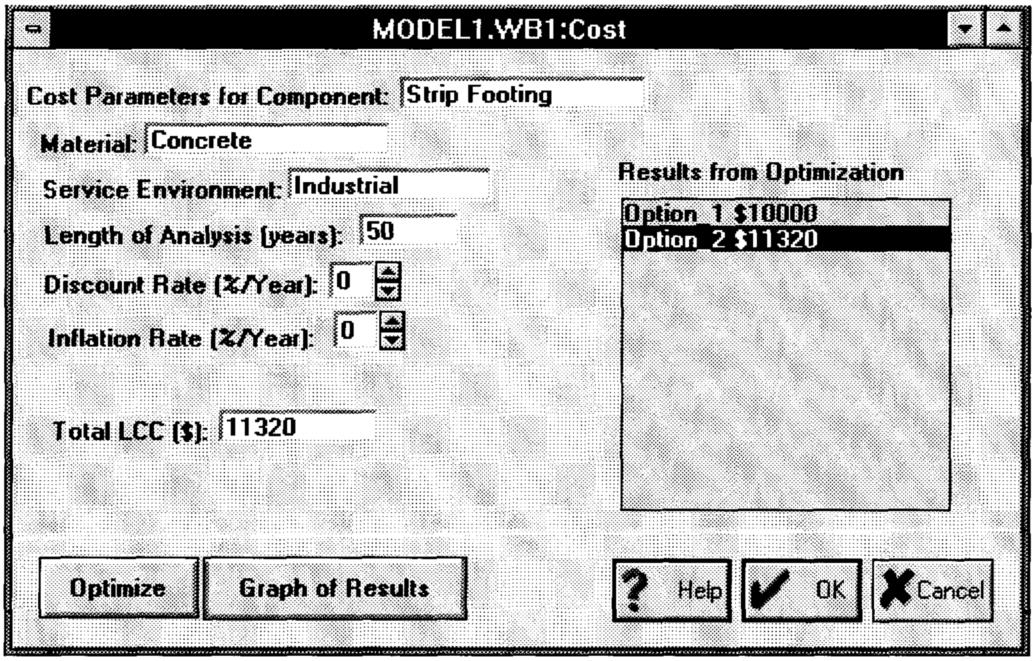

Figure 4.8 Life Cycle Cost Estimate Calculation

Once the calculation has been completed the expenditure schedule would be graphed so that a visual display of the results can be observed. Viewing these results is an opportunity to verify that the output obtained is reasonable. The parameters used in the discount cost analysis could be varied to see the sensitivity of these parameters on the life cycle cost of the component. The expenditure schedule would be a simple bar graph as shown in Figure 4.9. At each period in time over the structures entire life that the component requires maintenance, a bar indicating the amount of estimated expenditure will be shown at that particular point in time.

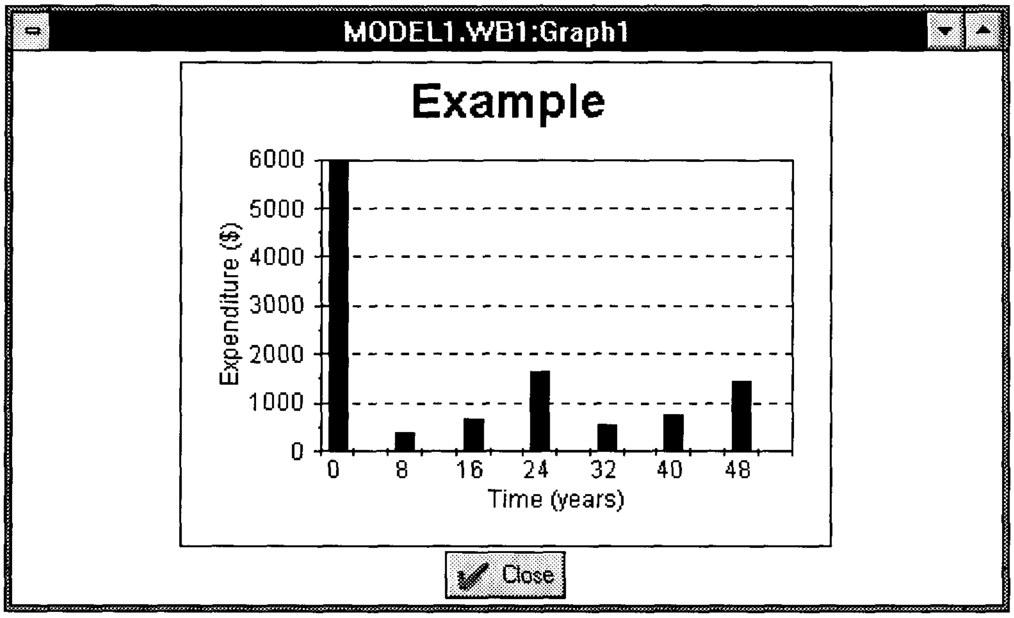

Figure 4.9 Expenditure Schedule

Using a discount cash flow analysis to determining the most cost effective alternative will provide the designer with the figures to back up his recommendation for the design option. A sensitivity analysis on the cost and deterioration function parameters would indicate which options incur much higher maintenance costs with only a small changes in the parameters. The designer would then take this into consideration for his recommendation on which option to choose. Combining a discount cost analysis and a sensitivity analysis will assist the designer in making sound design decisions on an equal comparison basis.

Once the cost analysis is complete, the maintenance schedule defined, and the material properties have been confirmed, the appropriate standards that will be used in the design and over the life of the project can be chosen. To assist the designer in making these choices, a list of common standards is given and he can select the standards that will be appropriate. A dialog box representing such a setup is shown in Figure 4.10. Quality Assurance and Quality Control standards would also be selected at this stage and the format would be virtually identical as that for the design standards. This is shown in Figure 4.11.

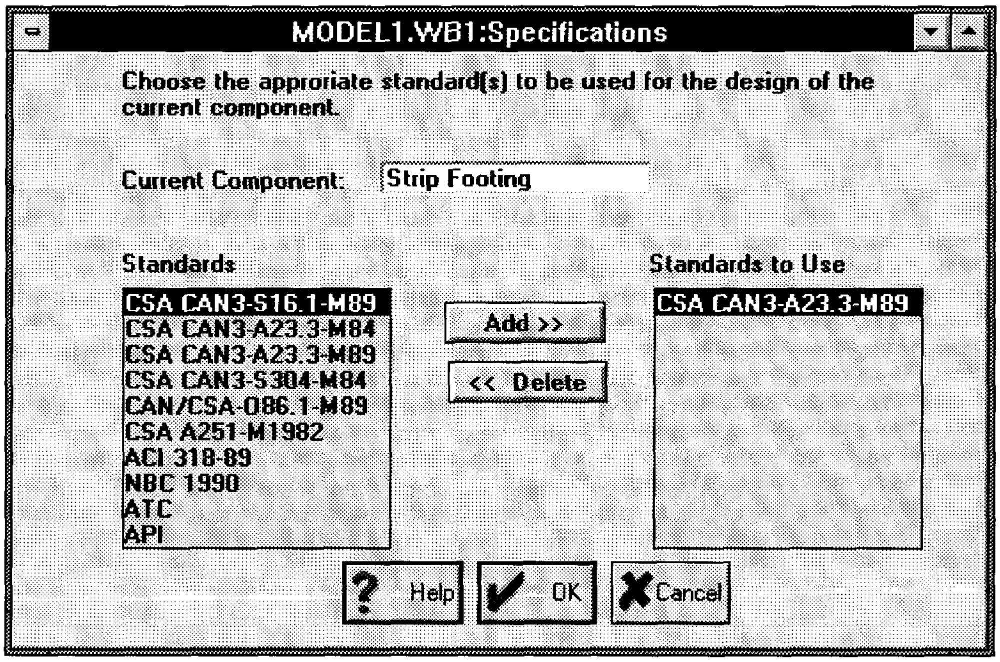

Figure 4.10 Codes and Specifications

The design standards and codes will eventually be in electronic form and hence they could all be stored in the knowledge base. If the designer would like to see the appropriateness of a code or standard, he would simply use the on-line Help features to see the standard and then make his choice. The program could also make suggestions for the designer automatically by indicating standards that pertain to the type of material that was chosen for the component.

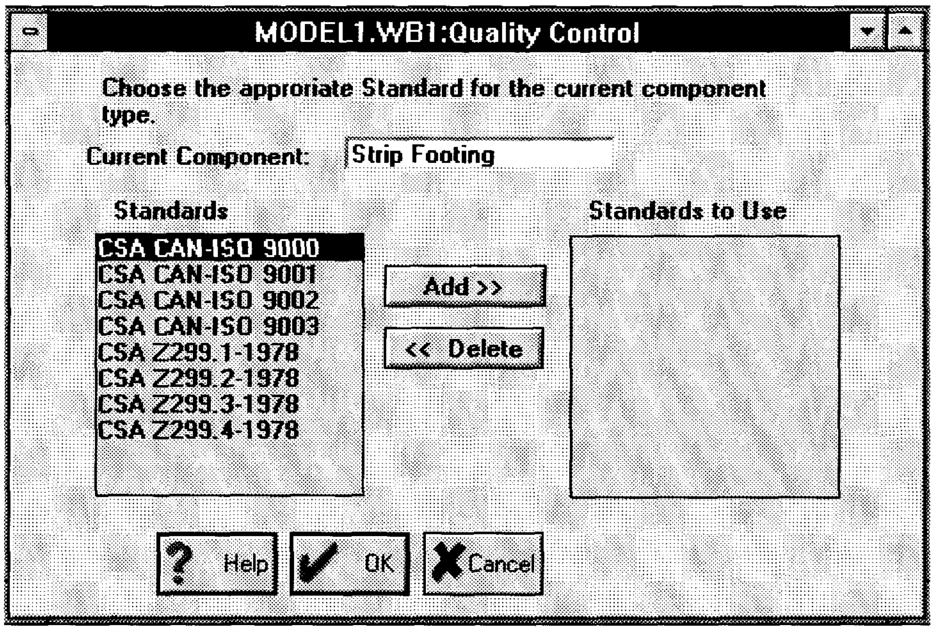

Figure 4.11 Quality Assurance and Quality Control

Once the standards have been chosen the program would compile all the input information as well as the cost analysis results into a design life data sheet. The design life data sheets provide the designer with the information to complete the detailed design of the structure and provides an efficient and consistent way to convey the design requirement to other designers working on the project. An example of the design life data sheet is shown in figure 4.12

Once the design life data sheet is compiled the program would ask the designer if all the components have been completed. If not, the process would start all over again at the component identification stage. Once all the components have been classified and all the design life data sheets have been compiled, the detailed design of the structure can begin.

The procedure in this example follows a path which is similar to that done in typical design offices except for the determination of life cycle costs. The most cost effective

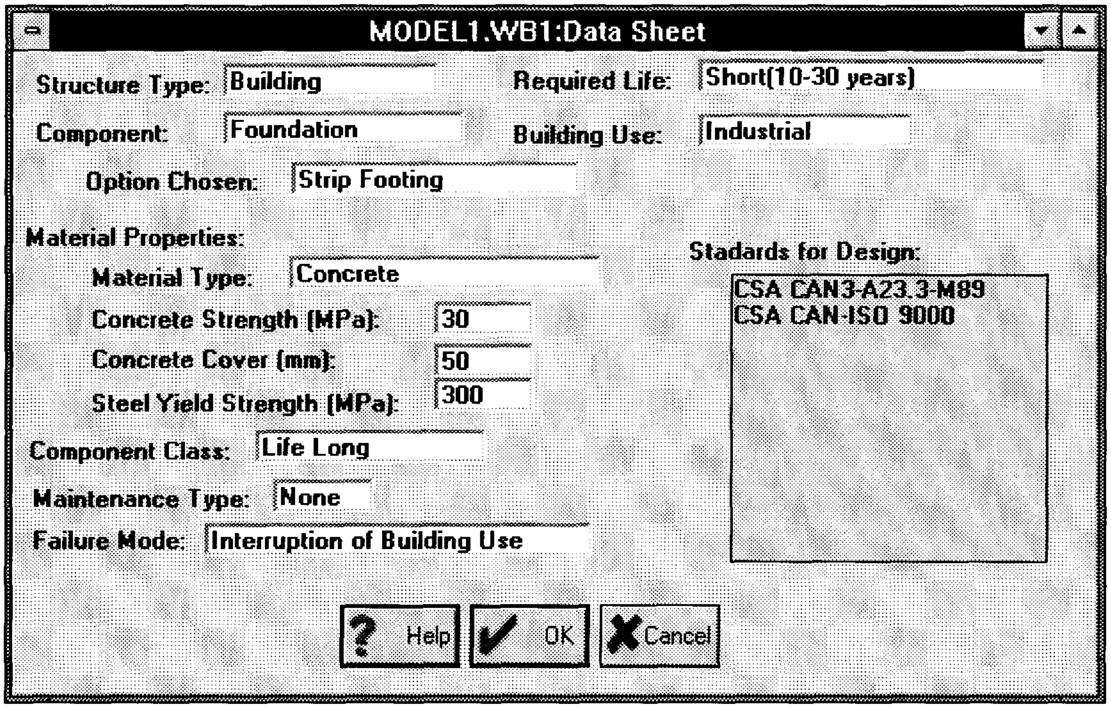

Figure 4.12 Design Life Data Sheet

alternatives are selected on the basis of determining the minimum initial construction of the structure. This is no guarantee that this will be the most cost effective option when considering the complete life span of the structure. Only the combination of a comprehensive knowledge base with performance and maintenance information and a life cycle cost analysis will provide designers with tools that will assist them in making more informed choices and hopefully produce better performing and more cost effective structures.

The exact form of the knowledge base is difficult to describe at this time, since the type of information that is currently available about the various components of a structure was not obtained. Every component has its own characteristics and properties which will define its performance in any given environment. The establishment of which properties to include in the knowledge base and how to manage all this information are some issues that need to be resolved before such an information base can be complied. Each material has its own features and properties which indicates that there will be several databases to manage. The relational database programs currently available appear to be capable of dealing with this issue. The gathering of the performance information appears to be the largest step that must be overcome. Once this information is in electronic form, the management and access to it can be manipulated by currently available database programs. Another aspect of working with a knowledge base is the need for continually updating the information contained in it. As new materials are being developed and used in the construction of structures, the actual performance of the materials should be monitored and the characteristics updated in the knowledge base. This should be done for all materials and not just new or improved ones. This would assist all designers using this knowledge base since their future designs would reflect the actual performance of the material.

References

[1] Tam, C. 1993. A Contribution of Parametric Coating Maintenance Schemes Based on Probabilistic Methods. Masters of Applied Science Thesis, The University of British Columbia, Vancouver, B.C.

CHAPTER 5

CONCLUSION

The aim of this research effort was to investigate the use of life cycle considerations in structural engineering for the purpose of improving overall building performance. Life cycle considerations are simply a means of approaching the design, construction and maintenance of a structure from a holistic point of view. This means that the choices made at each progressive stage are evaluated for their performance and cost implications over the entire life of the structure. Directly related to life cycle considerations is the issue of design life. Can we design a structure for a defined life span with any certainty and also estimate the cost associated with the structure over its service life? For any long life structure (life span greater than 50 years), the answer to this question is most likely in the negative. The implementation of life cycle considerations should, however, bring designers one step closer to achieving this goal.

The design life of a structure is influenced by decisions made at each stage of progression that it passes through. From conception of the building, through the final design and construction stage, to the maintenance while in service, all of these influence the design life of the structure. At each of these stages various aspects of the structure must be dealt with and all the choices made will determine the performance characteristics of the structure. The information that is necessary to make informed decisions over various options is not usually readily available, which currently presents the designer with the most difficulties. An ideal situation exists within the aerospace industry where the feedback of system performance and design flaws is related directly to the designers because the company that designs and manufactures the product, typically also services it. In the civil engineering field, this scenario normally does not exist and hence, similar design flaws can continuously repeat themselves. It is imperative that some form of feedback mechanism be implemented so that designers are kept informed as to what aspects of the design need improvement. When serviceability problems occur the owner of the structure usually calls upon the contractor to remedy the problem. The designer is rarely consulted unless a major failure has occurred, in spite of the fact that many problems which seem to be attributed to poor workmanship can be traced back to and are rooted in the design of the structure. If the designers would be more involved in dealing with the serviceability problems or simply be aware of them, they would be able to take steps early on in a new project to prevent similar problems from happening.

A thorough knowledge and understanding of the material properties used in construction are important to achieve the desired results. Using inappropriate materials for certain service environments as well as poor detailing could significantly shorten the service life of a structure and result in excessive maintenance cost during the life of the structure. Improving the education and training of designers to recognize the importance of understanding of materials would result in better performing structures and avoidance of long term problems. Moreover, senior design personnel should make an effort to document and convey their experiences to junior designers so their acquired knowledge is not lost once they leave the business. The company quality control standard or the specification standard can be used to document certain design and detailing information that should be used in design when dealing with specific materials and types of structures. This will ensure that the information will be passed on to other designers in the company as well as providing a formal means of documentation, which would also help to produce more consistent designs.

The construction phase of most civil engineering structures requires extensive human resources to accomplish the finished product. Ensuring good workmanship during construction, however, is an area that is difficult to monitor with great accuracy. As this research has indicated, the development and implementation of quality assurance and quality control (QA/QC) measures need to be pursued during the design and the construction phases of civil engineering projects. Since virtually every civil engineering structure is a one-of-a-kind entity, it becomes very difficult to devise a QA/QC plan that is appropriate for all. The new ISO 9000 standard which is very rigorous yet adaptable may provide the means of dealing with this issue more effectively. Further research into this topic would give an indication of the benefits that could result from developing a practical QA/QC standard which could be modified easily to suit each individual current project.

To make appropriate choices between various options one must have the relevant information and facts available to assist in the decision making process. In the design field a knowledge base containing the material, performance and cost data would be one means of making this information available to the engineers and designers. To develop an effective knowledge base will require the accumulation and compilation of performance and cost data. The aerospace industry, unlike the civil engineering field, has a structure that allows this performance and cost information to be conveyed to the designers. Such a framework is a result of requirements from customers who typically request the estimate of total ownership cost rather than simply the purchase price to make their product selection. This stems from the fact that typically 50% of the total cost of ownership occurs in the maintenance and support aspect of the product. Determining the operation costs for typical buildings, relative to the cost of their design and construction, would provide some insight into the potential for cost savings. Information obtained from a development company indicated that support costs for their buildings reached 50% of total expenditure at the age of 20 years. This means that if the buildings last longer than 20 years (which most do) the operating and support costs will exceed 50% of total cost. With such a large expense during an important stage of the life cycle, one would expect that this be incentive enough to investigate cost reducing options for this stage. Until the civil engineering professionals seriously consider overall costs of the various options as the selection criteria, however, little effort will be made to collect and process performance and cost data. Maintenance strategies are another aspect of the support stage of a structure which should be investigated to determine what method should be used to provide the desired level of service at the minimum cost. Computer simulated maintenance strategies for steel bridges have been successfully implemented to determine the expected costs of various options in cases where the deterioration rates and material performance characteristics had been established. Again, existence of appropriate information is crucial for any life cycle analysis to be successful in determining total building costs.

It is without doubt that a higher level of performance and cost savings can be achieved by implementing design life and life cycle techniques, yet incentives for development in this area seem to be lacking. Some of the reasons are that actual savings and performance gains depend on many factors and will only be known after further research and development. The large cost of collecting and compiling the performance data to enable an effective computer simulation are a major impediment, while laboratory testing is often unsuitable or very costly, as is the case in determining changes of service loads over time. The civil engineering field, for obvious reasons, is primarily driven by economic incentives and the first step in assessing the need for further development of cost saving techniques is to assess where the true cost of ownership is incurred. So far it has been shown that an exponential growth occurs in the cost of identifying and repairing a defect as a product, in this case a building, matures. If the deficiencies can be detected in the design stage, for example, they could easily be corrected at minimal cost while the structure still only exists on paper (or computer).

The design life concept involves more than just the traditional concerns about cost, schedule and performance, and includes items such as buildability, maintainability, durability, and upgradeability, all of this during the design stage, pending on the availability of appropriate information. To implement such an approach would require additional resources, time, and expense at the planning stage. The benefit would be a significant reduction in total life cycle costs since the process would provide a higher overall quality and performance with lower maintenance and repair costs. The *design life concept* and *life cycle considerations,* if applied correctly, are very powerful tools to address the issues of infrastructure renewal and maintenance, in addition to concerns about environmental impact. A computer based approach to process a large amount of data related to a multitude of variables appears to be a step in the right direction by making designers consider the implications of their decisions and choices on the overall life of the structure.

APPENDIX A

Example of a quality control frame work for structural design

PROJECT PRE-DESIGN MEETING

DATE:____________________ ATTENDEES:

Project Number: ____________________
Project Name: ____________________
Proposal: ____________________

____
____
____
____
____
____

BASIC INFORMATION:

	Yes	No
1) Project data sheet complete?		
2) Confirmation of Assignment returned from client?		
3) Agreement returned from client?		
4) Letter outlining scope of work & fees accepted?		

PROJECT MANAGER:______________________________
PROJECT LEAD ENGINEER:______________________________
PROJECT LEAD TECHNICIAL:______________________________
PROJECT TEAM:

Engineer	Technician	Structure

GENERAL STRUCTURAL DESIGN CRITERIA

LOCATION: ____
____
____

CLIMATE:

Ground snow load: ____________________kPa
Basic wind pressure: ____________________kPa
Winter Design Temp. ____________________°C Summer design temp ________°C
Frost protection: ____________________ m

SITE SOIL INFORMATION

Geotechnical Engineers: ______________________________
Contact: ____________________ Phone:________________ Fax: ________________
Allowable bearing pressure: ____________ kPa
Coefficient for lateral earth pressure: ____________ kPa
Sliding coefficient: ____________ kPa
Soil unit weight: ____________ kN/m^3
Allowable pile bearing: ____________ kPa
Lateral load capacity: ____________ kN
Pull out capacity: ____________ kN

OTHER SUBCONSULTANTS

1) Company name: ____
Contact: __________________ Phone: ______________ Fax: ________________
Description of service: ____
____
____

2) Company name: ____
Contact: __________________ Phone: ______________ Fax: ________________
Description of service: ____
____
____

3) Company name: ____
Contact: __________________ Phone: ______________ Fax: ________________
Description of service: ____
____
____

4) Company name: ____
Contact: __________________ Phone: ______________ Fax: ________________
Description of service: ____
____
____

DESIGN CODES: (Include year of code) __________________________________
____
____
____
____
____
____

STRUCTURAL DESIGN

1) Earthquake(EQ): As per NBC or applicable ATC or API(for tanks)
The weight to be considered shall include dead load and fixed live load. Tanks and chests shall be considered at normal operating levels. Temporary live loads on floors not usually loaded can be ignored for EQ calculations. Loads from EQ shall not be considered to act simultaneously with wind.
2) Wind: As per NBC
3) Snow: As per NBC, allow for build-up and sliding of snow
4) Impact: Shall be considered on all temporary live loads
5) Factor of Safety:

Against overturning	2.0	For Earthquakes _____
Against sliding	2.0	
Against uplift	2.0	

6) Load combination as per NBC _______ Other _______
7) Check vibration

8) Material grades:

Minimum concrete compressive strength		________	MPa (everywhere)
otherwise	____________	________	MPa
	____________	________	MPa
	____________	________	MPa
Reinforcing steel		400	MPa
Structural steel	rolled shapes	300	MPa
	HSS	350	MPa
	misc. plates	250	MPa
Welding electrodes		E480	
Structural bolts		A325	
Anchor bolts		A307	
Masonry	grout	________	MPa
	blocks	________	MPa
Timber	________________________		
	________________________		
	________________________		

9) Floor and roof loads

Dead loads ________________________

Fixed live loads ________________________

Suspended live loads ________________________

Temporary live loads ________________________

Special loading or equipment loads should be obtained from client or manufacturer. These loads should be confirmed in writing and included in the design notes.

Special loading criteria or design conditions include construction loads, erection conditions, corrosion, future use, etc.

10) All design assumptions shall be recorded.
11) Will calculations have to be submitted? Yes ______ No _______ Do not know ________
12) Specify type of CHECK required on this project.

No check	
Check of main members	
Check of design assumptions	
Check of complicated areas	
Complete check of calculations and drawings	
General overview of calculations and drawings for completeness	

13) Checker(s):

Name	Structure or Area

14) Record of Computer programs used:

Program	Source

15) Reference Drawings used for the proposal:

1) ____________________
2) ____________________
3) ____________________
4) ____________________
5) ____________________
6) ____________________

16) Tender documents and specifications required? Yes _____ No _____

17) Agreed Design Approach (conceptual):

18) Schedule:

	Stage	Engineering Start Date	Drafting Start Date	Comments
1	Conceptual Design			
2	Preliminary design			
3				
4	Final Design			
5				
6				
7	50% complete			
8				
9				
10	100% complete			
11	Checking to start			
12				
13				
14	Tender			
15				
16	Issued for construction			
17				
18				