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WHOLE LIFE COSTING IN CONSTRUCTION: A STATE OF THE ART REVIEW

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ABSTRACT

This report is a state of the art review of whole life costing in the construction industry. It is the first of a series reporting on-going research undertaken within the research project ‘Developing An Integrated Database For Whole Life Costing Applications In Construction’. This project is funded by the EPSRC and undertaken by a unique collaboration between two teams of researchers from the Robert Gordon University and the University of Salford.

The fundamental basics of whole life costing (WLC) are introduced. First, the historical development of the technique is highlighted. Then, the suitability of various WLC approaches and techniques are critically reviewed with emphasis on their suitability for application within the framework of the construction industry. This is followed by a review of WLC mathematical models in the literature. Data requirements for WLC are then discussed. This includes a review of various economic, physical, and quality variables necessary for an effective WLC analysis of construction assets. Data sources within the industry are also highlighted with emphasis on current data collection and recording systems. In addition, the requirements of a data compilation procedure for WLC are outlined.

The necessity of including the analysis of uncertainty into WLC studies is discussed. Attempts to utilise various risk assessment techniques to add to the quality of WLC decision-making are reviewed with emphasis on their suitability to be implemented in an integrated environment.

Essential requirements for the effective application of WLC in the industry are outlined with emphasis on the design of the cost break down structure and the information management throughout various life cycle phases. Then, directions for further future research are introduced.

CHAPTER 1

WHOLE LIFE COSTING - AN INTRODUCTION

1.1 BACKGROUND

Historically, designs were aimed at minimising initial construction costs alone. However, during the 1930s many building users began to discover that the running costs of buildings began to impact significantly on the occupiers' budget (Dale, 1993). It became obvious that it is unsatisfactory to base the choice between different alternatives on the initial construction cost alone. This becomes even clearer by the emergence of a number of recent trends as issues of concern for design professionals, including: facility obsolescence, environmental sustainability, operational-staff-effectiveness, total quality management (TQM), and value engineering (VE) (Kirk and Dell'Isola, 1995). Thus, another costing technique currently known as 'whole life costing' (WLC) has developed over the years. The designation of Whole Life Costing (WLC) has altered considerably over the years. The technique has previously been called, in no particular order, terotechnology, life cycle costing (LCC), through-life-costing, costs-in-use, total-life-costing, total-cost-of-ownership, ultimate life cost, and total cost (Kirk and Dell'Isola, 1995; Hodges, 1996; Seeley, 1996; Whyte *et al.*, 1999, Edwards *et al.* 2000). These terms are now less commonly applied and therefore WLC is used throughout this document.

Practical interest in WLC in the construction industry dates back to 1950s when the Building Research Establishment (BRE) supported a research on 'costs-in-use' (Stone, 1960). Then, the British Standards Institution published BS 3811 (BSI, 1974), which describes the sequence of life cycle phases. A guide to WLC was published by the department of industry (Committee of Terotechnology, 1977). Next, the Royal Institute of Chartered Surveyors (RICS) commissioned many studies on WLC (Flanagan *et al.*, 1983; RICS, 1986, 1987). The Society of Chief Quantity Surveyors in Local Government prepared a report in the form of a practice manual (Smith et al, 1984). Another guide to WLC-related techniques was published by HM Treasury (HMSO, 1991) and was later updated in 1997 (HMSO, 1997).

In the last decade, numerous papers and textbooks in the area of WLC and related topics have been published reflecting the increased interest in the technique. Examples include

Flanagan *et al.* (1989), Fabrycky and Blanchard (1991), Ferry and Flanagan (1991), Bull (1993), Kirk and Dell'Isola (1995), Garnett and Owen (1995), Ashworth (1996a, 1996b), Woodward (1997); Asiedu and Gu (1998), Al-Hajj and Horner (1998), El-Haram and Horner (1998), Al-Hajj and Aouad (1999), Whyte *et al.* (1999), Kishk and Al-Hajj (1999, 2000a, 2000b, 2000c, 2000d, 2001a, 2001b) and Edwards *et al.* (2000), among others.

Recently, a centre for Whole Life Performance has been established at the Building Research Establishment (BRE) to provide the Secretariat to an industry-led Whole Life Costs Forum (WLCF) (CPN, 2000). This Forum is intended to enable members to pool and receive typical WLC information through a members-only database, and produce industry-accepted definitions, tools, and methodologies (Edwards *et al.*, 2000).

1.2 DEFINITION OF WHOLE LIFE COSTING

Several definitions of WLC exist. At its most basic, WLC includes the systematic consideration of all costs and revenues associated with the acquisition, use and maintenance and disposal of an asset. The BS ISO 15686-1 of service life planning (BSI, 2000) defines WLC as

> *'a tool to assist in assessing the cost performance of construction work, aimed at facilitating choices where there are alternative means of achieving the client's objectives and where those alternatives differ, not only in their initial costs but also in their subsequent operational costs.'*

Another useful definition is adopted by the construction best practice programme (CBPP, 1998a)

> *'... the systematic consideration of all relevant costs and revenues associated with the acquisition and ownership of an asset'*

1.3 USES OF WHOLE LIFE COSTING

Ferry and Flanagan (1991) argue that application of WLC, in any environment, exists on two levels. The lower level of life cycle costing is represented as a 'Management Tool' to aid the decision making process. The higher level of life cycle costing is termed the 'Management System' whose continuous operation dictates that responsibility for asset management should be retained. In general terms, they argue that during the management of a typical project, all stages, except project initiation, have a potential use for WLC.

1.3.1 Whole Life Costing as a Decision-Making Tool

The primary use of WLC is to be used in the effective choice between a number of competing project alternatives. Although this can be done at any stage of the project, the potential of its effective use is maximum during early design stages (figures 1.1 and 1.2). This is mainly because most, if not all, options are open to consideration (Griffin, 1993). In addition, the ability to influence cost decreases continually as the project progresses, from 100% at project sanction to typically 20% or less by the time construction starts (Paulson, 1976; Fabrycky and Blanchard, 1991). Further more, once the building is delivered, there is a very slim chance to change the total cost of ownership because the decision to own or to purchase a building normally commits users to most of the total cost of ownership (HMSO, 1992). According to Kirk and Dell'Isola (1995) and Mackay (1999), 80-90% percent of the cost of running, maintaining and repairing a building is determined at the design stage.

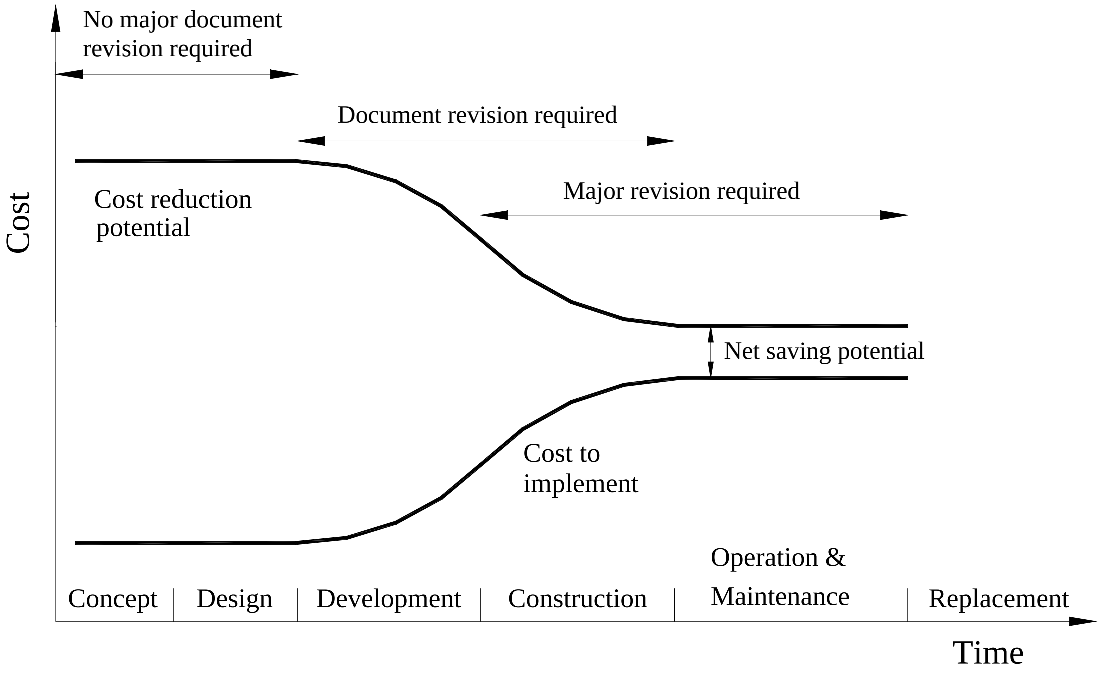


Fig. (1.1): Relationship of whole life cost savings and time of implementation (Flanagan *et al.*, 1989).

1.3.2 Whole life costing as a Management Tool

The use WLC can also be used as a management tool to identify the actual costs incurred in operating assets. The primary objective is to relate running costs and performance data. Thus, it could be useful for clients who want to estimate the actual running costs of the building and also for budgeting purposes. In addition, it can be a valuable feedback device to assist in the design. This issue is discussed in more detail in chapter 5.

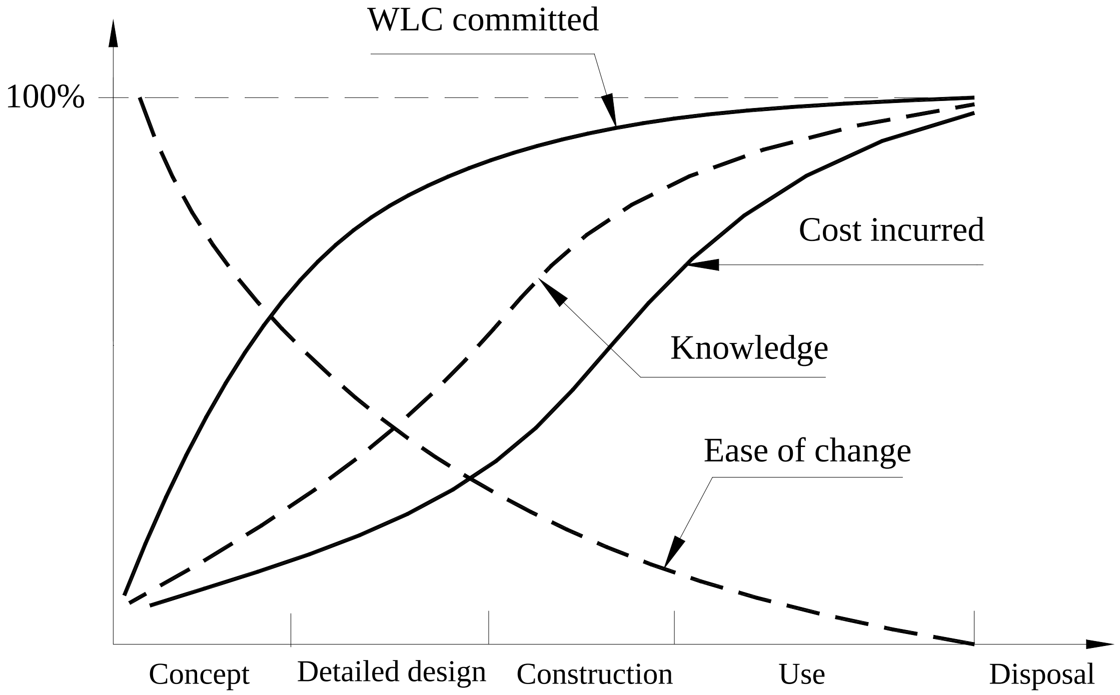


Fig. (1.2): WLC committed, cost incurred, knowledge, and ease of change (Fabrycky and Blanchard, 1991).

1.4 IMPLEMENTATION OF WLC IN THE INDUSTRY

1.4.1 Current WLC Practice

Although most principles of WLC are well developed in theory, it has not received a wide practical application yet. Larsson and Clark (2000) described WLC as ‘the dog that didn’t bark’. A recent survey undertaken by BRE for DETR indicates that life cycle costing is currently used extensively only in PFI projects and public procurement (Clift and Bourke, 1999; CBPP, 2000b). Other surveys indicate also that building sectors in other international countries have not fully adopted the WLC methodology (Wilkinson, 1996; Sterner, 2000).

1.4.2 Barriers Facing WLC Implementation

Many researchers (Brandon, 1987; Ashworth, 1987, 1989, 1993, 1996; Flanagan *et al.*, 1989; Ferry and Flanagan, 1991; Al-Hajj, 1991; Bull, 1993; Wilkinson, 1996; Bhuta and Sarma, 1997; Smith et al., 1998; Sterner, 2000; among others) have tried to highlight areas causing difficulties in the application of WLC in the industry. Kishk and Al-Hajj (1999) categorised these difficulties on the parts of the industry practices, the client, and the analyst and the analysis tools currently employed in WLC.

1.4.2.1 Industry Barriers

The capital cost of construction is almost always separated from the running cost. It is normal practice to accept the cheapest initial cost and then hand over the building to others to maintain. In addition, there is no clear definition of the buyer, seller, and their responsibilities towards the operating and maintenance costs (Bull, 1993). Furthermore, there is a lack of motivation in cost optimisation because the design and cost estimating fees are usually a percentage of the total project cost (McGeorge, 1993). However, the expansion of new project delivery systems such as private finance initiative (PFI) and build, operate and transfer (BOT) seems to overcome these obstacles.

1.4.2.2 Client Barriers

Bull (1993) pointed out that there is also a lack of understanding on the part of the client. This may increase the possibility of subjective decision making. In addition, there are usually multiple aspects of needs desired by clients (Chinyio *et al.*, 1998). Most of these aspects can not be assessed in a strict WLC framework (Kishk *et al.*, 2001). This is mainly because either they are in conflict with the main WLC objective or because they are mostly ‘non-financial’. Some of these factors are even intangible such as aesthetics. In many cases, these intangibles are also in conflict with results of WLC (Picken, 1989; Wilkinson, 1996).

1.4.2.3 Analysis Difficulties

The major obstacle facing the analyst is the difficulty of obtaining the proper level of information upon which to base a WLC analysis. This is because of the lack of appropriate, relevant and reliable historical information and data (Bull, 1993). In addition, costs of data collection are enormous (Ferry and Flanagan, 1991). Furthermore, the time needed for data collection and the analysis process may leave inadequate time for the essential dialogue with the decision-maker and the re-run of alternative options. This is one of the reasons why computerised models are valuable (Griffin, 1993). Another difficulty is the need to be able to forecast, a long way ahead in time, many factors such as life cycles, future operating and maintenance costs, and discount and inflation rates (Ferry and Flanagan, 1991). Besides, the uncertainty surrounding the variables in any WLC exercise should be properly assessed.

1.4.3 The Way Ahead

As discussed in the previous section, the absence of sufficient and appropriate data was, and still is, the major barrier to the application of WLC in the industry. According to and Al-Hajj

(1991), WLC application, in a way, is still trapped in a vicious circle containing a series of causes and consequences (figure 1.3). In order to move forward in the application of WLC, the circle would have to be broken somewhere. This state of the art review is the starting point in an EPSRC funded project to achieve this objective.

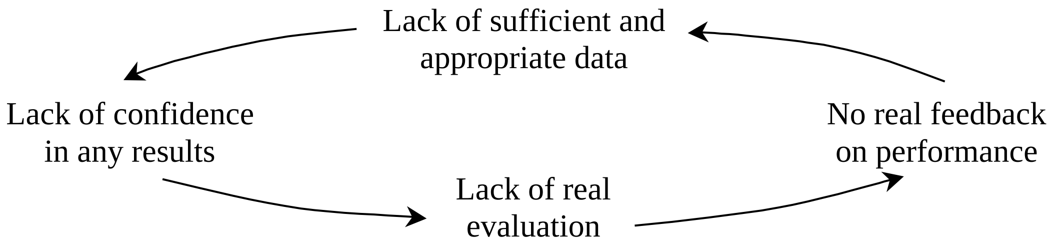


Figure (1.3): The viscous circle of WLC implementation (Al-Hajj, 1991).

1.5 AIM AND OBJECTIVES

The aim of the research work reported in this paper is to undertake a state-of-the-art review of whole life costing to identify the strengths and gaps in existing knowledge in order to inform the development of an integrated computer-based WLC system.

The objectives are:

- To review WLC fundamentals and models.
- To outline WLC data requirements.
- To review risk assessment techniques applicable to WLC modelling.
- To review existing WLC implementation models.

1.6 LAYOUT OF THE REPORT

The rest of the report consists of three parts. The first part includes chapters 2 and 3, and deals with the basic principles and requirements of WLC. Chapter 2 is a critical review of the basic principles of WLC with emphasis on the advantages and disadvantages of various WLC mathematical models and decision-making techniques. In chapter 3, the data requirements for WLC are discussed. This is followed by a review of potential sources of data. Then, the compilation of various data items for WLC is discussed in more detail with emphasis on the utilisation of databases.

The second part, chapter 4, is devoted to a critical review of various techniques proposed to handle risk and uncertainty in WLC modelling, with special emphasis on the suitability of these techniques to be utilised in an integrated environment.

The third part, chapters 5, deals with the logic of WLC implementation with emphasis on the essential requirements for an efficient information management system. Finally, conclusions and directions for further research are introduced in chapter 6.

CHAPTER 2

MATHEMATICAL MODELLING OF WHOLE LIFE COSTS

2.1 INTRODUCTION

An outline introduction to WLC, including its historical background, was provided in chapter 1, and this chapter aims to examine the technique in greater detail through a critical review of its basic concepts and modelling considerations. In the next section, the concept of time value of money is briefly introduced. Then, various approaches applicable to WLC-based decision-making are critically reviewed with emphasis on the suitability of these approaches to be used in the framework of the construction industry. Then, mathematical WLC models found in the literature are reviewed in.

2.2 TIME VALUE OF MONEY

In a typical WLC analysis, the analyst is concerned with a number of costs and benefits that flow throughout the life of a project. A sum of money in hand today is worth more than the same sum at a later date because of the money that could be earned in the interim. Therefore, alternatives can be compared to each other on a fair basis only if the time value of money is taken into consideration. Interest formulas are simple mathematical equations that quantify the impact of time on money. The basic interest formula is expressed as

$$PA = t_f \cdot FA \tag{2.1}$$

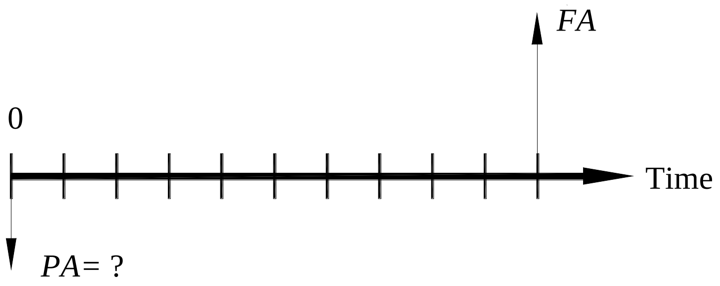
where PA is the present amount of money, FA is the future amount of money, and t_f is a factor required to transform future money to present money.

The factor t_f is a function of the interest rate r, and the time(s) of occurrence(s) of the sum FA. Thus, there are various factors for different situations. These factors are easily derived and are available in most financial and engineering economic texts (e.g. Fabrycky and Blanchard, 1991; Kirk and Dell'Isola, 1995). For example, the present worth factor, PWS, used to determine the present amount, PA, of a single future amount FA, incurred at time t (figure 2.1a) is given by:

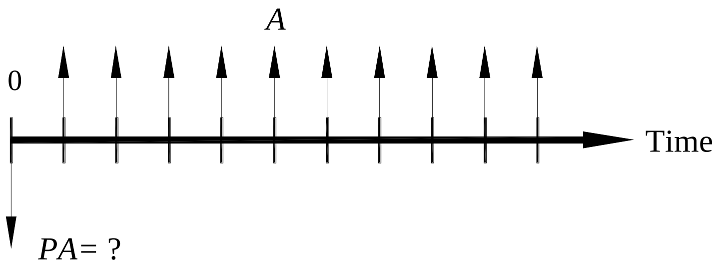
$$PWS = (1+r)^{-T} \tag{2.2}$$

Another example is the PWA factor used to calculate the present worth of a series of T equal annual sums of money (figure 2.1b),

$$PWA = \frac{(1+r)^T - 1}{r(1+r)^T} \tag{2.3}$$



a) A single present worth *(PWS).*



b) Present worth of annuity *(PWA).*

Figure (2.1): Visualisation of the use of interest formulas.

Because future costs are ‘discounted’ to a smaller value when transformed to the present time, it is common practice to use the term ‘discount rate’ in reference to the interest rate.

2.3 WLC DECISION RULES

As discussed in chapter 1, the primary objective of a whole life costing analysis is to facilitate the effective choice between a number of competing alternatives. Many decision criteria that can be used to rank alternatives in a WLC context have been proposed. These criteria are briefly reviewed in this section.

2.3.1 Net Present Value

Based on the definition of WLC (Sec. 1.2), the most obvious decision approach is to base the choice on whole life costs as represented by the net present value (NPV) of various competing alternatives. The NPV of an alternative i, NPV_i, is defined as the sum of money that needs to be invested today to meet all future financial requirements as they arise throughout the life of the project. Obviously, the best alternative, $A*$, is the one with minimum NPV.

Because WLC focuses on cost rather than income, it is usual practice to treat costs as positive and income as negative. Mathematically, the NPV is expressed as

$$NPV_i = C_{0i} + \sum_{t=1}^{T} {}^{d}O_{it} + \sum_{t=1}^{T} {}^{d}M_{it} - {}^{d}SAV_i \tag{2.4}$$

where

C_{0i} ≡ The initial construction costs of alternative i.

$\sum_{t=1}^{T} {}^{d}O_{it}$ ≡ The sum of discounted operation costs at time t.

$\sum_{t=1}^{T} {}^{d}M_{it}$ ≡ The sum of discounted maintenance costs at time t.

${}^{d}SAV_i$ ≡ The discounted salvage value $= {}^{d}RV_{iT} - {}^{d}DC_{iT}$.

${}^{d}RV_{iT}$ ≡ The discounted resale value at the end of the analysis period.

${}^{d}DC_{iT}$ ≡ The discounted disposal costs.

T ≡ The analysis period in years.

Some researchers (e.g. Khanduri *et al.*, 1993) criticised the NPV as being a large number which may not have much meaning to the client. Another limitation of the NPV approach arises when comparing alternatives with different lives because a residual arbitrary value has to be attributed to cover the remaining years (Flanagan *et al.*, 1989).

2.3.2 Equivalent Annual Cost (EAC)

Rather than being expressed as a one-time net present value, this method converts all costs of an alternative to a uniform equivalent annual cost (EAC). The EAC is related to the NPV by the PWA factor (Eq. 2.3) as follows

$$EAC_i = \frac{NPV_i}{PWA_i} \tag{2.5}$$

In this way, alternatives with different lives can be compared without the need to attribute residual values. However, it should be noted that the EAC is an average number and do not indicate the actual cost that will be incurred during each year of the life cycle (Khanduri et al., 1993, 1996). The ranking criterion in this case is that the preferred alternative, $A*$, has the minimum EAC.

2.3.3 Discounted Payback Period

The discounted payback period (DPP) is defined, as the time, usually in years, required for the expected annual savings, taking into account the time value of money, to accumulate to payback the invested amount. Obviously, the preferred alternative, $A*$, should have the shortest payback period.

Although this method considers the time value of money, it has two drawbacks. First, it ignores all cash flows outside the payback period (HMSO, 1997). Secondly, an evaluation of the acceptable payback period is necessary, for which no method is established. Thus, many researchers (e.g. Flanagan *et al.*, 1989; Dale, 1993, Kelly and Male, 1993) recommend that it should only be used as a screening device before the application of more powerful criteria.

2.3.4 Internal Rate of Return (IRR)

The internal Rate of Return (IRR) is defined as the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested. The ranking criterion is that the preferred alternative, $A*$, has the maximum IRR. Mathematically, the IRR for an alternative i, is the interest rate r^* that makes $NPV = 0$, i.e.

$$IRR_i = r* \big| NPV_i = 0 \tag{2.6}$$

The IRR has an obvious advantage because it is presented as a percentage with an obvious interpretation (Flanagan *et al.*, 1989). Besides, it does not require a discount rate unlike the preceding approaches. However, it has two drawbacks (Flanagan *et al.*, 1989; Dale, 1993; Ashworth, 1999). First, the calculation of IRR needs a trial and error procedure. Secondly and more importantly, it assumes that an investment will generate an income which is not always the case in the construction industry.

2.3.5 Net Savings (NS)

The net savings (NS) is an easily understood traditional investment appraisal technique. It is calculated as the difference between present worth of the income generated by an investment to the amount invested (Kelly and Male, 1993). The ranking criterion is that the preferred alternative, $A*$, has the maximum NS. This method, however, suffers from the main disadvantage of the IRR method, i.e. it implies that an investment will generate an income.

2.3.6 Savings to Investment Ratio (SIR)

The savings to investment ratio (SIR) is another traditional investment appraisal technique. It is calculated as the ratio of the present worth of the income generated by an investment to the initial investment cost. The higher the ratio, the greater the pound savings per pound spent and consequently the preferred alternative, $A*$, should have the maximum SIR. Again, this method suffers from the same disadvantage of the NS method.

2.4 Mathematical WLC MODELS

Almost all models found in the literature employ the NPV approach (Eq. 2.4a). However, different nomenclature and/or cost breakdown structure (chapter 5) are used to describe principal components of WLC. The American Society for Testing and Materials (ASTM, 1983) published the following model

$$\boldsymbol{NPV = C + R - S + A + M + E} \tag{2.7}$$

where

$\boldsymbol{C}$ ≡ Investment costs;

$\boldsymbol{R}$ ≡ Replacement costs;

$\boldsymbol{S}$ ≡ The resale value at end of study period;

$\boldsymbol{A}$ ≡ Annually recurring operating, maintenance, and repair costs (except energy costs);

$\boldsymbol{M}$ ≡ Non-annually recurring operating, maintenance, and repair costs (except energy costs); and

$\boldsymbol{E}$ ≡ Energy costs.

The most unique feature of this model is the separation of energy costs, and hence different discount rates can be employed to reflect different inflation rates.

Bromilow and Pawsey (1987) proposed a model as a generalisation of a previous model developed by Bromilow and Tucker (1983). This model is expressed as

$$NPV = C_{0i} + \sum_{i=1}^{n}\sum_{t=1}^{T} C_{it}(1+r_{it})^{-t} + \sum_{j=1}^{m}\sum_{t=1}^{T} C_{jt}(1+r_{jt})^{-t} - d(1+r_d)^{-T} \tag{2.8}$$

where

C_{0i} ≡ the procurement cost at time t=0, including development, design and construction costs, holding charges, and other initial associated with initial procurement;

C_{it} ≡ the annual cost at time t ($0 \le t \le T$), of function i ($0 \le i \le n$), which can be regarded continuous over time such as maintenance, cleaning, energy and security;

C_{jt} ≡ the cost at time t of discontinuous support function j ($0 \le j \le m$), such as repainting, or replacement of components at specific times.

r_{it} & r_{jt} ≡ discount rates applicable to support functions i and j respectively.

d ≡ the value of asset on disposal less costs of disposal; and

r_d ≡ the discount rate applicable to asset disposal value.

The main feature of this model is the classification of maintenance activities as non-annual recurring costs and those that remain continuous.

Many researchers (e.g. Flanagan et al., 1989) have employed the following simple NPV formula based on the discounted cash flow (DCF) technique

$$NPV_i = \sum_{t=0}^{T} \frac{C_t^i}{(1+r)^t} \tag{2.9}$$

To use this formula, it is necessary first to express every cost by a number of equivalent cash flows over the analysis period. However, this may be computationally expensive. Besides, the contribution of each cost to whole life costs can not be easily followed.

Al-Hajj (1991) and Al-Hajj and Horner (1998) developed simple cost models to predict the running and maintenance costs in buildings. These models are based on the finding that for defined building categories identical cost-significant items can be derived using a statistical approach. These models can be expressed in the form

$$R_c = \frac{1}{cmf}\sum_{i=1}^{n}\sum_{t=1}^{T} C_{(csi)it}(1+r)^{-t} \qquad (2.10)$$

where

R_c ≡ the present discounted running costs over period T measured from time of procurement;

cmf ≡ cost model factor (constant for various building categories).

$C_{(csi)}$ ≡ cost significant items: decoration, roof repair, cleaning, energy, management cost, rates, insurance and porterage.

Then, NPV can be calculated as (Al-Hajj, 1996):

$$NPV = C_O + \frac{1}{cmf}\sum_{i=1}^{n}\sum_{t=1}^{T} C_{(csi)it}(1+r)^{-t} - d(1+r_d)^{-T} \qquad (2.11)$$

These models represent a significant simplification. However, their accuracy lie outside the expected range specified by Al-Hajj (1991) as revealed by the investigation carried out by Young (1992). She pointed out that these inaccuracies might be due to three reasons. First, the data recording system of one of the sources is different from the BMI-based system used to develop the models. Secondly, the models do not take account of different materials or components used in various buildings. Thirdly, the occurrence of occasional high cost items. The first two reasons were mentioned by Al-Hajj (1991) as limitations of his models. In addition, he employed the moving average technique to account for the third limitation.

However, there are four more shortcomings that seem to limit the generality of these models. First, the cost-significant relationships are assumed to be linear which might not be always the case. Secondly, data sets used to develop the models are limited. Thirdly, a simple data normalisation procedure ($£/m^2$) is adopted. This procedure does not yield accurate results (Kirkham *et al.*, 1999) because it ignores other factors such as age, location, level of occupancy, and standards of operation and management. Fourthly, historic maintenance data, in terms of time and cost, represent only that which was affordable (Ashworth, 1999). This issue is discussed in more detail in the following chapter.

Sobanjo (1999) proposed a WLC model based on the fuzzy set theory (FST). Assuming that, all costs and values can be treated as either single future or annual costs, the model employs the PW and PWA factors (Eqs. 2.2 and 2.3) to calculate the NPV, as follows

$$NPV = \sum C_0 + \sum FA(1+r)^{-t} + \sum A \frac{(1-(1+r)^{-t})}{r} \tag{2.12}$$

Sobanjo's model has the apparent advantage of being simple. Besides, it assumes that each cost type, e.g. initial, consists of the summation of a number of costs, which gives the analyst some flexibility. However, the model can handle only single future costs and annual costs. This means that non-annual recurring costs can only be treated as a number of single future costs which is a computationally expensive procedure. In addition, the frequencies of these costs must be assumed certain to determine the number of the recurrences of these costs. Other aspects of this model will be discussed in chapter 4.

The model developed by Kishk and Al-Hajj (2000a) calculates the life cycle cost of an alternative i, as the net present value, of all costs and the salvage value of that alternative as

$$NPV_i = C_{0i} + PWA\sum_{j=1}^{nar_i} A_{ij} + \sum_{k=1}^{nnr_i} C_{ik} PWN_{ik} - PWS \cdot SV_i \tag{2.13}$$

where

$$PWN_{ik} = \frac{1-(1+r)^{-n_{ik} f_{ik}}}{(1+r)^{f_{ik}} - 1} \tag{2.14}$$

$$n_{ik} = \begin{cases} \text{int}(\dfrac{T}{f_{ik}}), & \text{provided that rem}\left(\dfrac{T}{f_{ik}}\right) \neq 0 \\ \dfrac{T}{f_{ik}} - 1, & \text{elsewhere} \end{cases} \tag{2.15}$$

This model has three unique features. First, a discount factor (equation 2.14) was formulated to deal with non-annual recurring costs. Secondly, the derivation of an automatic expression for the number of occurrences of these costs (equation 2.15). This expression accounts for the fact that non-annual costs recurring at the end of the last year of the analysis period are not taken into consideration. Thirdly, annual costs are assumed to be the summation of nar_i components, A_j, e.g. maintenance and operating costs. This was done to allow for more flexibility in the assignment of different uncertainty levels to various annual costs depending on the nature of every cost.

In a subsequent paper (Kishk and Al-Hajj, 2000d), they developed a model that calculates the life cycle cost of an alternative i, as an equivalent annual cost

$$EAC_i = \sum_{j=1}^{nar_i} A_{ij} + AEI_i C_{0i} + \sum_{m=1}^{nno_i} F_{im} AEO_{im} + \sum_{k=1}^{nnr_i} C_{ik} AEN_{ik} - AES_i SV_i \tag{2.16}$$

where AES_i, AEI_i, AEO_i, and AEN_i are uniform annual equivalence factors for salvage value and initial, non-recurring, non-annual recurring costs, respectively. These factors are given by

$$AEI_i = \frac{r}{1-(1+r)^{-T_i}} \tag{2.17}$$

$$AEN_{ik} = \frac{r\left(1-(1+r)^{-n_{ik} f_{ik}}\right)}{\left(1-(1+r)^{-T_i}\right)\left((1+r)^{f_{ik}} - 1\right)} \tag{2.18}$$

$$AES_i = \frac{r}{(1+r)^{T_i} - 1} \tag{2.19}$$

$$AEO_{im} = \frac{r(1+r)^{-t_{im}}}{(1+r)^{-T} - 1} \tag{2.20}$$

This model has the same advantages of the previous model. Besides, the calculation of whole life costs as EACs is another merit when dealing with options with different lives as discussed in Sec. 3.3.2. Other aspects of these models are discussed in Chapter 4.

2.5 SUMMARY

This chapter was devoted to review the key fundamentals of WLC modelling. The time value of money and the concept of economic equivalence allow money spent over various points in time to be converted to a common basis. Six economic evaluation methods commonly used in whole life costing analyses were reviewed. The most suitable approaches for WLC in the framework of the construction industry are the net present value and equivalent annualised methods. The later is the most appropriate method for comparing alternatives of different lives.

A review of the mathematical LCC models was also carried out. Most of these models use the same basic equation. However, they differ in the breakdown of cost elements. Each of these models seems to have some advantages and disadvantages. The ASTM WLC model distinguishes between energy and other running costs which is useful in adopting different discount rates for these two cost items. The model developed by Bromilow and Pawsey (1987) distinguishes between periodic and continuous maintenance activities. The concept of cost significance was introduced into WLC by Al-Hajj (1991). This concept simplifies WLC by reducing the number of cost items required. However, these simple models have some shortcomings that seem to limit their generality. Sobanjo’s model is simple but it can not effectively handle non-annual recurring costs. The models developed by Kishk and Al-Hajj (2000a, 2000d) are developed such that calculations are both automated and optimised. This is mainly facilitated by the derivation of automatic expressions for calculating the number of occurrences on non-annual recurring costs. Besides, compact expressions are formulated for various discount and annualisation factors. In this way, the main disadvantage of Sobanjo’s model has been tackled.

CHAPTER 3

ON THE DATA REQUIREMENTS OF WHOLE LIFE COSTING

3.1 INTRODUCTION

An investigation into the variables in the mathematical models discussed in chapter 2 would reveal that data requirements fall into two main categories: discounting-related data and cost-related data. The first category includes the discount and inflation rates and the analysis period. The second category includes cost data and the time in the life cycle when associated activities are to be carried out (i.e. life cycle phases). On the other hand, Flanagan *et al.* (1989) realised that buildings are different from other products, e.g. cars, in that buildings tend to be ‘one-off’ products. Other data categories like quality, occupancy and performance data are therefore also crucial when dealing with buildings. In the following three sections, various WLC data categories are outlined with emphasis on characteristics and sources of these data items. Then, the process of data compilation is discussed in some detail.

3.2 Discounting-Related Data

3.2.1 The Discount Rate

The selection of an appropriate discount rate has a significant influence on the outcome of any WLC exercise (Flanagan *et al.*, 1989; Ashworth, 1999). Various criteria proposed in the literature to the election of the discount rate are discussed in the following subsections.

3.2.1.1 Cost of Borrowing Money

The discount rate may be established as the highest interest an organisation expects to pay to borrow the money needed for a project. This method is favoured by Hoar and Norman (1990) as it indicates the marketplace value of money. However, it does not take into account for risk of loss associated with the loan (Flanagan *et al.*, 1989).

3.2.1.2 Risk Adjusted Rate

In this approach, the disadvantage of the cost of borrowing money is eliminated by including an increment which reflects variable degrees of risk between projects and the uncertainty of future events as suggested by Rueg and Marshall (1990). However, it is not easy to quantify risk as a percent increment (Flanagan and Norman, 1993, Kirk and Dell’Isola, 1995). Hoar and Norman (1990), even argue that it is inappropriate to include a risk premium in the discount rate.

3.2.1.3 Opportunity Rate of Return

In this approach, the discount rate is defined as the rate of return that could be earned from the best alternative use of the funds devoted for the project under consideration. It is the most realistic one, since it is based on the actual earning power of money (Kelly and Male, 1993). However, such an opportunity cost may be ambiguous because it is often impossible to identify the best alternative use (Finch, 1994). Besides, it is difficult to apply for public sector projects (Kirk and Dell'Isola, 1995).

3.2.1.4 After-Inflation Discount Rate

This method is based on the assumption that the private sector will seek a certain set rate of return over the general inflation rate. This rate is also called 'the net of inflation discount rate', r_f , and is calculated as

$$r_f = \frac{1+r}{1+f} - 1 \qquad (3.1)$$

where f is the inflation rate. This method is favoured by Many researchers (e.g. Flanagan *et al.*, 1989; Dale, 1993; Kirk and Dell'Isola, 1995). Other researchers, however, prefer to ignore inflation on the assumption that it is impossible to forecast future inflation rates with any reasonable degree of accuracy (Ashworth, 1999).

3.2.1.5 Role of Judgement

Because the discount rate should reflect the particular circumstances of the project, the client and prevailing market conditions, Ashworth (1999) recognised the role of judgement in the selection of the most correct rate. However, he emphasised that this judgement should be done within the context of best professional practice and ethics.

3.2.2 The Time-Scale

Flanagan *et al.* (1989) differentiated between two different time-scales: the life of the building, the system, or the component under consideration and the analysis period.

3.2.2.1 The Life

The life expectancy of a building may be theoretically indefinite, if it is correctly designed and constructed and properly maintained throughout its life. However, in practice, this life is frequently shorter due to physical deterioration and various forms of obsolescence (Flanagan *et al.*, 1989). This view is supported by the opinions of Aikivuori (1996) and Ashworth (1996a, 1999) who questioned the usefulness of scientific data because it is almost solely concerned with component longevity and not with obsolescence. Different sorts of obsolescence that need to be considered by designers and users are summarised in Table (3.1).

Table (3.1): Building life and obsolescence (RICS, 1986).

Condition	Definition	Examples
Deterioration Physical	Deterioration beyond normal repair	Structural decay of Building components
Obsolescence Technological	Advances in sciences and engineering results in outdated building	Office buildings unable to Accommodate modern Information and Communication technology.
Functional (Useful)	Original designed use of the building is no longer required	Cotton mills converted in shopping units Chapels converted into Warehouses
Economic	Cost objectives are able to be achieved in a better way	Site value is worth more than the value of the current activities.
Social	Changes in the needs of society result in the lack of use for certain types of buildings	Multi-storey flats unsuitable for family accommodation in Britain
Legal	Legislation resulting in the prohibitive use of buildings unless major changes are introduced	Asbestos materials, Fire regulations

Ashworth (1999) pointed out that obsolescence relates to uncertain events as can be clearly seen in Table (2.1). He analysed data about the estimated life expectancy of softwood windows from a RICS/BRE paper (RICS/BRE, 1992). The analysis shows a life expectancy of about 30 years, with a standard deviation of 22 years and a range of 1 to 150 years. Consequently, he concluded that it is not possible to select a precise life expectancy for a particular building component on the basis of this sort of information. This is mainly because important data characteristics, e.g. the reason for the variability of life expectancies, are not included. Ashworth (1999) listed other published sources of information such as the HAPM's component life manual (HAPM, 1992, 1999a), guide to defect avoidance (HAPM, 1999b) and workmanship checklists (HAPM, 1999c) However, these sources provide further evidence of the variability of building component data.

Flanagan *et al.* (1989) identified manufacturer and suppliers as another valuable source of lifespan data. However, their information may be described under ideal or perfect circumstances that rarely occur in practice (Ashworth, 1999). Another possible problem is that it might be of a commercial nature, i.e. suppliers might tend to favour their products. Kelly and Male (1993) pointed out another difficulty as manufacturers' data is usually obtained in terms of ranges of life. They gave the following example

> *'... these fans work for two years, they come with a two year guarantee but providing they are well maintained will run for 8-12 years no bother. We've some, which are still going after 16 years'*

Kelly and Male (1993) identified also trade magazines as a source that gives similar sort of data.

3.2.2.2 The Analysis Period

Anderson and Brandt (1999) and Hermans (1999) reported that information on the actual, real-life periods of use of building components is still lacking almost completely. Salway (1986) recommended that for whole life costing purposes the time scale should be the lesser of physical, functional and economic life. By definition, the economic life is the most important from the viewpoint of cost optimisation as pointed out by Kirk and Dell'Isola (1995). Other researchers, e.g. Hermans (1999), recommended that the technological and useful lives must also be considered when the economic life of an item is estimated.

In general, almost all researchers agreed that it is not recommended to assume a very long analysis period. The main reason, pointed out by Mcdermott *et al.* (1987), is that the further one looks into the future the greater the risk that assumptions used today will not apply. In addition, cash flows discounted on long time horizon are unlikely to affect significantly the ranking of competing alternatives (Flanagan et al, 1989). Furthermore, refurbishment cycles are likely to become shorter in the future for many buildings (Ashworth, 1996a, 1996b, 1999).

3.3 Cost and Time Data

By definition, cost data required for WLC purposes include initial costs and future follow-on costs that may include maintenance and repair costs, alteration costs, replacement costs, salvage value, among others.

3.3.1 Initial Costs

These are the costs for the development of the project including design and other professional fees as well as construction costs. Compared to future costs, initial costs are relatively clear and visible at early stages of projects (Kirk and Dell’Isola, 1995). However, even initial cost estimates may not be reliable as observed by Ashworth (1993) referring to the finding of Ashworth and Skitmore (1982) that estimates of contractors tender sums are only accurate to about 13%.

3.3.2 Maintenance and Repair Costs

Maintenance has been defined to include the costs of regular custodial care and repair including replacement items of minor value or having a relatively short life (Kirk and Dell’Isola, 1995). Sources of maintenance and repair data cited in the literature include historical data from clients and/or surveyors’ records, cost databases and maintenance price books.

The basic problem of with historical maintenance data is that it is mostly combined for accounting purposes falling into broad classification systems that are too coarse to disclose enough information for other purposes (Ashworth, 1993, 1999; Kelly and male, 1993; Wilkinson, 1996). A second problem with historical maintenance data is that not all companies and organisations have preventive and planned maintenance policies and in many situations, maintenance work is budget oriented rather than need oriented (Flanagan *et al.*, 1989; Ashworth, 1996a, 1996b, 1999). Another related problem was identified by Mathur and McGeorge (1990) who argued that maintenance costs are heavily dependent on management policy. Some owners endeavour to maintain their buildings in an as new condition whilst others accept a gradual degradation of the building fabric.

The second source of maintenance data cited in the literature is cost databases (e.g. Neely and Neathammaer, 1991; Ciribini et al., 1993; Kirk and Dell'Isola, 1995). Neely and Neathammaer (1991) developed and implemented four databases at the US Army Construction Engineering Research Laboratory. The simplest database contains average annual maintenance per square foot by building use. The most detailed database contains labour hours per square foot, equipment hours per square foot, and material costs per square foot. Kirk and Dell'Isola (1995) referred to a similar database called BMDB available through ASTM. These databases are 'constructed' rather than 'historical-based' in that they are mostly based on 'expert opinion', trade publication data, and data in manufacturers' literature. They pointed out that maintenance task frequencies are the most subjective portion of these databases as they are mostly based on professional experience. The validity of existing cost databases is, however, questionable as Smith (1999) reported that there was a 38% difference between two commercially available cost databases when estimating the cost for new facilities for an American federal agency.

Another resource of maintenance data is the BMI building maintenance price book published annually by the BMI (e.g. BMI, 2001). The contents of this book are based on the experience of the compilers, together with estimators specialising in the maintenance field and some on the results of work-studies carried out in maintenance departments. In this context, it is useful to quote the following note from the BMI building maintenance price book (BMI, 2001)

> *'... The measured rates represent a reasonable price for carrying out the work described. However, the very nature of maintenance work means that no two jobs are identical and no two operatives tackle tasks in exactly the same way'.*

Again, this highlights the importance of high quality professional judgement in adjusting data from historical records and other sources to suit a particular project.

3.3.3 Replacement Costs

Replacement costs are those expenses incurred to restore the original function of the facility or space, by replacing facility elements having a life cycle shorter than that planned for the entire facility and not included the previous category (Kirk and Dell'Isola, 1995). As discussed in Sec. 3.2, data required to maintain a building in its initial state is seldom available. Another problem in dealing with replacement costs is their dynamic nature due to the changes of the quality and standards of components as pointed out by Ashworth (1999). He concluded that this might distort any cost retrieval system and consequently any WLC predictions that may already have been made. This highlights once more the need to high quality judgement and the incorporation of the analysis of uncertainty into WLC studies.

3.3.4 Refurbishment and Alteration Costs

Many buildings may incur costs, which can not be categorised as repair, maintenance or replacement costs in the context of fair wear and tear, e.g. refurbishment and alteration costs. These are usually associated with changing the function of the space or for modernisation purposes. For example, when a tenant leaves an office, the owner must have the space redone to suit the functional requirements of the new tenant (Kirk and Dell'Isola, 1995).

In handling this cost category, it is required to anticipate both the costs and cycle of alteration, which seems to be a difficult task. Analysts can work around this difficulty by either studying the alteration cycles in comparable buildings. If data is not available, the ease of change or alterability of various design schemes can still be treated as a non-financial factor which can be incorporated in the decision making process (Kishk et al., 2001).

3.3.5 Operating Costs

This category includes cost items relating to energy, cleaning, general rates, insurance and other costs related to operating the facility under consideration (Kirk and Dell'Isola, 1995). Energy costs of buildings depend heavily on the use and hours of building systems operations, weather conditions, the performance level required by owners, the building's design and insulation provisions. This why Kirk and Dell'Isola (1995) emphasised the role of professional skills and judgement in adjusting historical data on energy costs before projecting for the expected level of use in a proposed design alternative. Bordass (2000) discussed in some detail the danger of making comparisons of costs without having good reference information. He illustrated his arguments in the context of comparing energy consumption of some offices in the UK with comparable Swedish data.

Cleaning costs of buildings, depend on the type of building, function of spaces to be cleaned, type of finishes, cleaning intervals (Flanagan *et al.*, 1989; Ashworth, 1999). It should be noted, however, that cleaning costs of some elements, e.g. windows, seems to be identical and can therefore be eliminated in the decision-making process.

Other operating costs such as rates, insurance premiums and security costs seems to affect the whole life costs of buildings. Ashworth (1999) listed some factors affecting the rateable values of buildings including the location, size, and amenities available. He pointed out also that safety factors such as type of structure, materials used and class of trade affect the insurance premiums and security costs.

3.3.6 Taxes

The inclusion of taxes in WLC calculations is important in the assessment of projects for the private sector. According to Ashworth (1999), this tends to favour alternatives with lower initial costs because taxation relief is generally available only against repairs and maintenance.

3.3.7 Denial-to-Use Costs

These costs include the extra costs occurring during the construction or occupancy periods, or both, because income is delayed. For example, an earlier availability of the building for its intended use by selecting a particular alternative may be considered as a monetary benefit because of the resulting additional rental income and reduced inspections, and administrative costs (Lopes and Flavell, 1998).

3.3.8 Salvage Value

The salvage value is the value of the facility at the end of the analysis period. This could be resultant of the component having a remaining life, which could be used or sold. It is calculated as the difference of the resale value of the facility and disposal costs, if any.

3.4 Other Data Requirements

Other data requirements include physical, occupancy and quality data. Cost data are of uncertain value without being supplemented by these types of data (Flanagan *et al.*, 1989). Physical data relate to physical aspects of buildings that can be measured such as areas of floor and wall finishes. Physical data are necessary in all cost estimating methods. Besides, cost data need to be interpreted with physical data. Different buildings used for the same purpose but with different physical aspects will incur different costs as previously mentioned when discussing energy costs. Al-Hajj (1991) has shown that building-size and number-of-storeys as well as design purpose, influence the running costs of buildings.

Hobbs (1977) and Flanagan *et al.* (1989) stressed the importance of the hours of use and occupancy profile as other key factors especially for public buildings such as hospitals and schools. This view was supported by Martin (1992) who showed that users and not floor-area had the greatest correlation with costs-in-use of hospitals.

On the other hand, quality and performance data are influenced by policy decisions such how clean it should be and how well it should be maintained. Data related to quality is highly subjective (Flanagan et al. 1989) while performance data is often incomplete, diffuse and largely unstructured (Bartlett and Howard, 2000).

3.5 SUMMARY

The data requirements to carry out a life cycle costing analysis are outlined. Five data categories were identified: (1) the economic variables. (2) cost data; (3) occupancy data; (4) physical data; and (5) performance and quality data. The economic variables that influence whole life costing were discussed. Various factors affecting the selection of an appropriate discount rate were also discussed. The 'the net of inflation discount rate' is recommended by many researchers to be used in WLC. This is because it takes into consideration the effect of inflation on costs. The analysis period or the time frame over which costs are projected is a key issue in any WLC analysis. Many definitions of the expected life of a building or a component are used. The most important lives are the economic life and the useful life. In addition, various deterioration and obsolescence forms that affect the choice of the period of analysis were outlined.

Cost data include initial costs, maintenance and repair costs, alteration and replacement costs, associated costs, demolition costs, and other costs. Cost data are essential for the research. However, without being supplemented by other types of data, they are of uncertain value. This is mainly because cost data need to be interpreted in the context of other data categories. Sources of WLC data were also discussed.

Main sources include historical data, manufacturers' and suppliers' data, predictive models and professional judgement. Some attempts to build WLC databases utilising these sources were critically reviewed. Existing databases have two limitations. A simple data normalisation procedure was used. In addition, almost all of these databases do not record all the necessary context information about the data being fed into them.

CHAPTER 4

UNCERTAINTY AND RISK ASSESSMENT IN WHOLE LIFE COSTING

4.1 INTRODUCTION

WLC, by definition, deals with the future and the future is unknown. As discussed in chapter 2, there is a need to be able to forecast a long way ahead in time, many factors such as life cycles, future operating and maintenance costs, and discount and inflation rates. This difficulty is worsening by the difficulty in obtaining the appropriate level of information and data as discussed in chapter 3. This means that uncertainty is endemic to WLC. Therefore, the treatment of uncertainty in information and data is crucial to a successful implementation of WLC. In this chapter, various risk assessment techniques applicable to WLC are critically reviewed. These approaches are the sensitivity analysis, probability-based techniques, and the fuzzy approach.

4.2 THE SENSITIVITY ANALYSIS

The sensitivity analysis is a modelling technique that is used to identify the impact of a change in the value of a single risky independent parameter on the dependent variable. The method involves three basic steps (Jovanovic, 1999):

- The assignment of several reasonable values to the input parameter,
- The computation of corresponding values of the dependent variable, and
- The analysis of these pairs of values.

In WLC calculations, the dependent variable is usually a whole life cost measure (usually the NPV or the EAC) of the least-cost alternative and the input parameter is an uncertain input element. The objective is usually to determine the break-even point defined as ‘the value of the input-data element that causes the WLC measure of the least-cost alternative to equal that of the next-lowest-cost alternative’ (Kirk and Dell’Isola, 1995). Flanagan *et al.* (1989) recommend the use of the spider diagram to present the results of the analysis. As shown in Fig. (4.1), each line in the spider diagram indicates the impact of a single parameter on WLC. The flatter the line the more sensitive WLC will be to the variation in that parameter.

The major advantage of the sensitivity analysis is that it explicitly shows the robustness of the ranking of alternatives (Flanagan and Norman, 1993, Woodward, 1995). However, the sensitivity analysis has two limitations. First, it is a univariate approach, i.e., only one parameter can be varied at a time. Thus, it should be applied only when the uncertainty in one input-data element is predominant (Kirk and Dell'Isola, 1995). Secondly, it does not aim to quantify risk but rather to identify factors that are risk sensitive. Thus, it does not provide a definitive method of making the decision.

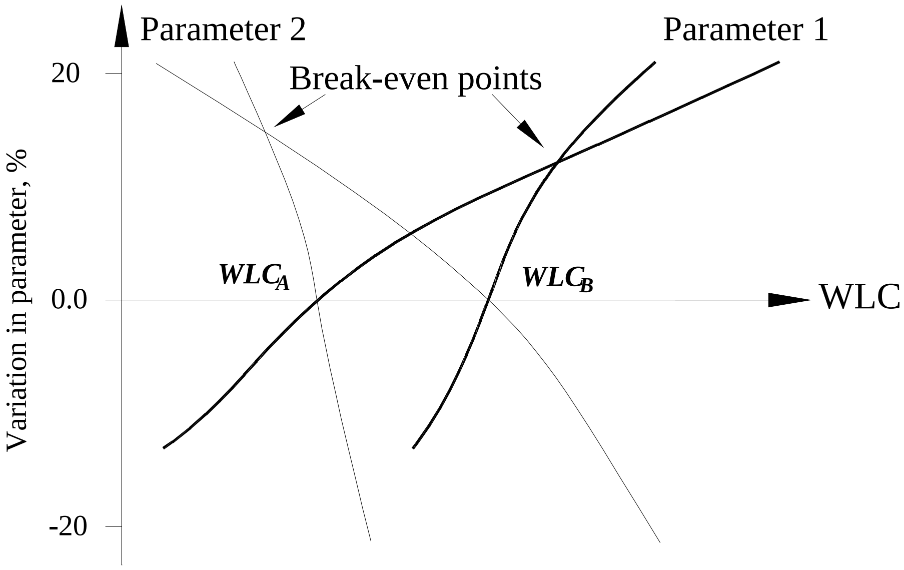


Figure (4.1): Sensitivity analysis spider diagram (Flanagan *et al.*, 1989).

4.3 PROBABILITY-BASED TECHNIQUES

In the probabilistic approach to risk analysis, all uncertainties are assumed to follow the characteristics of random uncertainty. A random process is one in which the outcomes of any particular realisation of the process are strictly a matter of chance. In the following subsections, two probability-based techniques are reviewed: (1) the confidence index approach; and (2) the Monte Carlo simulation technique.

4.3.1 The Confidence Index Approach

The confidence index technique (Kirk and Dell'Isola, 1995; Kishk, 2001) is a simplified probabilistic approach. It is based on two assumptions: (1) the uncertainties in all cost data are normally distributed; and (2) the high and low 90% estimates for each cost do in fact correspond to the true 90% points of the normal probability distribution for that cost. For two alternatives A and B, a confidence index, *CI*, is calculated and a confidence level is assigned to the WLC calculations according to the value of *CI* as follows:

- For *CI* < 0.15, assign low confidence. This is equivalent to a probability less than 0.6.
- For 0.15 < *CI* < 0.5, assign medium confidence. This is equivalent to a probability between 0.6 and 0.67.
- For *CI* < 0.5, assign high confidence. This is equivalent to a probability over 0.67.

The CI approach is considered valid as long as (Kirk and Dell'Isola, 1995):

- The low and high 90% estimates are obtained from the same source as the best estimates; and considered to represent knowledgeable judgement rather than guesses.
- The differences between the PW of the best estimate of each cost and the PWs of the high and low 90% estimates are within 25% or so of each other, i.e.

The necessary assumption of normally distributed data and the above two restrictions limit the generality of the confidence index technique.

4.3.2 The Monte-Carlo Simulation

Monte Carlo simulation is a means of examining problems for which unique solutions cannot be obtained. It has been used in WLC modelling by many authors (e.g. Flanagan et al., 1987, 1989; Ko et al., 1998; Goumas et al., 1999). In a typical simulation exercise, uncertain variables are treated as random variables, usually but not necessarily uniformly distributed. In this probabilistic framework, the WLC measures, usually the NPVs, also become random variables. In the last phase of evaluation, various alternatives are ranked in order of ascendant magnitude and the best alternative is selected such that it has the highest probability of being first. Figure (4.2) illustrates this process for the case of two competing alternatives. As noted by Flanagan *et al.* (1989), the decision-maker must weigh the implied trade-off between the lower expected cost of alternative A and the higher risk that this cost will be exceeded by an amount sufficient to justify choice of alternative. They also noted that although the technique provides the decision-maker with a wider view in the final choice between alternatives, this will not remove the need for the decision-maker to apply judgement and there will be, inevitably, a degree of subjectivity in this judgement

Simulation techniques have been also criticised for their complexity and expense in terms of the time and expertise required to extract the knowledge (Byrne, 1997 and Edwards and Bowen, 1998).

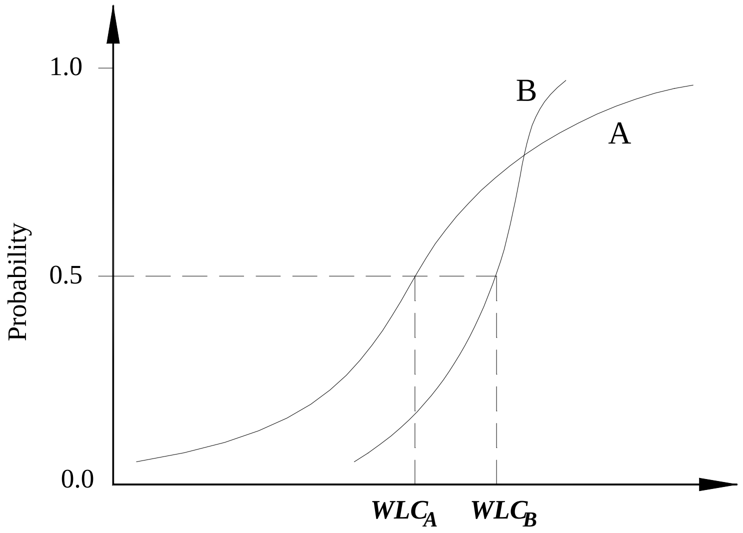


Figure (4.2): Choice between alternatives in a probability analysis (Flanagan *et al.*, 1989).

4.3.3 Other Limitations of the Probabilistic Techniques

The main assumption in probabilistic risk assessment techniques is that all uncertainties follow the characteristics of random uncertainty. This implies that all uncertainties are due to stochastic variability or to measurement or sampling error; and consequently are expressible by means of probability distribution functions (PDFs). Therefore, PDFs are best derived from statistical analysis of significant data. But, as previously discussed, historic data for WLC is sparse. In view of the limited availability of ‘hard data’, subjective assessments for the likely values of uncertain variables have to be elicited from appropriate experts (Byrne, 1996; Clemen and Winkler, 1999). Some researchers claim that it is possible to produce meaningful PDFs using subjective opinions (Byrne, 1996). However, the authenticity of such assessments is still suspected as Byrne (1997) pointed out

As revealed by the review of various data elements (chapter 3), facets of uncertainty in WLC data are not only random but also of a judgmental nature. This mainly because most data rely on professional judgement. Besides, WLC data for a particular project is usually incomplete. Vesely and Rasmuson (1984) identified lack of knowledge to be virtually always of a judgmental nature as well. This suggests that probabilistic risk assessment fall short from effectively handle uncertainties in whole life costing.

4.4 The Fuzzy Approach

The shortcomings relating to the sensitivity analysis and probabilistic techniques suggest that an alternative approach might be more appropriate. Recently, there has been a growing interest in many science domains in the idea of using the fuzzy set theory (FST) to model uncertainty (Kaufmann and Gupta, 1988; Ross, 1995; Kosko, 1997, to mention a few). The fuzzy set theory seems to be the most appropriate in processes where human reasoning, human perception, or human decision making are inextricably involved (Ross, 1995; Kosko, 1997). In addition, it is easier to define fuzzy variables than random variables when no or limited information is available (Kaufmann and Gupta, 1985). Furthermore, mathematical concepts and operations within the framework of FST are much simpler than those within the probability theory especially when dealing with several variables (Ferrari and Savoia, 1998).

Byrne (1995) pointed out the potential use of fuzzy logic as an alternative to probability-based techniques. In a subsequent paper (Byrne, 1997), he carried out a critical assessment of the fuzzy methodology as a potentially useful tool in discounted cash flow modeling. However, his work was mainly to investigate the fuzzy approach as a potential substitute for probabilistic simulation models. However, some researchers claim that probability may be viewed as a subset of the fuzzy set theory (e.g. Zadeh, 1995). In this sense, FST should not treated as a replacement of the probability theory. Rather, it should be viewed as the source of additional tools that can enlarge the domain of problems that can be effectively solved (Kishk and Al-Hajj, 2000b).

Kaufmann and Gupta (1988) described how to manipulate fuzzy numbers in the discounting problem. They introduced an approximate method to simplify the mathematical calculations with fuzzy numbers. In this method, a function $f(A)$, where A is a triangular fuzzy number (TFN), can be approximated in general by another TFN. Sobanjo (1999) employed this simplified method to introduce a methodology for handling the subjective uncertainty in life cycle costing analyses. The model has the apparent advantage of being simple. However, it has the following limitations. First, the interest rate, rehabilitation times, and the analysis period were assumed to be certain. Moreover, only TFNs were considered in representing decision variables. However, an expert should give his own estimates together with a choice of the most appropriate membership function for every state variable.

Kishk and Al-Hajj (2000a, 2000b) developed a powerful algorithm based on the fuzzy set theory (FST) and interval analysis (Fig. 4.6). This algorithm is superior to that presented by

Sobanjo (1999) due to its ability to deal with judgmental assessments of all state variables. In addition, it can manipulate various shapes of fuzzy quantities. The algorithm employs an exceptionally derived WLC mathematical model (equations 2.13-2.15). A similar algorithm to deal with alternatives with different lives was proposed in Kishk and Al-Hajj (2000d).

Figure (4.3) illustrates how to choose between two competing alternatives in the fuzzy approach. The net present values of two alternatives are shown in the figure. In areas A_2, alternative A is better than B, whereas B is better than A in areas A_3. Kishk and Al-Hajj (2000c) outlined the following two confidence measures

$$CI_1 = \frac{A_2}{2A_1 + A_2 + A_3} \tag{4.1}$$

$$CI_1 = \frac{A_1 + A_2}{2A_1 + A_2 + A_3} \tag{4.2}$$

The factors CI_1 and CI_2 may be interpreted as measures of the confidence in the two statements: ‘A is better than B’ and ‘A is at least as good as B’, respectively.

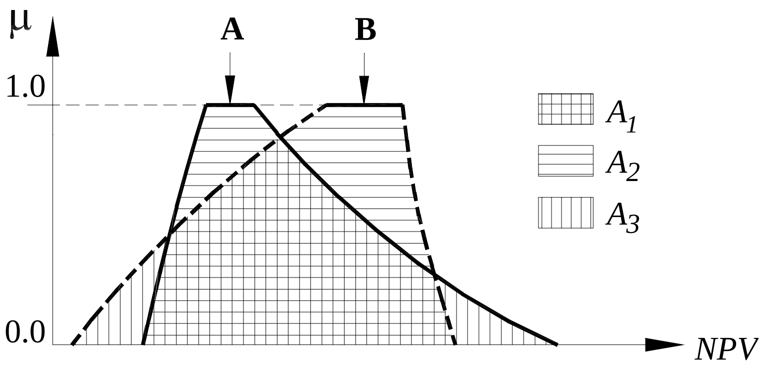


Figure (4.3): Choice between alternatives in the fuzzy approach (Kishk and Al-Hajj, 2000c).

The FST have been also employed by several researchers to deal with discounted cash flow (DCF) analysis. Examples include Buckley (1987), Ward (1985, 1989), Chiu and Park (1994), Wang and Liang (1985), Lai and Ching-Lai (1993), Liang and Song (1994), Perrone (1994), Chen (1995), Kahraman and Tolga (1995), Sobanjo (1999), Kuchta (2000), Kahraman et al. (2000), Mohamed and McCowan (2001), among others. However, almost all these methodologies focus on DCF as a budgeting tool rather than a decision making tool. Besides, they have many drawbacks that limit their effective implementation (Kishk, 2001).

4.5 The Integrated Approach

Kishk and al-Hajj (1999) and Kishk (2001) proposed an integrated framework to handle uncertainty in WLC. It is based on the simple idea that a complex problem may be deconstructed into simpler tasks. Then, the appropriate tools are assigned a subset of tasks that match their capabilities as shown in figure (4.4). Data is evaluated in terms of availability, tangibility and certainty. The levels of these measures increase, and hence the problem complexity decreases, from left to right. In situations where all data can be known with certainty, the problem is deterministic and can be modelled as such (Curwin and Slater, 1996). Thus, closed form solutions can provide the basis for decision making. If outcomes are subject to uncertainty, however, alternative modelling techniques are required. According to the type of uncertainty, either the probability theory or the fuzzy set theory can be used. This way, the manner in which parameter uncertainty is described in the model can be more consistent with the basic nature of the information at hand. The lower part of Fig. (4.4) reflects the need to integrate all forms of solutions attained through various theories before a decision can be made. Certain data, i.e. represented by ordinary real numbers, may be seen as special cases of FNs or PDFs, and consequently can be easily integrated with either random or non-random data as represented by FNs or PDFs, respectively.

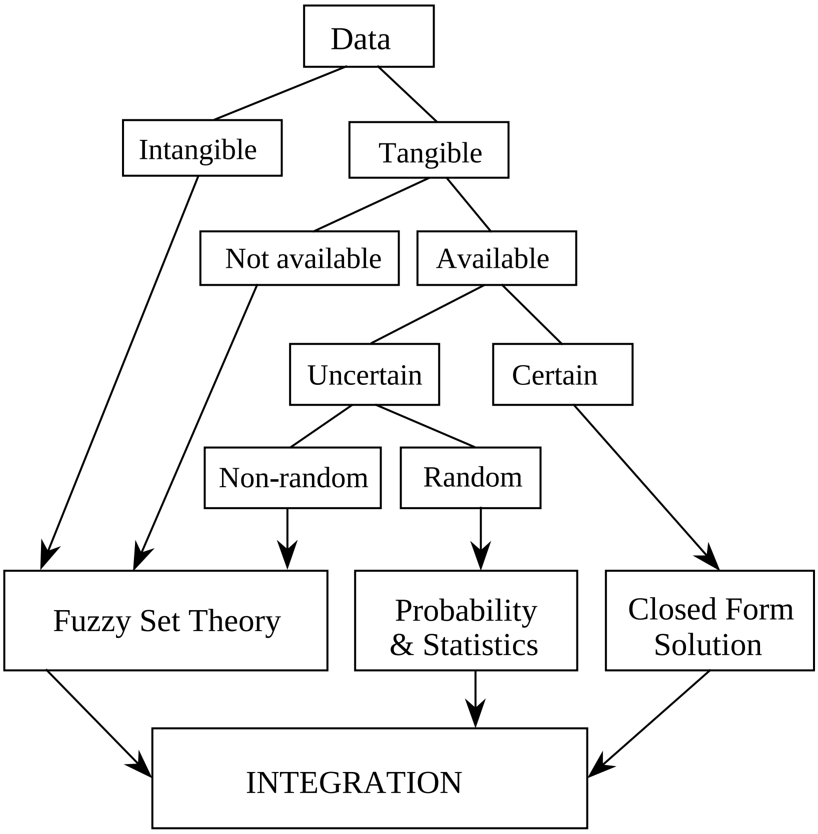


Figure (4.4): The integrated WLC framework (Kishk, 2001).

More recently, Kishk and Al-Hajj (2001a, 2001c) have developed an algorithm to combine stochastic and subjective data as represented by probability density functions (PDFs) and fuzzy numbers (FNs), respectively, within the same model calculation. This algorithm is motivated by the fact that historic data may exist for some uncertain input parameters; and consequently, meaningful statistics can be derived for these parameters. In such cases, one might consider it more realistic to assign PDFs to these parameters. All PDFs are then properly transformed to equivalent FNs using a sound transformation technique (Kishk and Al-Hajj, 2001a). Thus, the fuzzy approach discussed in the previous section can be used.

4.6 SUMMARY

The commonly used approaches to uncertainty and risk assessment in WLC modelling were critically reviewed. These are: the sensitivity analysis, probabilistic and fuzzy techniques. Although the sensitivity analysis approach is simple, it is effective only when the uncertainty in one input-data element is predominant. Furthermore, it does not provide a definitive method of making the decision. The confidence index method is a simplified probabilistic method that has been found to lack the generality of application. Simulation techniques are more powerful but they have been criticised for their complexity and expense in terms of the time and expertise required. Besides, probability theory can deal only with random uncertainty.

Two fuzzy approaches were critically reviewed. The fuzzy algorithms designed by Kishk and al-Hajj (2000a, 2000b, 2000c, 2000d) are superior to that presented by Sobanjo (1999) due to their ability to deal with judgmental assessments of all state variables. In addition, these algorithms can manipulate various shapes of fuzzy quantities. Finally, a recent integrated approach proposed by Kishk and Al-Hajj (2001a, 2001c) is outlined. This approach can handle both statistically significant data and expert assessments as represented by probability density functions (PDFs) and fuzzy numbers (FNs), respectively, within the same WLC model calculation. This way, the manner in which parameter uncertainty is described in the model can be more consistent with the basic nature of the information at hand.

CHAPTER 5

IMPLEMENTATION OF WLC

5.1 INTRODUCTION

In this chapter, the implementation of WLC in a typical project is discussed in more detail. The next two sections are devoted to discuss the main activities of WLC in a typical project. Then, the level of WLC implementation in a typical project is discussed with emphasis on its implications regarding data collection, recording and feedback. Special emphasis is given to the required features of the cost break-down structure (CBS). The chapter concludes with an overview of the whole life costing software in use within the construction as well as other industries.

5.2 STAGES OF IMPLEMENTATION

Although opinions differ as to the sequence in which various WLC activities should be implemented, three stages of the application of WLC can be identified (Flanagan and Norman, 1983; Seeley, 1996). The first activity is called whole life cost analysis (WLCA) and includes collecting and analysing historic data on the actual costs of occupying comparable buildings. The primary objective is to relate running costs and performance data and provide feedback to the design team about the running costs of occupied buildings. The second activity, known as whole life costing management (WLCM), is derived from WLCA. It identifies those areas in which the costs of using the building as detailed by WLCA can be reduced. The primary objective is to assess and control costs throughout the whole life of the building to obtain the greatest value for the client. The third activity, known as whole life costing planning (WLCP), can be considered as part of WLCM. It constitutes the prediction of total costs of building, part of a building, or an individual building element. It also includes planning the timing of work and expenditure on the building, taking into account the effects of performance and quality (Seeley, 1996).

Flanagan and Norman (1983) devised a method of grouping WLC activities into a hierarchical structure as illustrated in Fig. (5.1). The main point is that as the design develops, the initial WLC plan based on level 1 will be replaced by a detailed plan at level 3. As shown in the figure, this structure fits into the RIBA plan of work with the conventional cost planning sequence on the left-hand side of the figure.

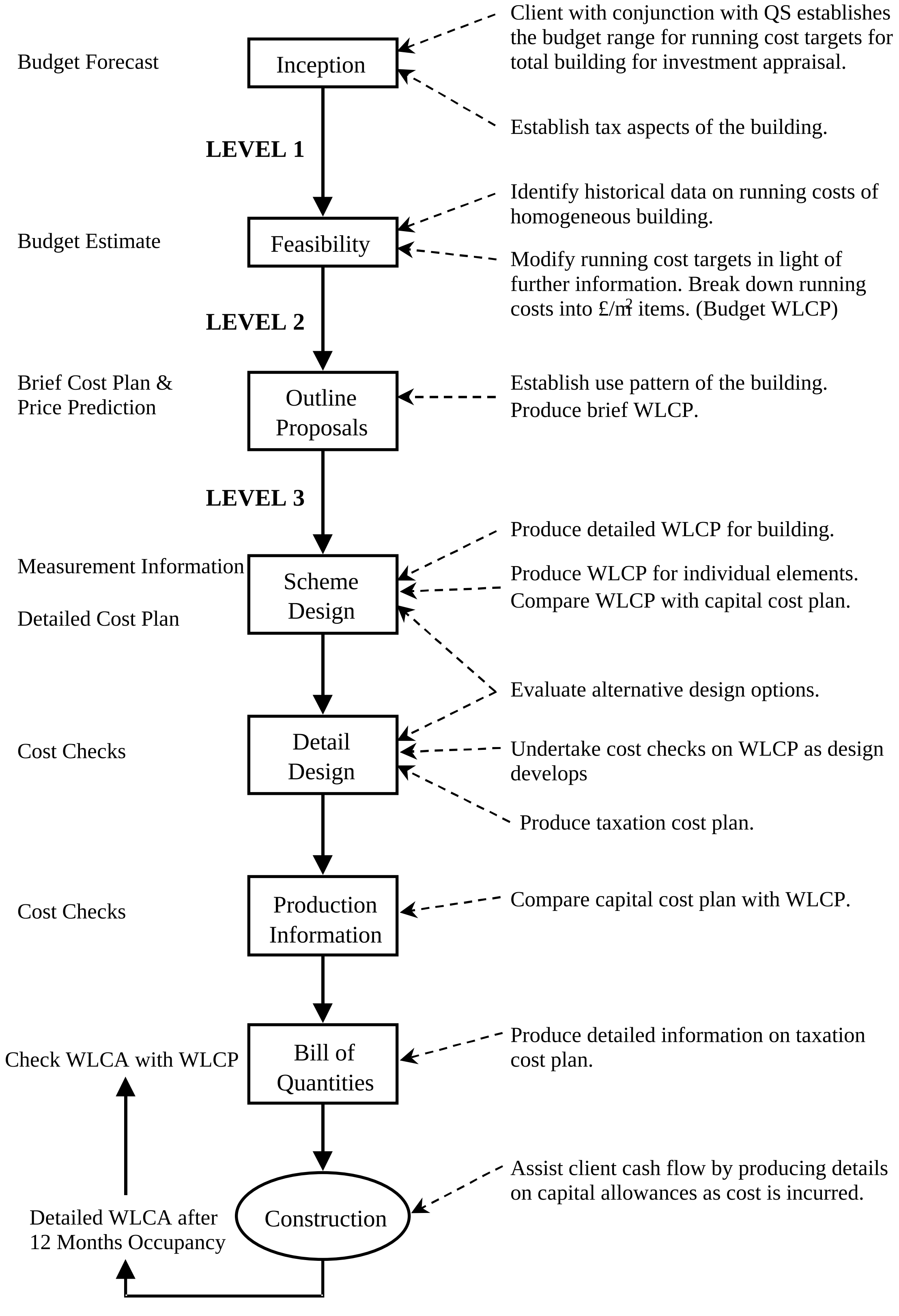


Fig. (5.1): WLC and the RIBA plan of work (Flanagan and Norman, 1983).

The main point is that as the design develops, the initial or budget WLC plan based on level one will be replaced by a detailed plan at level three. As shown in the figure, this structure fits into the RIBA plan of work with the conventional cost planning sequence on the left hand side of the figure. It should be noted, however, that WLC can be used at any time in the design process (Flanagan and Norman, 1983).

Kirk and Dell'Isola (1995) stressed that owners must take the responsibility for setting realistic goals in planning and budgeting phases and giving assistance as necessary to design professionals. In this way, WLC does not become just another paperwork exercise.

5.3 LOGIC OF IMPLEMENTATION

In the last two decades, the search for a practical WLC implementation approach has been the concern of many groups of practitioners and researchers. Two of these implementation methodologies are briefly outlined in the following paragraphs. Figure (5.2) shows schematically a seven-step implementation model described in Ferry and Flanagan (1991). As shown, the implementation steps flow sequentially in a logical order. This model is typical of various sequential methodologies available in the literature.

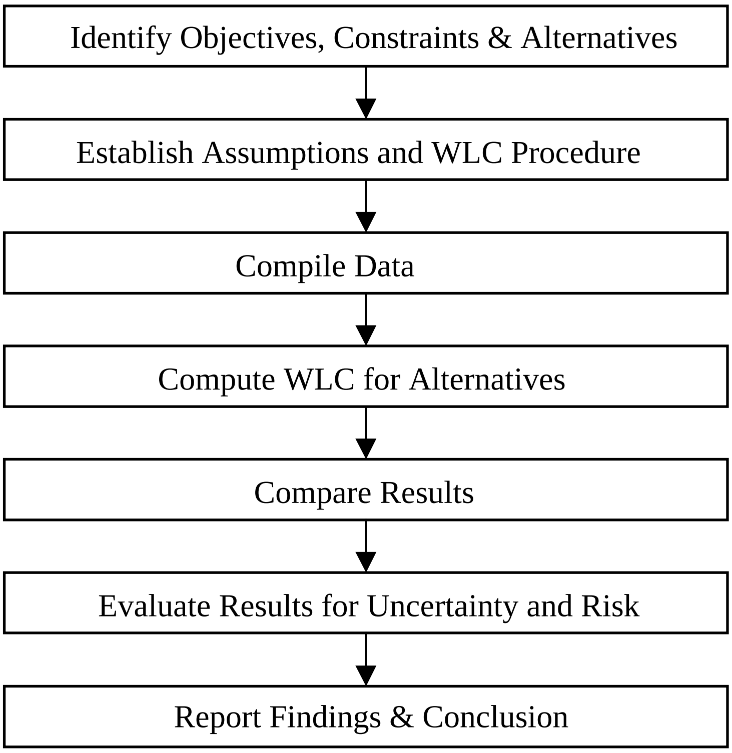


Fig. (5.2): The Seven-Step implementation model of Ferry and Flanagan (1991).

Figure (5.3) shows another WLC logic flow recommended by Kirk and Dell'Isola (1995). The first requirement is the input data with which alternative would be generated. Then, various WLC components are predicted. These predictions would be tempered by non-economic comparisons before the final selection is made. This is sometimes necessary because in many cases these intangibles have a decisive role to play. For example, the decision to replace a window would require analysis of energy efficiency, maintenance requirements, aesthetics as well as elemental juxtaposition before optimum choice can be determined (Piper, 1996).

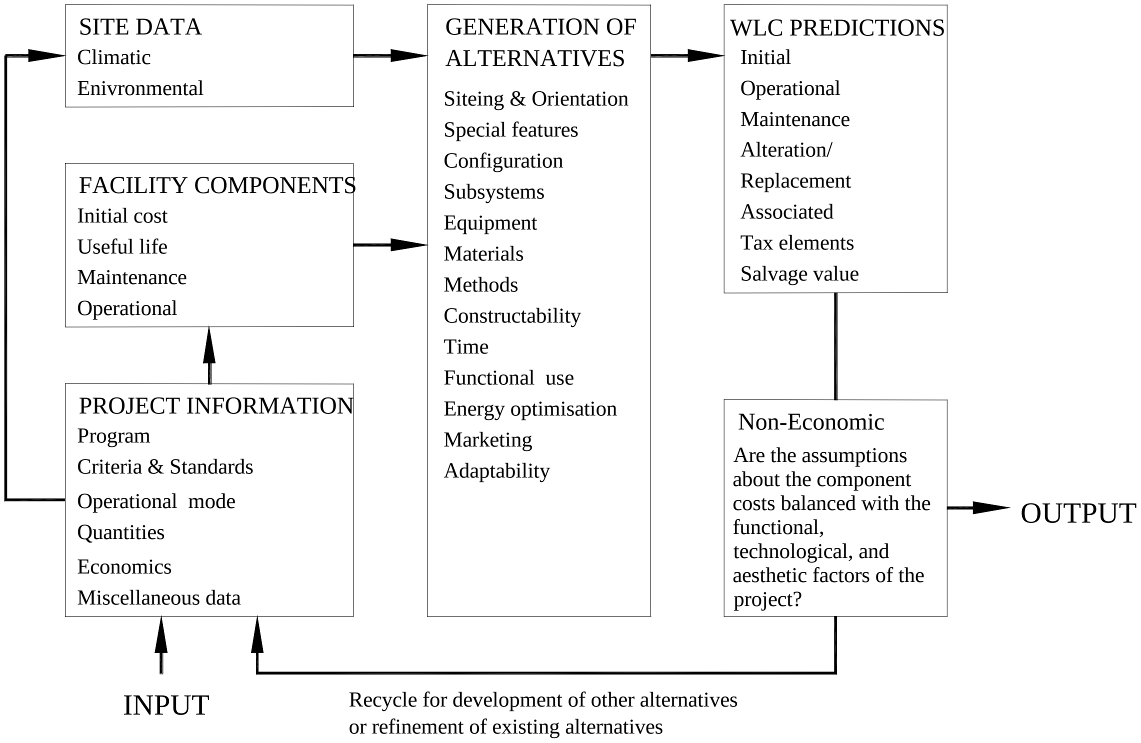


Fig. (5.3): WLC implementation logic (Kirk and Dell'Isola, 1995).

As shown, input data requirements are classified into three main categories: the specific project information, site data and facility components data. The first two categories are usually easily accessible. However, there is no readily available a storage and retrieval format containing facility components data. Another unique feature of this model is that it adopts a feedback procedure for the implementation of WLC. A recycle is usually needed for development of other alternatives or refinement of existing alternatives. Furthermore, this procedure is in line with the basic nature of design as an iterative process towards the achievement of the goal of cost optimisation.

5.4 The Cost Break Down Structure

In WLC implementation, two costing methods can be identified: systems' costing; and detailed costing (Kirk and Dell'Isola, 1995). System costs allocates funds to the various functional elements of a facility and allows the designer to make early cost comparisons among alternatives. In the detailed costing approach, it is necessary to breakdown the facility into its constituent elements whose costs can be distinctly defined and estimated. This cost break down structure (CBS) may be seen as another way of classifying costs, with the classification being WLC oriented. It links objectives and activities with resources and constitutes a logical subdivision of cost by functional activity, area, major element of a system, and/or more discrete classes of common items (Fabrycky and Blanchard, 1991).

5.4.1 Basic Characteristics of a CBS

The complexity of a CBS and the identification of cost elements and their corresponding scope depend on the scope and objectives of the WLC exercise. However, any CBS should exhibit the following desirable characteristics (Fabrycky and Blanchard, 1991; HMSO, 1992)

- All cost categories should be considered and identified in the CBS.
- Each cost element included in the CBS should be clearly defined so that all parties involved have a clear understanding of what is included in a given cost category and what is not.
- Costs must be broken down to the level necessary to provide visibility required in the decision-making process. Besides, cost-significant areas should be easily identifiable.
- The CBS should be designed in a way that different levels of data could be inserted within various categories. Besides, each cost element should be identifiable with a significant level of activity/work.
- The CBS should be coded to allow an analysis of specific areas of interest while virtually ignoring other areas.
- Costs that are reported through various information systems must be compatible and consistent with those comparable cost factors in the CBS.

5.4.2 Examples of CBSs

Table (5.1) show an example of the cost breakdown structure given in The Surveyors' Construction Handbook (RICS, 1999). In this CBS example, the cost categories identified are obviously too broad to be useful at all design stages. Fabrycky and Blanchard (1991) criticised this sort of CBSs also in that they do not ensure accountability and control

In addition, the cost analyst cannot readily determine what is and what is not included, nor can he or she validate that the proper relationships or parameters have been utilised in determining that are inputted into such a structure. Furthermore, this CBS lacks many of the desirable characteristics mentioned in the previous section.

Table (5.1): Major project break down structure (RICS, 1999).

A. Capital / Initial Costs: • General - Land - Fees on acquisition - Construction cost. - Taxes. • Financing Cost - Finance for land purchase and construction. - Loan charges. **B. Operation Cost:** • Energy. • Cleaning. • Insurance. • Security and Health. • Manpower. - Staff. - Management & administration of the building. • Land charges (Rates). • Equipment associated with occupier's occupation.	**C. Maintenance Costs** • Main structure. • External decorations. • Internal decorations. • Finishes, fixtures and fittings. • Plumbing and sanitary services. • Heat source. • Ventilation and air treatment system. • Electrical installations. • Gas installations. • Lift and conveyor system. • External works. **D. Occupancy Cost** • Client occupancy costs. **E. Residual Values** • Resale value • Demolition and site clearance. • Renovation /refurbishment cost.

One way to work out these limitations is to utilise the cost element concept outlined in the BS 5760 (BSI, 1997). This concept can be illustrated by a three-dimensional matrix as shown in Fig. (5.4). This matrix involves identification of the following aspects of a product/work:

- Breakdown of the product to lower indenture levels.
- The time in the life cycle when the work/activity is to be carried out.
- The cost categories of applicable resources such as labour, materials, fuel/energy, etc. (that is the cost categories).

This approach has the advantages of being systematic and orderly, thus giving a high level of confidence that all essential costs have been included.

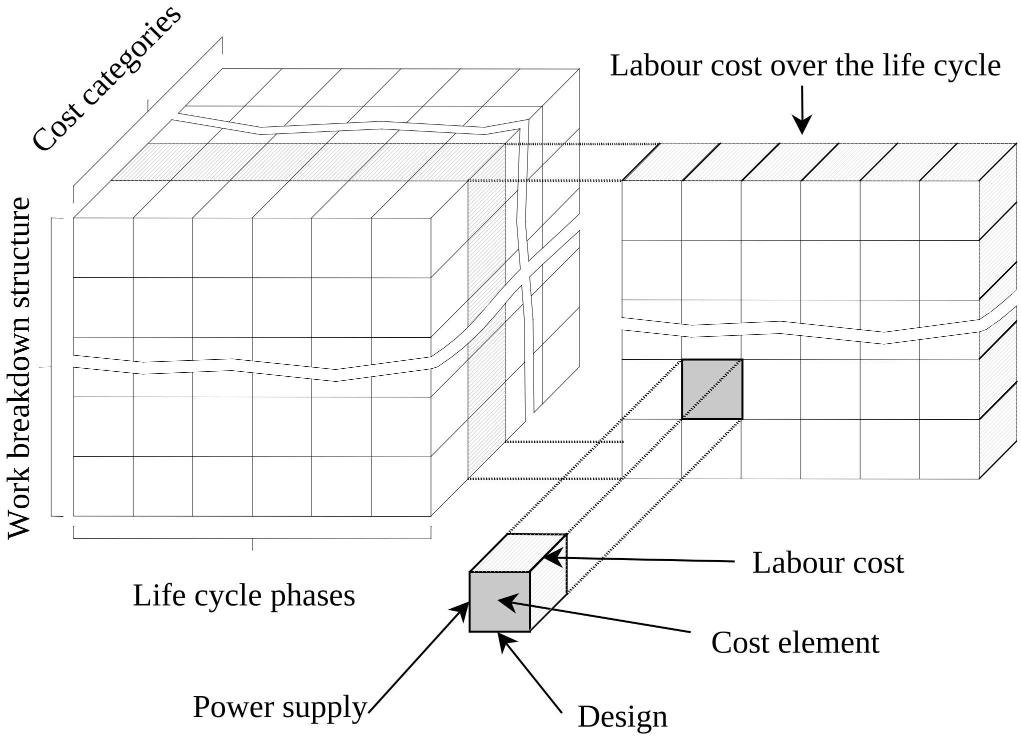


Figure (5.4): The cost element concept (BS 5760, 1997).

5.4.3 The CBS and the Management of Information

As discussed in Sections 5.2 and 5.3, the management of information within a WLC exercise includes the collection, analysis, recording of data and feedback of the WLC results. To support the WLC process, the costs information should be collected and recorded in a format consistent with the defined breakdown structure.

Costs associated with various elements may be further allocated between recurring and non-recurring costs, or expanded to a detailed year by year costs. In this way, the appropriate mathematical model can be employed to predict various contributions of the whole life cycle costs. Obviously, a database should be established and maintained to capture the results of these various WLC exercises, in order to serve as a source of experience feedback. In this way, the CBS may be considered as a standard framework within which costs can be tracked and related from project inception through construction and occupancy stages.

5.4.4 The CBS and the CAD Application

Within this project, the implementation medium will be an integrated environment with a CAD application (Autodesk® Architectural Desktop) to allow the user to create, manage and manipulate various components of the facility under consideration. Thus, it is essential to discuss other essential features of the CBS to be in line with CAD applications. In a typical

CAD application, a facility is defined as a collection of objects. These objects are usually the components, elements, systems or subsystems of the facility. In other words, these objects represent the work breakdown structure (WBS) of the facility. This suggests that an elemental format of the CBS is crucial for the implementation in the integrated environment. Furthermore, an elemental format relate well with the kind of decisions that are made at various design stages as noted by Kirk and Dell'Isola (1995). They described how previously in the USA, a 16 division Construction Specification Institute (CSI) format was common, using trade packages (which were heavily product and materials based). However relatively recently an elemental format called UNIFORMAT continues to gain popularity.

5.4.5 The CBS: Further Considerations

5.4.5.1 Standardisation

Because the CBS should be coded to allow an analysis of specific areas of interest and to facilitate the flow of information around various life cycle phases, a selection of a standard WBS seems inevitable. Whyte *et al.* (1999) studied this issue in some detail. They reviewed vrious attempts to standardisation through the Co-ordinated Project Information (CPI) and other initiatives. Some of these systems are summarised in the following. Table (5.2) shows a taste of the elemental code (Holmes *et al.*, 1985). Holmes pointed out that most elemental code is hierarchical with up to 6 digits at the most detailed level but only three digits at the recommended minimal level. They also suggest that that practice of Elemental coding has been around for several years, not least in the 1964 Report on the Costing of Management and Maintenance for Local Authority Housing.

Table (5.2): Elemental Codification (Holmes *et al.*, 1985).

1	External Painting				
2	Internal Painting				
3	Structure	34: roofs	344: roof gutters	3441: pitched roof	34411: valley gutter
4	Structural fixings and internal finishes				
5	plumbing (excl. heating)				
6	heating and other services				
7	external site works				
8	ancillary services				
9	other buildings etc.				

Table (5.3): BMI Property-Occupancy-Cost-Analysis Form (BMI, 1991).

- 0.0 Improvements and adaptations

- 1.0 Decoration
    - 1.1 External decoration
    - 1.2 Internal decoration

- 2.0 Fabric
    - 2.1 External walls
    - 2.2 Roofs
    - 2.3 Other structural items
    - 2.4 fittings and fixtures
    - 2.5 Internal finishes

- 3.0 Services
    - 3.1 Plumbing and internal drainage
    - 3.2 heating and ventilation
    - 3.3 lifts and escalators
    - 3.4 electrical power and lighting
    - 3.5 other M & E services

- 4.0 Cleaning
    - 4.1 windows
    - 4.2 external surfaces
    - 4.3 internal

- 5.0 Utilities
    - 5.1 gas
    - 5.2 electricity
    - 5.3 fuel oil
    - 5.4 solid fuel
    - 5.5 water rates
    - 5.6 effluent and drainage costs

- 6.0 Administrative costs
    - 6.1 services attendants
    - 6.2 laundry
    - 6.3 portage
    - 6.4 security
    - 6.5 rubbish disposal
    - 6.6 property management

- 7.0 Overheads
    - 7.1 property insurance
    - 7.2 rates

- 8.0 External works
    - 8.1 repairs & decoration
    - 8.2 external services
    - 8.3 cleaning
    - 8.4 gardening

Table (5.3) shows the standard form for Property-Occupancy-Cost-Analysis produced by the Building Maintenance Information service (BMI). The aim of this standard format is to allow standardisation of the system of collection and presentation of data. Expected elements for occupancy costs are detailed with elemental divisions standardised and referenced as shown in Table (5.3). The BMI defined an element for occupancy cost analysis purposes as:

> *'… expenditure on an item which fulfils a specific function irrespective of the use or form of the building.'*

The actual list of elements is, however, a compromise between this definition and what is considered practical. Cost elements are expressed as a 'cost per 100 m^2 per annum' to allow comparisons between the cost of achieving various defined functions, or maintaining defined elements, in one building with those in another.

The BMI publishes a price information book that seeks to establish realistic competitive rates for maintenance services work. The contents of this book (e.g. BMI, 1999) are based on the experience of the compilers, together with estimators specialising in the maintenance field and some on the results of work study carried out in maintenance departments The BMI coding of elements (with firstly *labour rates* in £/hr and then *measured work rates* in £/unit, following a similar pattern) that divides and subdivides work as shown in Table (5.4).

Table (5.4): BMI rate codes (BMI, 1999).

1. scaffolding; ..., ..., ...	7. plumbing; ..., ..., ...
2. demolition's and alterations; ..., ..., ...	8. electrical work; ..., ..., ...
3. excavation and concrete; ..., ..., ...	9. internal and external finishing; ...,
4. brickwork, underpinning & stonework; ...	10. glazing; ..., ..., ...
5. roofing; ..., ..., ...	11. painting and decorating; ..., ..., ...
6. woodwork; ..., ..., ...	12. external works and drainage; ..., ...,

According to Whyte *et al.* (1999), if a standardised breakdown of building elements is sought to improve the processes of whole life costing, BMI codifications appear to offer a logical choice. This conclusion seems reasonable in the sense that these publications are virtually the only regular sources of information on occupancy and maintenance data in the UK. However, it seems more reasonable to choose the well-known codification of the BCIS standard form of cost analysis (Table 5.5) because it is more element oriented. Besides, it is originally designed for initial costs and is combatable with existing systems such as OSCON (Aouad et al., 1997).

5.4.5.2 Elemental Interaction

As discussed above, a standard format for the WBS is important but is not enough. The collection, recording and feedback of information through the CBS should reflect interaction between various elements in the CBS as discussed in the window example in Sec. 5.3.

5.4.5.3 Cost Significance and Cost Indifference

Because WLC requires the compilation of large databases and that these are costly to compile, it seems useful to employ the concept of ‘cost significance’ proposed by Al-Hajj (1991). This concept has its roots in the famous '20:80' Pareto’s rule. It seeks to isolate the major variables that contribute significantly to costs over the life span of a building. For the principle to be employed for an elemental CBS, however, a new definition is needed Al-Hajj work was based on generic running costs of buildings.

Table (5.5): The BCIS Standard Form of Cost Analysis for Building Projects.

- 1- Substructure
- 2- Superstructure
  - 2A Frame
  - 2B Upper floors
  - 2C Roof
  - 2D Stairs
  - 2E External walls
  - 2F Windows and external doors
  - 2G Internal walls and partitions
  - 2H Internal doors

- 3 - Internal finishes
  - 3A Wall finishes
  - 3B Floor finishes
  - 3C Ceiling finishes

- 4 - Fittings and furnishings

- 5 - Services
  - 5A Sanitary appliances
  - 5B Services equipment
  - 5C Disposal installations
  - 5D Water installations
- 5- Services, continued
  - 5E Heat source
  - 5F Space heating and air treatment
  - 5G Ventilating system
  - 5H Electrical installations
  - 5I Gas installations
  - 5J Lift and conveyor installations
  - 5K Protective installations
  - 5L Communication installations
  - 5M Special installations
  - 5N Builder’s work in connection with services
  - 5O Builder’s profit and attendance on services

- 6 - External Works
  - 6A Site works
  - 6B Drainage
  - 6C External services
  - 6D Minor building works

- 7 - Preliminaries

- 8 - Contingencies

Another potential for reducing the size of the database is to exclude costs that are identical for all alternatives under consideration. In this way, only costs that will contribute to the final choice between competing alternatives are considered. An example of the usefulness of this principle is that the cleaning cost of a window can be excluded in the choice between ‘double-glazed’ and ‘single-glazed’ windows. It should be noted, however, that the utilisation of these principles depends on the scope and objectives of a particular WLC exercise. For example, when an analyst is interested in predicting the whole life cycle costs, it is necessary to include all cost elements of the facility under consideration.

5.4.5.4 Handling Various Data Sources

As discussed in chapter 3, the gathered data is expected to be from different sources and with different uncertainty types and levels. The CBS should be designed to accommodate the variability of data collection method(s), parameter definitions, statistics indicating variability in parameter values, references, reliability, geographical relevance, ... etc. In other words, the context of the data should be recorded.

5.5 WLC SOFTWARE

Whyte *et al.* (1999) reviewed in some detail several applications purporting to provide WLC support. They felt that opportunities to complement the decision making process of building design remain under-exploited. Besides, there appear to be gaps in areas that examine elemental links. Currently, there exist new user-friendlier versions of some of these software applications (Table 5.6). To identify the usefulness of these applications, they have been evaluated against four criteria: (1) availability; (2) WLC models employed; (3) risk analysis capabilities; and (4) scope of application.

Table (5.6): Existing WLC software.

Software	Vendor
ACEIT 5.x	Tecolote Research, Inc. http://www.aceit.com/
Ampsol	Ampsol Ltd. http://www.ampsol.com
AssetDesk 1.1	Richmond Systems. http://www.richmondsys.co.uk/
BLCC 5.1	National Institute of Standards and Technology (NIST), USA. http://www.eren.doe.gov/femp/resources.html
BridgeLCC 2.0	National Institute of Standards and Technology (NIST), USA. http://www.bfrl.nist.gov/bridgelcc/
CAMSLCC 2.2	CAMS Consulting Group. http://www.camsco.net
CASA	LOGSA. http://www.logsa.army.mil/alc/casa/
EDCAS 3.1	TFD Group. http://www.tfdg.com/
PipeCost	Armtec Ltd. http://www.big-o.com/constr/softw.htm
RelexLCC 7.3	Relex Software. http://www.relexsoftware.com/products/lcc.asp

Table (5.7) summarise the main characteristics of these applications in relation to the above criteria. As shown, these applications vary from free simple spreadsheet models to sophisticated, commercial stand-alone applications. Besides, three main categories can be identified. In the first category, e.g. Ampsol, the application is used only as a financial tool to calculate the whole life cost of a single alternative. Obviously, the usefulness of this category is limited. In the second category, including most of the applications, an application is mainly used as a decision-making tool to identify the ideal alternative from a number of competing alternatives. In general, an NPV model with a generic CBS is employed. Besides either the SA and/or MCS is used to risk assess the results. One limitation of almost all these applications is that the CBS is built manually by the user and is mostly non-elemental. In the third category, e.g. AssetDisk, the application is used as an asset management system. Typically, it is mainly a database manager that has the capability to record, modify, analyse and manage WLC data for an asset. All existing applications within this class are commercial, general-purpose systems that would require extensive training of users. Thus, there is still a need to develop a WLCM application for building components.

Table (5.7): Characteristics of existing WLC software.

Software	Availability	Models	Risk	Scope of Application
ACEIT 5.x	• Commercial. • Windows.	NPV.	MCS	• Integrated suite of analysis tools. • WLC decision-making. • Generic CBS.
Ampsol	• Free. • Web based.	NPV	None	• Basic WLC calculations only. • Generic CBS.
AssetDesk 1.1	• Commercial. • Windows.	None	None	• WLC management. • Activity-based CBS.
BLCC 5.1	• Free. • Platform-independent	NPV NS SIR IRR DPP	SA	• WLC decision-making. • Generic CBS. Single energy & water cost items and unlimited items for other categories.
BridgeLCC 2.0	• Free. • Windows.	NPV	SA MCS	• WLC decision-making. • Specific CBS suitable only to analyse bridges.
CAMSLCC 2.2	• Free. • Spreedsheet.	NPV	None	• WLC decision-making. • Generic CBS. Single cost item per cost category.
CASA	• Free. • Windows.	NPV	SA	• WLC decision-making. • Generic CBS.
EDCAS 3.1	• Commercial. • Windows.	NPV	None	• WLC decision-making. • Generic activity-based CBS.
PipeCost	• Free. • Windows.	NPV	SA	• WLC decision-making. • Generic CBS. Single cost item per cost category.
RelexLCC 7.3	• Commercial. • Windows.	NPV	SA	• WLC decision-making. • User-defined CBS. Unlimited cost items per category.

5.6 SUMMARY

This chapter was devoted to outline the main requirements of effective implementation of whole life costing. There are two approaches to implement the technique as a decision-making tool. In the first approach, the implementation is carried out sequentially. In the second approach, a logical order is also followed but a recycle procedure is adopted to generate new alternatives or refine existing alternatives if the decision is inconclusive. The latter approach is in line with design as an iterative process. On the other hand, WLC can be used as a management system to assess and control costs of various activities of occupied buildings, plan the timings of these activities and to provide feedback to the design stage of other projects

In WLC implementation, it is necessary to breakdown the facility into its constituent elements whose costs can be distinctly defined and estimated. Several cost breakdown structures are mentioned in the literature. Common characteristics of these CBSs have been reported. Besides, other key features of the CBS to be employed in the development of WLC applications for the design and management of construction assets have been identified.

Existing applications that provide whole life costing support have been also reviewed. In almost all these applications, an NPV model with a generic CBS is employed. Besides either the SA and/or MCS is used to risk assess the results. The main limitation existing applications is that the CBS is built manually by the user and is mostly non-elemental. Besides, various facets of uncertainty in WLC data are not effectively handled.

CHAPTER 6

CONCLUSIONS AND THE WAY FORWARD

6.1 CONCLUSIONS

A state-of-the-art review of whole life costing in the construction industry has been carried out to identify the strengths and gaps in existing knowledge in order to inform the development of an integrated WLC system being developed within an EPSRC funded research project. Issues covered included decision-making criteria, mathematical models, the nature and sources of various WLC data requirements, handling uncertainty and effective implementation of the technique. The main findings are summarised in the following.

- There are many difficulties in the implementation of WLC in the industry. Methods designed to tackle some of these difficulties exist but are, in general, disjointed.
- Six economic evaluation methods commonly used in whole life costing studies have been reviewed. The most suitable approaches for WLC in the framework of the construction industry are the net present value and the equivalent annual cost methods. The latter is the most appropriate method for comparing alternatives of different lives.
- Almost all published WLC models use the same basic equation but with a different cost breakdown structure. Two broad categories can be identified. The first category is based on the DCF technique and thus can only handle single future costs and annual costs. In the other category, non-annual recurring costs can be dealt with directly without the need to express each cost to a number of equivalent cash flows. Besides, the uncertainties of the frequencies of these costs can be effectively handled. Therefore, these models are more appropriate when WLC is used a decision-making tool.
- The financial status of the client and the particular circumstances of projects have the major impact on the selection of the discount rate. This process seems to be of a highly judgmental nature. Although there is a controversy on considering inflation in WLC, its effect can be included in the discount rate.
- Many definitions of the expected life of a building or a component are used. These definitions are based on various physical and obsolescence phenomena. The most important are the physical, economic and useful lives. The analysis period or the time frame over which costs are projected is mostly a result of obsolescence phenomena. Again, this is a highly judgmental factor because of the lack of data about the real life of building components. Even if this data exists, it is almost concerned with longevity and not with obsolescence.

- Cost data requirements include initial costs and future follow-on costs that might include maintenance, repair, alteration, replacement, operating costs and demolition costs. Other data categories including occupancy, performance and quality data, are also crucial.
- Sources of cost data including historical records, manufacturers’ and suppliers’ information and cost databases and price books have been also discussed. This discussion revealed the importance of high quality judgement in adjusting data from historical records and other sources to agree with particular projects.
- A number of WLC databases have been mentioned in the literature. These database are ‘constructed’ rather than ‘historical-based’ in that they are mostly based on ‘expert opinion’, trade publication data, and data in manufacturers’ literature. However, existing databases have two major limitations. First, a simple data normalisation procedure of cost per unit area of the building is usually employed. This ignores other crucial information such as hours of use, occupancy profile, building size, building height, building type, quality and performance requirements. Secondly, statistics and other measures indicating the type and level of uncertainty of various data elements are not recorded.
- The sensitivity analysis is effective only when the uncertainty in one input-data element is predominant and does not provide a definitive method of making the decision elsewhere. On the other hand, simulation methods have been criticised for their complexity and their expense. Other simplified probabilistic methods have been found to lack the generality of application. Another major flaw of probabilistic methods is that they follow the characteristics of random uncertainty. This implies that significant historic data should be available to produce a statistically meaningful analysis.
- WLC does not fit completely into the framework of probability and statistics theories. On the other hand, the FST is a source of many concepts and tools that can enlarge the domain of WLC-based decision-making problems that can be effectively solved.
- Two approaches for WLC implementation as a decision-making tool can be identified. In the first approach, the implementation is carried out sequentially. In the second approach, a logical order is also followed but a recycle procedure is adopted to generate new alternatives or refine existing alternatives if the decision is inconclusive.
- WLC is mainly used as a management system during the occupancy stage of buildings where three activities can be identified. The first activity is to relate running costs and performance data and provide feedback to the design stage of other projects. The second activity is to effectively assess and control costs. The third activity is to plan the timing

of work and expenditure on the building, taking into account the effects of performance and quality.

- To successfully implement WLC throughout the whole-life of buildings, it is crucial to employ an effective CBS. In addition to common desirable features, this CBS should be designed to accommodate the context information of WLC data and all the necessary measure that can reflect various facets of uncertainty of this data.
- Existing WLC applications have been criticised for their inability to effectively handle various facets of uncertainty in WLC data. Besides, the lack of a standard CBS suitable for constructions assets.

6.2 THE WAY FORWARD

The construction of a resource database to house crucial information of building components and systems would facilitate the implementation of WLC during the design stage. Obviously, various data categories reviewed in chapter 2 should be all considered. Because almost all these categories are of uncertain nature, the structure of the database should be designed such that it can accommodate all the necessary information to reflect this uncertainty. Obviously, a WLC Decision-making application should be developed to utilise the resource database to generate a set of design alternatives for a given building element and identifies the ideal option for that element by minimising its whole life costs.

A project specific database is also required to house data of the selected set of options for various elements. The project database will be utilised by another WLC management application to facilitate the management of the building during the occupancy stage. This application will allow four basic processes: (1) recording the actual performance and cost history of the building; (2) analysing this recorded data to predict future activities and their associated costs within the occupancy stage of the building (i.e. feed-forward of information) and to inform the design stage of other projects (i.e. feedback of information); (3) assessing and controlling costs whereby the main activity is to identify cost significant item; and (4) producing various work and expenditure planning profiles.

Detailed design of the structure of the resource and project databases, the WLC decision-making application and the WLC management application will be reported in a series of future papers.

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