Application of Life Cycle Costing Method to a Renovation Project

by

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ABSTRACT

In this study, we have examined the application of LCC analysis method to the construction and renovation stages of a building project. The application of the LCC analysis is currently limited to the very early stages of a project life, namely at the concept and design stages. We propose application of the LCC method, with several modifications, to the construction and renovation stages.

The simplified LCC method is proposed and examined in the first two case studies. The simplified method limits the range and complexity of data inputs, and is intended to be an LCC used by engineers practicing in the construction industry. In the third case study, the "LCC per square-foot", which implements the concept of the "square-foot" cost estimating, is proposed. This method is intended to be used to assess the residual value and to estimate running costs of an existing building. Necessary modifications of the LCC, as well as the accuracy and limits of these new methods are examined through three case studies.

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Makoto Mike TANEDA

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種田　　誠

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THESIS

The LCC analysis method can be used to make decisions in the construction and renovation stages of a building project.

INTRODUCTION

Everyone seems to agree that LCC (Life Cycle Costing) is a good idea. Using the LCC analysis method, one can estimate the total cost of a project including its running cost in addition to its initial capital cost. The concept became especially well known after the energy crisis in 1974. Many scholars write as if the LCC analysis is the industry standard for making every major decision in a building project.

I have been in practice as a construction engineer and consultant in a Japanese construction firm for 8 years (1987 to 1994), never using the LCC analysis. When I came to know more about the benefits of this method, a question arose: Why is the LCC analysis not conducted among construction engineers? This was the starting point of my study. The original intention was to understand and find a way to use this technique within my professional practice. However, as soon as it began, I faced many obstacles.

The first difficulty was my lack of understanding of many financial terms. These terms, which are not taught to engineers, make up the essential part of the LCC method. The next problem I encountered was the lack of a solidly established LCC method. Although various LCC studies agree in concepts, there are many inconsistencies in the procedure and formula. Probably the largest difficulty was the lack of available running-cost data. Even though there are so many cost guidebooks published annually, it is still extremely difficult to obtain desired data on running (maintenance and renovation) cost.

This study examines the possibility of applying the LCC method to the construction, renovation and maintenance stages of a building project. Proposed solutions to overcome these existing obstacles are presented as examples in the case studies.

1. ATTRIBUTES OF LIFE CYCLE COSTING

1.1 Life Cycle Costing

Known since the 1960s as "Costs-in-Use" or "Total Building Cost Appraisal" (Brandon, Spedding, ed.,1987), Life Cycle Costing (LCC) analysis is defined by Ruegg (1980) as:

> "A general method of economic evaluation which considers all relevant costs associated with an activity or project during its time horizon, comprising the techniques of total life-cycle cost, net savings, internal rate of return, and savings-to-investment or benefit/cost ratio analysis."

It will be necessary to briefly discuss the definition of LCC. In the course of this discussion, some of the reasons which limit the application of the LCC to the initial conceptual and design stages will be depicted.

1.1.1 Components of the LCC

Various scholars basically agree that LCC is the sum of the initial cost and the operational costs over the life span of a building. According to Magee (1988) LCC includes:

- Initial costs
- Iperating costs
  - — Indirect maintenance costs
  - — Direct maintenance costs
    - housekeeping
    - general maintenance
    - preventive maintenance
    - repair
    - replacement
    - improvement
    - modification
    - utilities

Researchers of LCC, like Dell'Isola and Flanagan, slightly widen the definition. Dell'Isola (1983) describes the LCC as "all significant costs of ownership," the categories include:

- Initial costs
- Financing costs
- Operation (energy) costs
- Maintenance costs
- Alteration/replacement costs
- Tax elements
- Associated costs
- Salvage value

Flanagan (1989) states that LCC is the "total cost of a project" which includes:

- Initial capital cost
- Running costs
  - — annual and intermittent maintenance
  - — cleaning
  - — energy
  - — security
  - — general and water rates

Clearly, it can be seen that there is no agreement among the scholars on the precise scope of LCC components. In this thesis, which examines new applications of LCC for the construction industry, the categories are confined to:

- Initial capital cost
- Running costs
  - — annual maintenance cost
  - — annual energy cost
  - — intermittent renovation cost

Definitions of the running costs will be further discussed in a later section (Section 3.1).

1.1.2 Percentage of LCC

The contribution of each of the above categories will vary significantly for each project and the length of the analysis. Shear (1983) emphasizes the importance of maintenance costs by a chart (reproduced here as Chart 1.1-1) which describes an LCC distribution for 50 years:

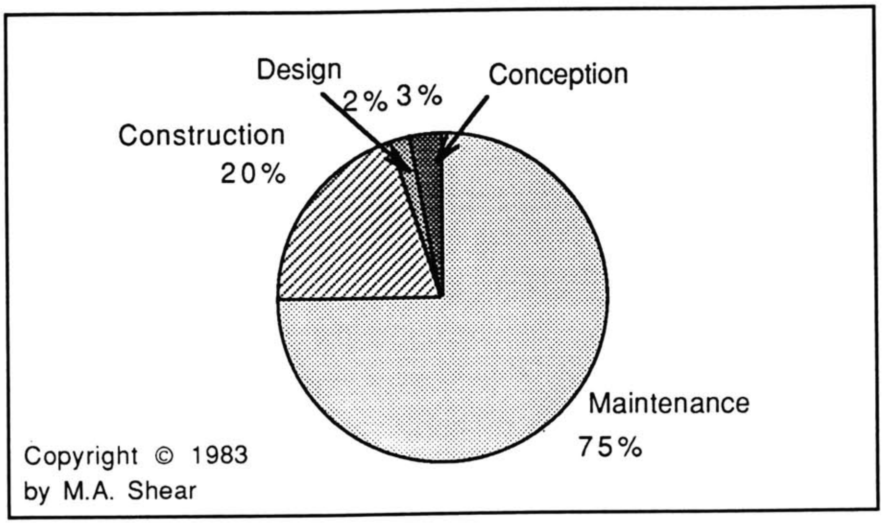


Chart 1.1-1: Percentage of Life Cycle Costs

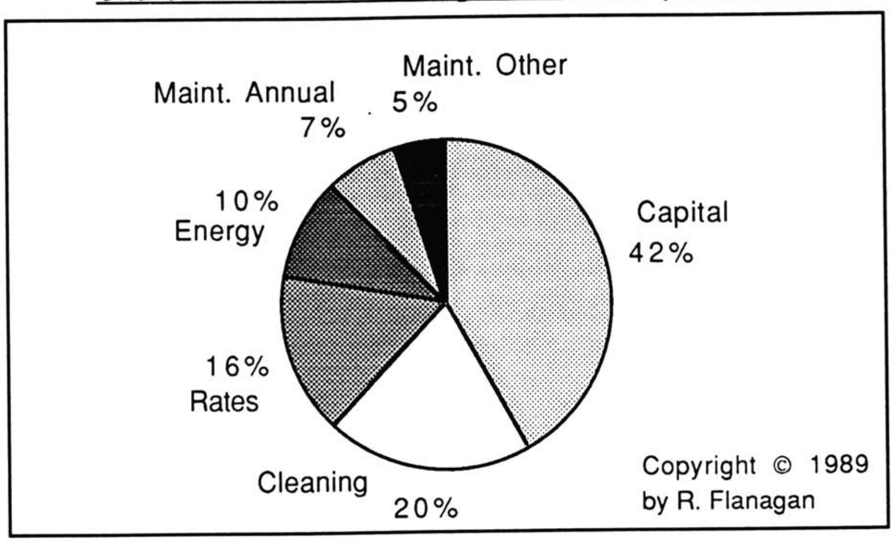


Chart 1.1-2: LCC of an Office building

Though not exactly in the same context, Flanagan (1989) shows a lower percentage for the maintenance costs. Chart 1-1-2 is a reproduction from several examples of a 40 year LCC calculation. The total cost here is the capital cost and the running cost, with running costs making up 58% of the total.

Although the ratios are different, both examples show that the running costs dominate the total costs. The scale of impact of the cost segments and other parameters on total costs will be studied later, using the results from the case study (Section 3.3).

1.1.3 Control over LCC

There is a very persistent notion among the scholars of LCC that effective control over the LCC can be done only in the early stages of a project. For example, Magee (1988) states that:

> "As soon as the life of the building or component begins, the control (or flexibility) of the total life cycle cost of the facility diminishes."

Dell'Isola (1975) states that the decision of the owner-using agency governs the total project expenditure. The scale of impact on total costs is described by a figure in his book (reproduced here as Figure 1.1-1).

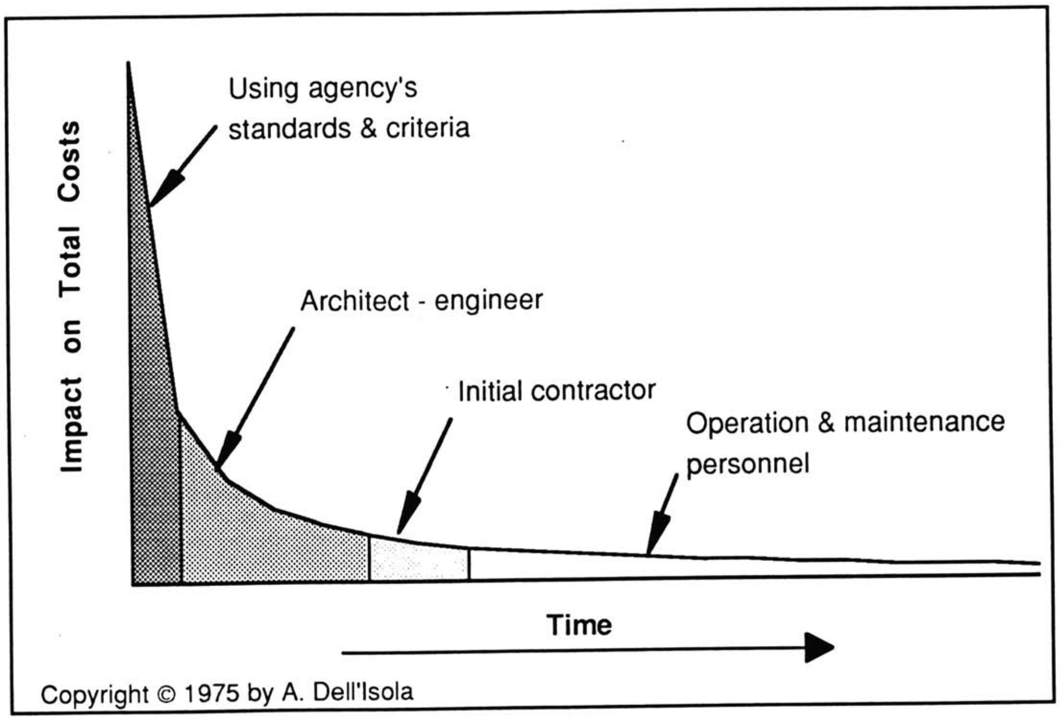


Figure 1.1-1: Major Decision Makers

Other scholars express similar notions on this point (Flanagan, 1983, Ruegg, 1980). Therefore, their books are often designer oriented. We agree that an LCC analysis at later stages of building project life will not be able to have a profound impact on the total project cost. Still, this study attempts to apply the LCC method to the "down-stream" stages: construction, renovation and maintenance. Our reasoning will be explained later (Sections 1.3).

1.2 On Finance

1.2.1 Time Value of Money

There are many financial terms that need to be understood to conduct the LCC analysis. As the Life Cycle Costing deals with various expenditures which occur at different points in time, the costs are all adjusted to their "Present Value" (PV) to maintain consistency. The process of adjustment becomes very complex when the analysis period extends over decades.

The basic principle is quite simple, being among the first topics learned in the study of finance. One hundred dollars today is worth more than $100 a year from today, because if it were invested for a year it would have generated an appropriate interest. Although we are dealing principally with costs and not with investments, the concept that the value of money changes over time is identical. The various documents on LCC, maintenance, real estate and finance utilize similar formulae to obtain the "Future Value" (FV) of a present amount (PV) invested for "n" years at an annual interest rate of "i":

$$FV = PV(1+i)^n \qquad (1)$$

where

$FV =$ Future Value

$PV =$ Present Value

$i =$ annual interest rate

$n =$ number of years

The present value can be obtained by manipulating formula (1) to the form:

$$PV = FV\frac{1}{(1+i)^n} \qquad (2)$$

1.2.2 Discount Rate

Unfortunately, the uniform accord among various documents seems to come to an end at this point. The definitions of "Discount Rate" or "Discounting Factor" differ in almost every source. In *'Real Estate Finance and Investment'* (Brueggemen, 1993), the discount factor is defined as being the ratio of the present value over the future value. The discount factor, "d", in this case, would be:

$$PV = FV\frac{1}{(1+i)^n}$$

$$d = \frac{PV}{FV}$$

$$d = \frac{1}{(1+i)^n} \qquad (3)$$

$d =$ discount factor

Flanagan (1989) simply treats the interest rate as the discount rate. The interest rate becomes the discount rate when trying to obtain the present value:

$$PV = \frac{FV}{(1+d)^n} \qquad (4)$$

where

FV = Future Cost in year n

d = Discount rate

n = number of years

In books on financial theory the terminology seems to be quite different. Hull (1993) refers to the discount rate as being "the annualized dollar return provided by an investment expressed as a percentage of the face value."

$$d = \frac{360}{n} \times \frac{(FV - PV)}{100} \qquad (5)$$

where

d = discount rate

FV = Future Face Value of investment

PV = Present cash price

n = number of days to maturity

In this paper, as the LCC analysis principally assesses costs and not investment (Ruegg, 1980), the concept of the discount rate is based on formula (4).

1.2.3 Net Discount Rate

As stated earlier, the LCC analysis primarily deals with costs. The discount rate is utilized merely as one of the calculation factors which is applied to each option uniformly. There is no concern for the risk component in this case. However, as the options might have different inflation rates, it will be necessary to separate the inflation component from the discount rate. Flanagan defines this risk-and-inflation-free discount rate as the "Net Discount Rate":

$$dn = \left[\frac{(1+i)}{(1+E)}\right] - 1 \qquad (6)$$

where

dn = net of inflation discount rate

i = interest rate including inflation

E = inflation rate

Therefore, the term "discount rate" in this paper means "net discount rate", according to formula (6).

If inflation is considered separately elsewhere, or is not considered at all, the net discount rate will be:

$$\begin{aligned} dn &= \left[\frac{(1+i)}{(1+E)}\right] - 1 \\ &= \left[\frac{(1+i)}{1}\right] - 1 \\ &= (1+i) - 1 \\ &= i \end{aligned}$$

Only in these special situations, the net discount rate will exactly equal the interest rate, or:

Net Discount Rate = Interest Rate

The present value, adjusted for the influence of the inflation component is called "Net Present Value" (NPV). And it is defined as:

$$NPV = \frac{FV}{(1+dn)^n} \qquad (7)$$

where

NPV = Net Present Value

FV = Future Cost in year n

dn = net discount rate

n = number of years

The most important point is to be consistent about the inflation and discount rates. (Ruegg, 1980) When costs include inflation, the net discount rate must be used. When costs do not include inflation, the discount rate must be used.

In this paper, the calculations of the present value are based on formula (7).

1.2.4 Present Value of Annual Cost

The advantage of formula (6) can be seen when dealing with annual costs. These costs will be influenced by the rate of inflation, as well as by the interest rate. The present value of cost "C" at year "t" can be expressed as:

$$C_t = C \times (1+E)^t$$

$$PV = \frac{C \times (1+E)^t}{(1+i)^t}$$

$$= C \times \left[\frac{(1+E)}{(1+i)}\right]^t$$

$$= C \times \left[\frac{1}{(1+dn)}\right]^t$$

thus

$$PV = \frac{C}{(1+dn)^t} \qquad (8)$$

here

C = Cost at year 0 (Present Estimate)

C_t = Cost at year t

i = interest rate

E = inflation rate

dn = Net discount rate

The simple formula (8) can be used to calculate the present value of costs with different inflation rates (i.e., labor and material). This formula (8) can further be incorporated with the formulae of Miles (1987) in order to obtain the total sum of the annual costs. "Present Value of the Cost Flow" (PVCF) will be:

$$PVCF = C \times \sum_{t=1}^{n} \frac{1}{(1+dn)^t}$$

$$= C \times \left[\frac{1}{(1+dn)} + \frac{1}{(1+dn)^2} + \ldots + \frac{1}{(1+dn)^{n-1}} + \frac{1}{(1+dn)^n}\right] \qquad (9)$$

here

$PVCF$ = Present Value of annual Cost Flow

n = number of years

In order to simplify the formula, both sides of the equation are multiplied by (1+dn) to produce:

$$(1+dn)\times PVCF$$

$$=C\times\left[\frac{1}{1}+\frac{1}{(1+dn)}+\frac{1}{(1+dn)^2}+\ldots+\frac{1}{(1+dn)^{n-1}}\right] \qquad (10)$$

The right hand sides of the equations (9) and (10) are identical except for the last item in (9) and the first item in (10). So, by subtracting equation (9) from (10), the whole formula is simplified to:

$$dn\times PVCF=C\times\left[1-\frac{1}{(1+dn)^n}\right] \qquad (11)$$

By dividing both sides of the equation (11) by the net discount rate "dn", a relatively simple formula is reached:

$$PVCF=C\times\frac{\left[1-\frac{1}{(1+dn)^n}\right]}{dn} \qquad (12)$$

In this paper, equation (12) is used to calculate the sum of the present value of annual costs.

1.2.5 Interest Rate

The interest rate in this paper is "compound interest rate" or compounded only once per annum. It will be appropriate to deal with flows of the costs which extend over a period of 15 to 75 years. The primary source of the interest rate is Table No. 820 from *'Statistical Abstract of the United States 1995'* (U.S. Department of Commerce, 1995). Past records of the effective rate of Federal funds are used to estimate the interest rate to be used within the calculation. Also it should be noted that the interest rate obtained this way is assumed to be a "risk-free" but "inflation-compounded" interest rate. The components of inflation are dealt with when converting the interest rate to the net discount rate.

"Internal rate of return" and "benefit/cost ratio" analyses will be explained and conducted in the first case study (Section 2.1).

1.3 Conclusions and Suggestions

1.3.1 Reasons for the Limited Application of LCC

The following are the possible reasons which obstruct a wider application of the LCC method.

1.3.1.1 Concepts

As mentioned in Section 1.1, there is a strong notion among scholars of LCC that analysis is most effectively conducted at the earliest stages of a project. Conceptual and design stages for new construction, which have the largest control over the building LCC, are defined as the only applicable segments.

1.3.1.2 Complexity

Proponents of LCC describe the method as simple. However, as can be seen from sections 1.1 and 1.2, it is far more complicated than ordinary estimating of initial capital costs. Many terms are unfamiliar to persons normally engaged in construction and maintenance. The operations involved in LCC are more complex than the ordinary multiplication and addition of construction cost estimates.

1.3.1.3 Data

The maintenance costs and the life expectancy of building components are difficult to assess compared to the initial construction costs which are easily obtainable from widely accepted estimation handbooks.

1.3.2 Objections and Solutions

1.3.2.1 Concepts

All stages in a building's life have some control over the costs which occur in the future. Also, unless the LCC design and concept are properly understood and executed by persons in later stages, a project's actual costs will differ from its expected life cycle performance. There seems to be no reason to limit the application of LCC to the conceptual and design stages.

It is suspected that the limited application originates from LCC's complexities. The execution of the complex LCC analysis requires high costs which needs to be justified from a large project expenditure saving. The early stages are the only time this large saving is possible. However, if a simplified and less costly LCC analysis is possible, downstream decisions may be better informed even where potential savings are reduced.

1.3.2.2 Complexity

The financial and LCC terms are eventually understandable. Their meanings and relations can be expressed mathematically, allowing engineers to understand them. Sections 1.1 and 1.2 represent examples of how to reason through various contradictory definitions. In our case, the single difficult point was the determination of the financial rates: interest, discount and inflation rates. Various studies about LCC do not describe thoroughly how to obtain the appropriate information to set these rates.

The complexity of calculations can be overcome easily with a personal computer and a spreadsheet program. Recent major spreadsheet programs have various useful functions that can help LCC calculations. (i.e., Lotus 123, Microsoft Excel)

1.3.2.3 Data

Collected LCC data will be a powerful tool to conduct the analysis and will save substantial research time. However, there are very few documents that actually collect LCC data (Dell'Isola, 1983 and NBA Construction Consultants, 1985). It is possible that the scarcity of LCC data originates from the limit of the LCC application. There are many differences, in accounting style and labor segments, as well as between the construction and maintenance industries. Unless given proper incentive to provide useful information, feedback from the maintenance industry will lack the necessary qualitative characteristics to support LCC (Ashworth, Spedding ed., 1987). Also, it is unrealistic to expect information feedback from people who do not correctly understand its purpose.

A short term solution, used in this thesis, is to substitute data from other sources for use in the LCC . Where possible, we have limited the data inputs to the ones easily available and widely accepted.

The long term solution would be to develop a better and wider understanding of the LCC concept across the construction and maintenance industries. The ideal results would be constant feedback of maintenance data, for example, in the form of the annual (or regular) publication of LCC data from major construction cost handbook publishers.

1.3.3 Scope of the Case Studies

This paper documents three case studies.

1.3.3.1 Examination of Simplified LCC

The first case study examines the accuracy of a simplified LCC. The primary purpose of the analysis is to provide an LCC comparison of choices for a building component. Basically, the analysis format follows Flanagan (1989) with the data inputs made as simple as possible. The scale of the data simplification is assessed by comparing the LCC and other analyses results.

1.3.3.2 Application of LCC to Construction

The second case study examines the application of the LCC method to the construction stage. The subjects of LCC analysis is a large building system. Using the findings from the first case study and from an appraisal of the running costs, a format for the simplified and reasonable LCC analysis is presented. Furthermore, a sensitivity analysis is conducted to assess the importance of various LCC parameters.

1.3.3.3 LCC as a Value Assessment Tool

The third case study proposes the use of the LCC method as a tool for evaluating the value of an existing building. A new format using the concept of "cost per square-foot" is presented.

2. EXAMINATION OF SIMPLIFIED LIFE CYCLE COSTING

2.1 Case Study No.1: Life Cycle Cost Analysis of Insulation Material

2.1.1 Scope of the Case Study

The scope of this study is to apply the Life Cycle Costing (LCC) analysis method on a small scale range. The LCC analysis is widely recognized to be potentially superior to the initial capital cost comparison. However, the method is usually used to compare choices for large-scale systems like HVAC. Complex handling of numbers and the laborious collection of necessary data are obstacles to its use on an everyday level.

This case study is intended to demonstrate that using the basic cost data normally available to the practicing engineer and with the help of a spread-sheet program on a personal computer, it is possible to conduct an accurate LCC analysis, even for a small decision point. To test its accuracy, comparisons with other common appraisal techniques are also conducted. An attempt to employ a more advanced LCC method forms the subject of the next study, using the feedback from this study.

2.1.2 Selection of the Analysis Subject

2.1.2.1 Selection

The LCC method is most appropriate when evaluating subjects which combine operating costs with capital investment. However, there is no common standard for estimating running costs within the building industry. The condition of use which has a direct impact on maintenance varies considerably among buildings and at different locations. Dell'Isola (1983) is one of the few authors who has attempted to present a standard for maintenance cost, but the number of entries in his handbook is very limited compared to the available capital cost data.

In this case, we have selected insulation materials as the subject of LCC analysis. To substitute the running cost, we use the annual energy cost saved by using each material, and compare them against a baseline case. The energy consumption of a building is calculated according to a standardized method, and is converted to an objective and justifiable cost flow.

2.1.2.2 Characteristics of Insulation

Basic Materials

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 1993), thermal insulations normally consist of the following basic materials:

- Inorganic, fibrous, or cellular materials such as glass, rock, or slag wool; calcium silicate, bonded perlite, vermiculite; and asbestos.
- Organic fibrous materials such as cotton, animal hair, wood, pulp, cane, or synthetic fibers, and organic cellular materials such as cork, foamed rubber, polystyrene, polyurethane, and other polymers.

Types and Classification in this Study

In this study, we divide the insulation materials into three groups according to their finished products, though basically following the division by ASHRAE. From each group, rigid and non-rigid products with thermal resistance value (R-value) around 10 are chosen, when possible, as the options for analysis.

Group I: Silicate Based Beads

Silicate based materials are usually produced in the shape of small beads. They are physically and chemically very stable, not affected by temperature below 1000°F, and they are virtually unchanging through time. This group includes:

- Perlite
- Vermiculite
- Insulating Concrete

Group II: Mineral Wool Batt and Board

These are glassy fibrous substances made by melting and fiberizing minerals. These are stable materials because of their inorganic nature, but fine fibers melt at a temperature above 200°F.

- Mineral Fiber Batt
- Fiber Glass Board and Batt

Group III: Cellular Insulation Board

Cellular insulations work by using the thermal resistance of air or other gas contained in the cells. Some are made of organic materials like paper or wood, but polymer plastic based products are common in the current construction industry. Those which use thermally high resistant gas instead of air may suffer slight performance degradation due to the diffusion of their cell contents.

- Expanded and Extruded polystyrene Board
- Polyurethane and Isocyanurate Board
- Urea-Formaldehyde and Urea-Based Foam

2.1.3 Methods of Analysis

2.1.3.1 Methods of Analysis

We have conducted three types of analysis, including the LCC.

Unit Cost Analysis

The initial costs of the options are compared with the same applied unit. This is the simplest cost comparison and is universally conducted.

Financial Analysis

Costs and savings of the options are compared using the financial appraisal techniques. "Benefit-cost ratio" and "Rate of return" are calculated.

- Benefit-cost ratio is, in our case, the ratio of savings to the initial investment.
- The rate of return is defined as "the discount rate that gives a net present value of zero." (Couper, 1986) It yields the rates to compare from which one can compare the speed of investment recovery.

LCC Analysis

The LCC method compares the sum of the initial investment and running costs over the estimated life of the subject. The costs, which occur at different points in time, are adjusted to the same standard of the Present Value (PV). The discount rate necessary to obtain the PV is defined by the inflation and the interest rates.

2.1.3.2 Common Data Input

Economic Data

Capital Cost and Inflation Rate

Capital costs are obtained from the cost data handbooks that are widely accepted within the construction and architecture industry. They are renewed annually to provide accuracy which also enables us to calculate the rate of change. The cost of each insulation material is from *'Means Building Construction Cost Data'* (1995). The estimated cost data for the year 1996 is used as the material cost (Table 2.1-1). The inflation rates are calculated from the last 6 years' costs (Table 2.1-2).

Abbreviations used within the tables include:

- 1 Carp: Requires 1 carpenter to install
- CF: Cubic Foot
- SF: Square Foot
- O&P: Overhead and Profit

Tables 2.1-1 and 2.1-2 are presented in the format of Means handbook. The summary of those material costs and inflation rates which suit our purpose comprise Table 2.1-3.

Table 2.1-1: Insulation Costs for Year 1996

		ITEMS	Crew	Daily out-put	Labor hrs	Unit	1996 Bare Cost Mat	Lab.	Eqp.	Total	Total incl. O&P
110	.0010	**POURED INSULATION**									
	.0020	Cellulose, R3.8/inch	1Carp	200	.040	CF	.41	1.01		1.42	2.06
	.0040	Perlite, R3.2/inch	,,	200	.040	,,	1.50	1.01		2.51	3.26
	.0080	Fiberglass wool, R4/in.	,,	200	.040	,,	.31	1.01		1.32	1.95
	.0100	Mineral wool, R3/inch	,,	200	.040	,,	.32	1.01		1.33	1.96
	.0300	Polystyrene, R4/inch	,,	200	.040	,,	1.72	1.01		2.73	3.50
	.0400	Vermiculite, R2.7/inch	,,	200	.040	,,	1.50	1.01		2.51	3.26
	.0700	Wood fiber, R3.85/inch	,,	200	.040	,,	.56	1.01		1.57	2.23
116	.0010	**WALL INSULATION, RIGID**									
	.0300	Fiberglass, 3#/CF, unfaced									
	.0370	1" thick, R4.3	1Carp	1000	.008	SF	.32	.20		.52	.67
	.0420	2-1/2" thick, R10.9	,,	800	.010	,,	.88	.25		1.13	1.37
	.1600	Isocyanurate, 4'*8' sheet, foil faced									
	.1610	1/2" thick, R3.9	1Carp	800	.010	SF	.27	.25		.52	.70
	.1650	1-1/2" thick, R10.8	,,	730	.011	,,	.67	.28		.95	1.18
	.1700	Perlite									
	.1710	1" thick, R2.77	1Carp	800	.010	SF	.31	.25		.56	.74
	.1900	Extruded polystyrene, 25 PSI compressive									
	.1920	1" thick, R5	1Carp	800	.010	SF	.31	.25		.56	.74
	.1940	2" thick, R10	,,	730	.011	,,	.57	.28		.85	1.07
	.2100	Expanded polystyrene									
	.2110	1" thick, R3.85	1Carp	800	.010	SF	.18	.25		.43	.60
	.2140	3" thick, R11.49	,,	730	.011	,,	.54	.28		.82	1.03
118	.0010	**WALL OR CEILING INSUL, NON-RIGID**									
	.0040	Fiberglass, kraft faced, batts or blankets									
	.0080	d=3.5", R11, w=15"	1Carp	1600	.005	SF	.20	.13		.33	.42
	.1300	Mineral fiber batts, kraft faced									
	.1320	3.5" thick, R13	1Carp	1600	.005	SF	.32	.13		.45	.55

Table 2.1-2: Inflation Rate Calculated from Means Data

		ITEM	R-value	Thickness	Inflation Rate				Total incl. O&P
					Mat	Labor	Equip	Total	
110	.0010	**POURED INSULATION**							
	.0020	Cellulose, R3.8/inch	3.8		-3.4%	2.7%		0.7%	1.8%
	.0040	Perlite, R3.2/inch	3.2		-4.5%	2.7%		-1.6%	-0.6%
	.0080	Fiberglass wool, R4/in.	4.0		-2.8%	2.7%		1.3%	2.3%
	.0100	Mineral wool, R3/inch	3.0		-20.9%	2.7%		-6.3%	-4.0%
	.0300	Polystyrene, R4/inch	4.0		0.4%	2.7%		1.2%	1.8%
	.0400	Vermiculite, R2.7/inch	2.7		-4.5%	2.7%		-1.8%	-0.8%
	.0700	Wood fiber, R3.85/inch	3.9		1.0%	2.7%		2.1%	2.8%
116	.0010	**WALL INSULATION, RIGID**							
	.0300	Fiberglass, 3#/CF, unfaced							
	.0370	1" thick, R4.3	4.3	1.0	-4.8%	2.4%		-2.4%	-1.4%
	.0420	2-1/2" thick, R10.9	10.9	2.5	-4.9%	2.7%		-3.4%	-2.8%
	.1600	sheet, foil faced, both sides							
	.1610	1/2" thick, R3.9	3.9	0.5	1.0%	2.3%		1.6%	1.9%
	.1650	1-1/2" thick, R10.8	10.8	1.5	-3.2%	2.7%		-1.6%	-0.9%
	.1700	Perlite							
	.1710	1" thick, R2.77	2.8	1.0	-6.3%	2.7%		-2.8%	-1.9%
	.1900	25 PSI compressive strength							
	.1920	1" thick, R5	5.0	1.0	-6.1%	2.7%		-2.7%	-1.7%
	.1940	2" thick, R10	10.0	2.0	-9.8%	2.9%		-6.6%	-5.4%
	.2100	Expanded polystyrene							
	.2110	1" thick, R3.85	3.9	1.0	0.1%	2.7%		1.6%	2.5%
	.2140	3" thick, R11.49	11.5	3.0	17.7%	3.8%		12.3%	10.7%
118	.0010	**WALL OR CEILING INSUL, NON-RIGID**							
	.0040	Fiberglass, kraft faced, batts or blankets							
	.0080	d=3.5", R11, w=15"	11.0	3.5	-5.8%	3.2%		-2.8%	-1.6%
	.1300	Mineral fiber batts, kraft faced							
	.1320	d=3.5", R13	13.0	3.5	1.9%	3.2%		2.3%	2.4%

Table 2.1-3: Cost and Inflation Rate

Group	Item	Configuration	Unit	Cost	Inflation
I	Perlite board	2" thick, R5.5	SF	1.48	-1.9%
II	Fiberglass board	2-1/2" thick, R10.9	SF	1.37	-2.8%
	Fiberglass batt	3-1/2" thick, R11	SF	0.42	-1.6%
	Mineral fiber batt	3-1/2" thick, R13	SF	0.55	2.4%
III	Isocyanurate	1-1/2" thick, R10.8	SF	1.18	-0.9%
	Extruded polystyrene	2" thick, R10	SF	1.07	-5.4%
	Expanded polystyrene	3" thick, R11.49	SF	1.03	10.7%

Running Cost

The insulation material itself does not require any maintenance. It is usually embedded within wall or roof system components, and replaced only when renovation of surrounding system necessitates it. In this paper we have used the energy saving as the annually recurring cost.

Interest Rate and CPI

The interest rate and the Consumer Price Index (CPI) figures are from the Statistical Abstract of the United States 1995. The interest rate for the calculation is set at 4.21%, from the effective rate of the Federal funds from 1994. CPI of Energy from 1985 to 1994 is used to estimate the inflation of the energy cost. These data are summarized in Table 2.1-4.

Table 2.1-4: Inflation Rate of Energy

Consumer Price Indexes (CPI-U):

Year	All items	Energy
1984	103.9	100.9
1985	107.6	101.6
1986	109.6	88.2
1987	113.6	88.6
1988	118.3	89.3
1989	124.0	94.3
1990	130.7	102.1
1991	136.2	102.5
1992	140.3	103.0
1993	144.5	104.2
1994	148.2	104.6
Inflation Rate	3.9%	1.1%

Energy Price

Average end-users' fuel prices of $0.60 per gallon of No. 2 fuel oil and 8.34 cents per kWh of electricity are used. (U.S. Department of Commerce, 1995)

Energy Data

ASHRAE Handbook of Fundamentals

In order to calculate annual energy consumption, an energy model was set up, based on an example from *'ASHRAE Handbook'*. The model building (Figure 2.1-1) is a single story detached house, located in Chicago, with medium grade wood construction.

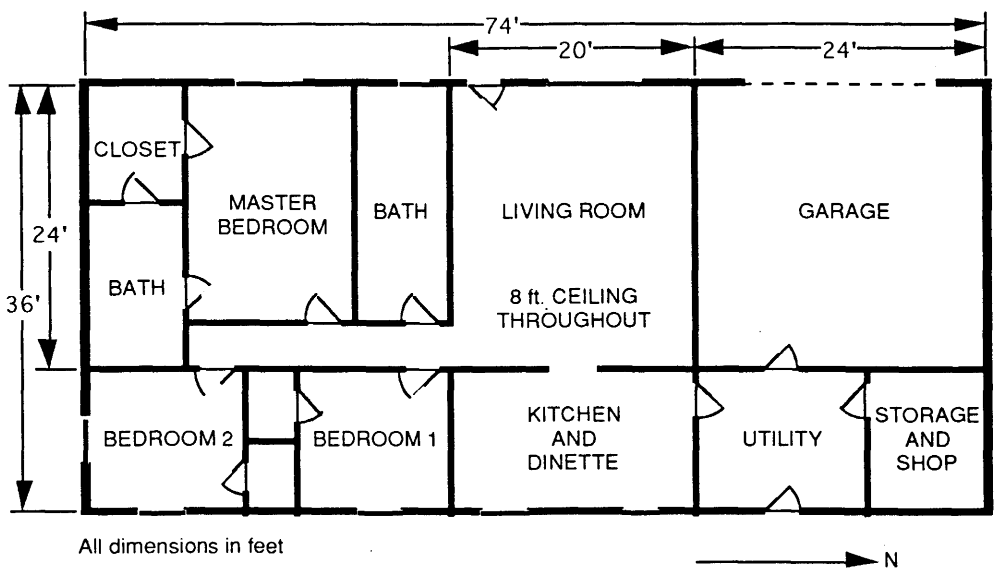


Figure 2.1-1: Plan of the Model

The worksheet of the energy cost calculation is supplied as the Appendix at the end of this chapter. The summary is given in Table 2.1-5.

Table 2.1-5: Annual Energy Requirement

Group	ITEMS	thick-ness (in)	Unit Cost ($/SF)	R-value	Annual Energy Cooling (kBtu)	Annual Energy Heating (kBtu)
Model	no insulation				33,299	163,368
	ASHRAE; wall R13, roof R19		.55/.72	13/19	20,578	106,632
I	Perlite	2.00	1.07	5.55	25,331	125,283
II	Fiberglass, 3#	2.50	1.37	10.90	22,374	112,746
	Fiberglass batts	3.50	0.42	11.00	22,339	112,585
	Mineral fiber batts	3.50	0.55	13.00	21,635	109,718
III	Isocyanurate	1.50	1.18	10.80	22,421	112,908
	Extruded polystyrene	2.00	1.07	10.00	22,744	114,279
	Expanded polystyrene	3.00	1.03	11.49	22,148	111,824

Energy Costs

Cooling costs are calculated assuming the use of a heat pump and an electric chiller. Using the efficiency factor, annual cooling energy requirement, Q_C, is converted to energy consumption, E_C. Cooling cost is obtained applying already specified fuel price.

$$E_C = Q_C \times 0.000293 / 2.5$$
$$C_C = E_C \times P(elec)$$

$$\begin{aligned} Q_C &= \text{Cooling energy requirement (kBtu)} \\ E_C &= \text{Cooling energy consumption (kWh)} \\ P(elec) &= \text{Price of electricity (\$ / kWh)} \\ &= 0.0834 \text{ (\$ / kWh)} \\ C_C &= \text{Cooling cost (\$)} \end{aligned}$$

Heating costs are calculated assuming the use of an oil fuel boiler. Once annual heating energy requirement, Q_h, is computed, corresponding energy consumption, E_h, is calculated from the system efficiency. Fuel consumption, F, and heating cost, C_h, are obtained applying consumption rate and price.

$$E_h = Q_h / 0.65$$
$$F = E_h / 144000$$
$$C_h = F \times P(oil)$$

Q_h = Heating energy requirement (kBtu)
E_h = Heating energy consumption (kBtu)
F = Fuel consumption (gallon)
$P(oil)$ = Price of oil (\$ / gallon)
= 0.60 (\$ / gallon)
C_h = Heating Cost (\$)

The initial and annual energy costs of each model are given in Table 2.1-6.

Table 2.1-6: Initial and Annual Energy Costs

Group	ITEMS	Costs	
		Initial ($)	Energy ($/yr)
Model	no insulation	0	1,373
	ASHRAE; wall R13, roof R19	2,175	885
I	Perlite	3,564	1,051
II	Fiberglass, 3#	4,563	941
	Fiberglass batts	1,399	940
	Mineral fiber batts	1,832	915
III	Isocyanurate	3,931	943
	Extruded polystyrene	3,564	955
	Expanded polystyrene	3,431	933

Degradation of Material

The thermal conductance, k, of expanded polystyrene degrades in the first 5 years from k=0.16 to 0.20. (Strother, 1990)

In attempting to take this degradation into account, the energy cost was calculated using each k-value. Assumption that the degradation continues at a constant rate will lead to an annual cost increase of 0.7%. However, another assumption with fixed k-value after reaching 0.20 will lead to an absolute cost increase of 3.7%. These are shown in Table 2.1-7.

Table 2.1-7: Energy Cost Change of Expanded Polystyrene

Year	thick. (in)	k-value	R-value	Annual Energy		Energy Cost ($)	Annual Change	Absolute Change
				Cooling	Heating			
0	2.00	0.16	12.50	21,794	110,379	921		
5	2.00	0.20	10.00	22,744	114,279	955	0.7%	3.7%

2.1.4 Analysis Results

2.1.4.1 Unit Cost Analysis

Insulation materials serve as the thermal barrier within the envelope of the building. In order to maximize the inner space of the building, thinner wall constructions are usually preferred. Therefore materials with larger R-values over small thickness are assumed to have better performance. To account for this fact, Means handbook supplies information about R-value (energy performance) and thickness along with the simple unit cost of insulation materials. Using these data, we compare the subjects by their thermal resistance per thickness, their costs of per thickness and per unit of thermal resistance.

- Thermal resistance per thickness (R-value/inch): It indicates the energy performance obtainable per unit thickness. The higher it is the better the value.
- Cost per thickness ($/inch): Simple cost index.
- Cost per thermal resistance ($/R-value): It indicates the cost that the users pay per unit of energy performance. The lower it is the better the value.

The result is given in Table 2.1-8 with data of the poured insulation materials (beads form) as Group X for comparison.

Table 2.1-8: Unit Cost of Insulation Materials

Group	ITEMS	Means Raw Data				Arranged Data		
		Unit	Cost	thick. in inch	R-value	R-value /inch	$/inch	$/ R-value
X	Cellulose fiber, R3.8/inch	CF	2.06	12.00	45.60	3.80	0.17	0.05
	Perlite, R3.2/inch	, ,	3.26	12.00	38.40	3.20	0.27	0.08
	Fiberglass wool, R4/inch	, ,	1.95	12.00	48.00	4.00	0.16	0.04
	Mineral wool, R3/inch	, ,	1.96	12.00	36.00	3.00	0.16	0.05
	Polystyrene, R4/inch	, ,	3.50	12.00	48.00	4.00	0.29	0.07
	Vermiculite, R2.7/inch	, ,	3.26	12.00	32.40	2.70	0.27	0.10
	Wood fiber, R3.85/inch	, ,	2.23	12.00	46.20	3.85	0.19	0.05
I	Perlite	SF	1.48	2.00	5.55	2.78	0.74	0.27
II	Fiberglass, 3#/CF, unfaced	, ,	1.37	2.50	10.90	4.36	0.55	0.13
	Fiberglass, kraft faced, batts	, ,	.42	3.50	11.00	3.14	0.12	0.04
	Mineral fiber batts, kraft faced	, ,	.55	3.50	13.00	3.71	0.16	0.04
III	Isocyanurate, 4'*8' sheet	, ,	1.18	1.50	10.80	7.20	0.79	0.11
	Extruded polystyrene	, ,	1.07	2.00	10.00	5.00	0.54	0.11
	Expanded polystyrene	, ,	1.03	3.00	11.49	3.83	0.34	0.09
	©	©	©	©	©			

R-value per thickness data are summarized in Chart 2.1-1. It can be seen that the rigid-board products (Group III and Fiberglass board) have the best energy performance relative to its thickness.

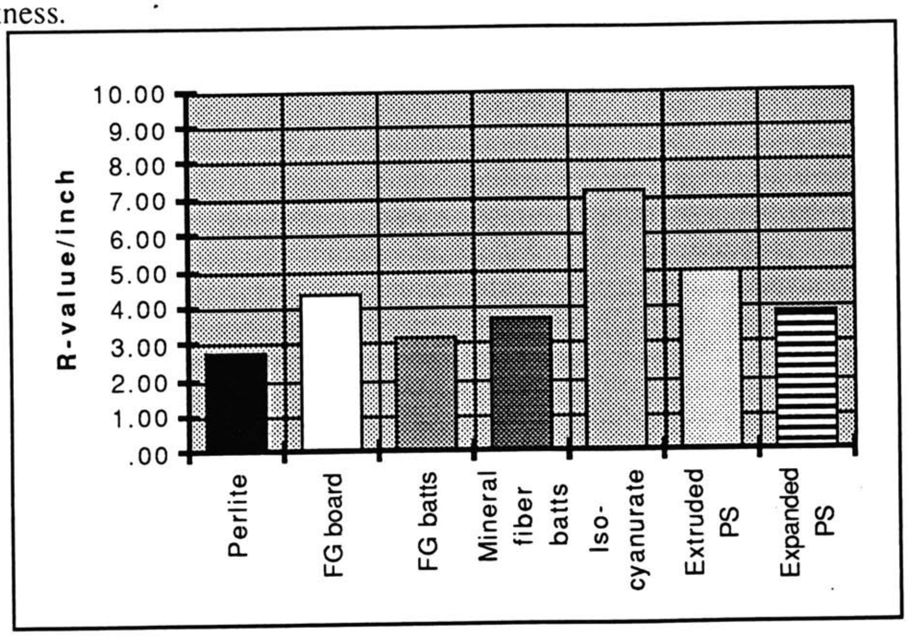


Chart 2.1-1: R-value per inch thickness

The cost per thickness is summarized in Chart 2.1-2. This time, the Batt products of Group II are the best options.

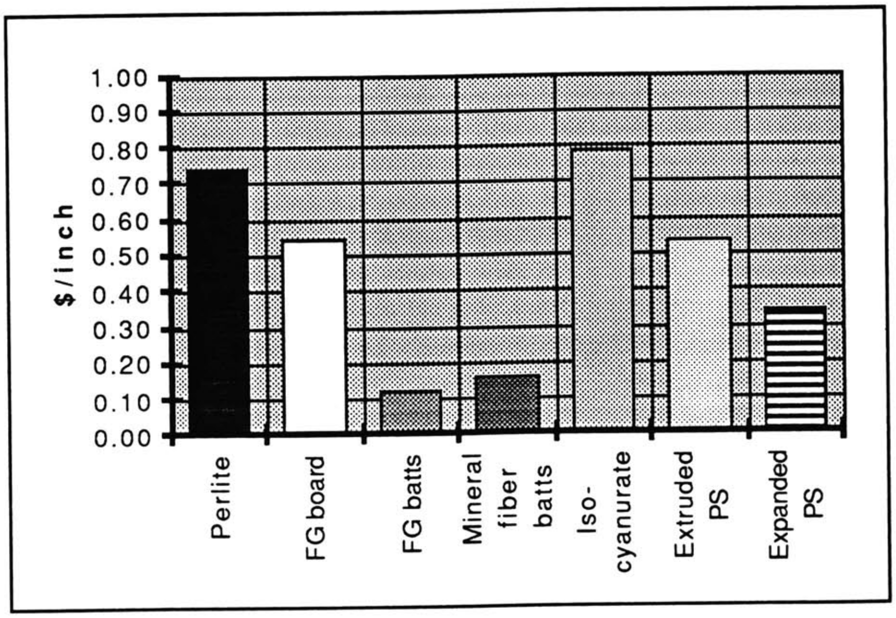


Chart 2.1-2: Cost per inch thickness

The cost per thermal resistance is summarized in Chart 2.1-3. The Batt products of Group II are the best options, followed by the rigid-boards. Perlite in Group I has the worst result.

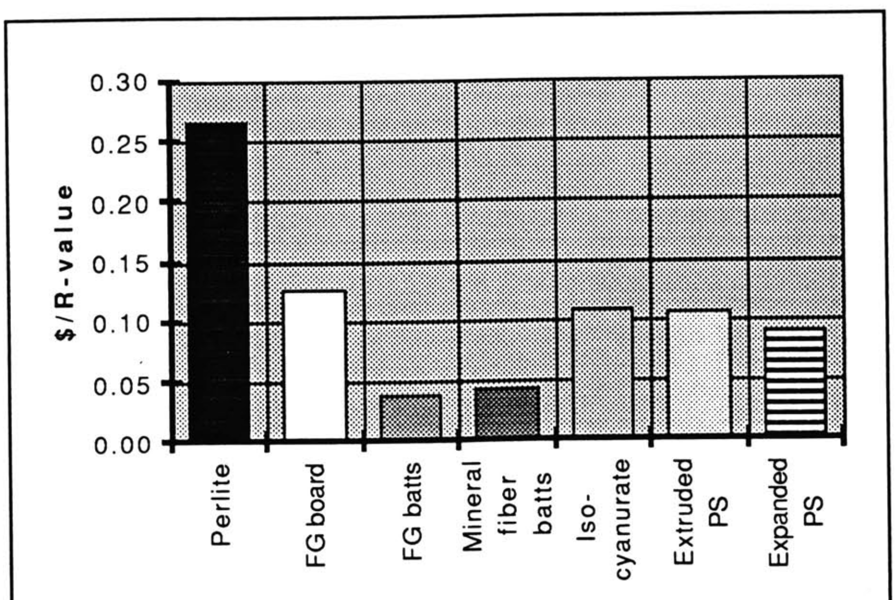


Chart 2.1-3: Cost per R-value

2.1.4.2 Financial Analysis

In this section, initial and annual savings are compared instead of costs. Saving is calculated by subtracting the cost of the baseline case from the corresponding costs of each option. The energy model with no insulation is used as the baseline case.

The initial and annual costs of the baseline case are $0 and $1,373 respectively. For example, an option using isocyanurate (Group III) has an initial cost of $3,931, so the saving in initial stage will be a negative number of $-3,931. The same option has the annual energy cost of $943 which makes the annual savings $430. Initial and annual savings for each material are given in Table 2.1-9.

Table 2.1-9: Initial and Annual Savings

Group	ITEMS	Savings	
		Initial ($)	Energy ($/yr)
Model	no insulation	0	0
	ASHRAE; wall R13, roof R19	-2,175	488
I	Perlite	-3,564	322
II	Fiberglass, 3#	-4,563	431
	Fiberglass batts	-1,399	433
	Mineral fiber batts	-1,832	458
III	Isocyanurate	-3,931	430
	Extruded polystyrene	-3,564	418
	Expanded polystyrene	-3,431	439

Using financial terms, the initial cost of insulation corresponds to the investment. The annual energy cost of the uninsulated model is subtracted from energy cost of other options to yield annual saving or profit.

The present values (PV) of saving for the first three years are calculated with an interest rate of 4.21%. The ratio between the PV of saving and initial investment is the benefit cost ratio. The speed of return of the initial investment is the rate of return. These figures are presented in Table 2.1-10.

Table 2.1-10: Financial Analysis Results

Group	ITEMS	Savings Initial ($)	Savings Energy ($/yr)	PV of Saving for 15 yrs I=4.21%	Benefit Cost Ratio	Rate of Return
Model	no insulation	0	0	0		
	ASHRAE; wall R13, roof R19	-2,175	488	5,347	2.46	21%
I	Perlite	-3,564	322	3,528	0.99	4%
II	Fiberglass board	-4,563	431	4,726	1.04	5%
	Fiberglass batts	-1,399	433	4,741	3.39	30%
	Mineral fiber batts	-1,832	458	5,017	2.74	24%
III	Isocyanurate	-3,931	430	4,709	1.20	7%
	Extruded PS	-3,564	418	4,578	1.28	8%
	Expanded PS	-3,431	439	4,814	1.40	10%

The benefit-cost ratio is summarized in Chart 2.1-4. The Batt products in Group II have the best ratio, followed by rigid-boards of Group III. Perlite in Group I shows the worst result.

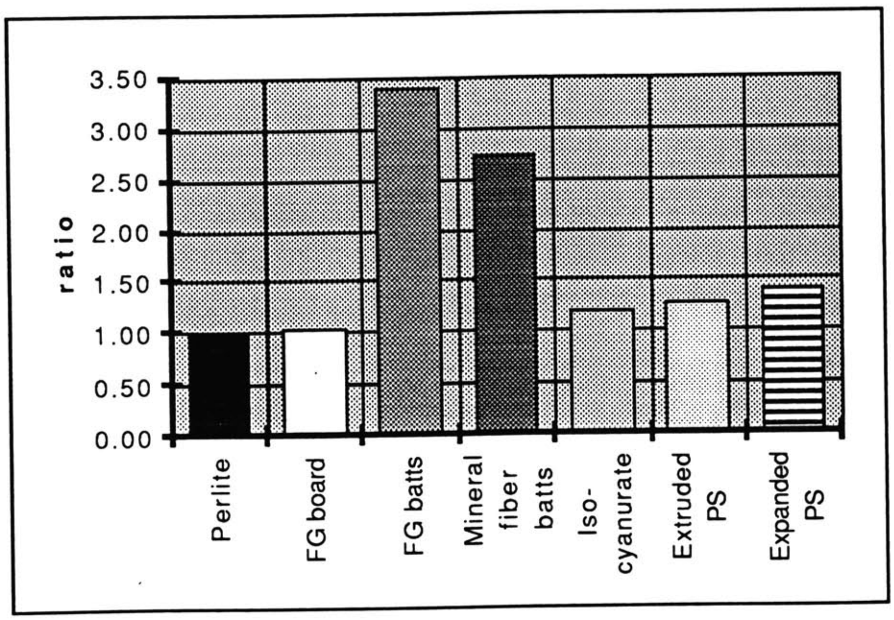


Chart 2.1-4: Benefit-Cost Ratio

The rate of return is summarized in Chart 2.1-5. The chart shows a close resemblance to Chart 2.1-4, in shape and proportion. Again the options with Batt products are the best options. Other subjects also show identical ranking.

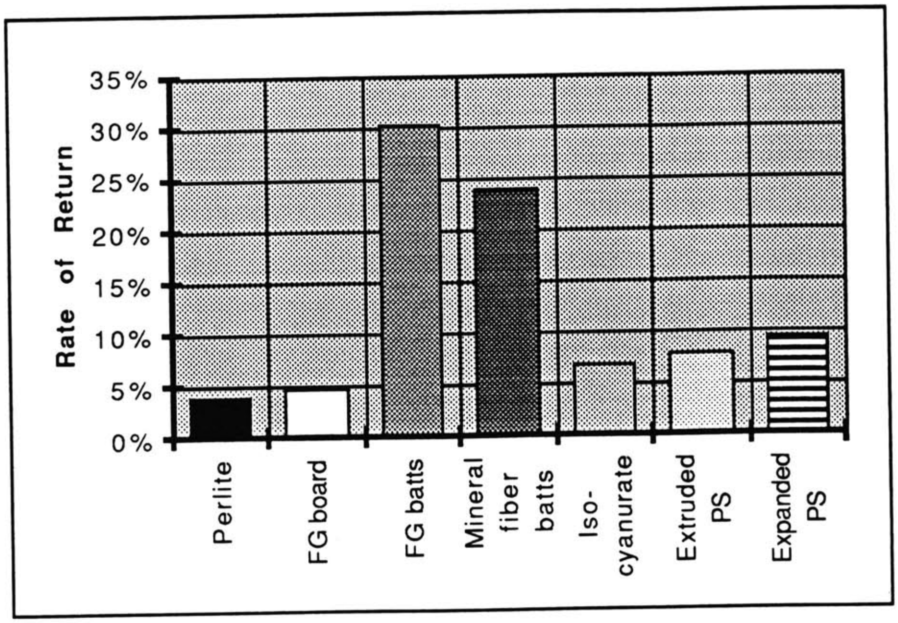


Chart 2.1-5: Rate of Return

2.1.4.3 Life Cycle Costing

LCC analysis is conducted for each of the subject material choices. The format for the analysis is given as Table 2.1-11 which compares the LCC between each group. The cost profile for the same analysis is given as the Chart 2.1-6. As LCC is dealing with cost, the lesser is the better. Analysis is conducted for the period of 45 years with life expectancy of the material at 30 years. The interest and inflation rates are set at the figures described in Section 2.1.3.2.

Costs are divided into capital costs, annual energy costs and replacement costs. The capital costs are not discounted because they occur at year 0. The annual energy costs are discounted using the PVCF (Present Value of Cash Flow) factor. The replacement costs which occur at the end of the material life expectancy, are discounted using the PV discount factor. It should be noted that an individual inflation rate is applied to each material and further, that expanded polystyrene is presumed to have an annual degradation rate of 0.07%.

Table 2.1-11: Table for LCC Analysis

			Option 1 (I) Perlite		Option 2 (II) Fiberglass Board		Option 3 (III) Expanded Polystyrene	
Project Life	(yrs)	45	Life	30	Life	30	Life	30
Interest Rate	(%)	4.21%	Infl.	-1.90%	Infl.	-2.80%	Infl.	10.70%
			Disc.	6.23%	Disc.	7.21%	Disc.	-5.86%
COSTS			Est.	PV	Est.	PV	Est.	PV
Capitals			3564	3564	4563	4563	3431	3431
Contingencies		*5.0%*		178		228		172
Total capital costs				3742		4791		3603
Annual Energy								
Inflation rate		*1.1%*						
Discount rate				*3.1%*		*3.1%*		*2.4%*
PVCF factor				*24.19*		*24.19*		*27.54*
			1051	25427	941	22766	933	25697
Total energy costs				25427		22766		25697
Replacement (intermittent)	*(year)*	*(Disc. factor)*						
(I) Perlite	*0*	*0.000*	3564	0				
	31	*0.154*	3564	548				
	0	*0.000*	3564	0				
	0	*0.000*	3564	0				
(II) Fiberglass Board	*0*	*0.000*			4563	0		
	31	*0.115*			4563	527		
	0	*0.000*			4563	0		
	0	*0.000*			4563	0		
(III) Expanded Polystyrene							3431	0
	0	*0.000*					3431	22326
	31	*6.507*					3431	0
	0	*0.000*					3431	0
	0	*0.000*						
Total NPV of LCC				548		527		22326
Total Costs				29717		28084		51625

The profile of LCC can be seen in Chart 2.1-6. At year 31, though expanded polystyrene displays a large jump for replacement cost, other materials make only a small one. This is due to the difference in inflation rates projected for these materials.

The costs of the LCC analysis are given in Table 2.1-12. From the table and accompanying Chart 2.1-7, the result of the LCC analysis can be recognized. Once again, the Batt products in Group II are the best options. Other rankings are identical to other analysis methods, except that the expanded polystyrene, dropping from other options in Group III, ends up to be the worst option.

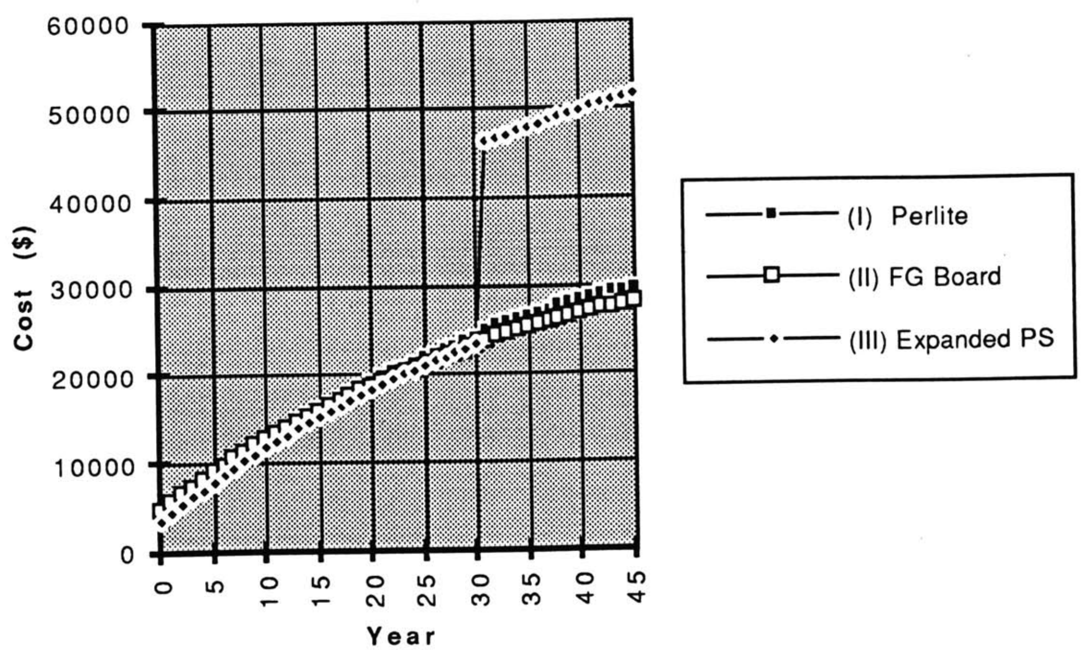


Chart 2.1-6: LCC Profile for Table 2.1-11

Table 2.1-12: Summary of LCC analysis

Group	ITEMS	LCC ($)
I	Perlite	29,717
II	Fiberglass board	28,084
	Fiberglass batts	24,447
	Mineral fiber batts	25,124
III	Iso-cyanurate	27,769
	Extruded polystyrene	27,024
	Expanded polystyrene	51,625

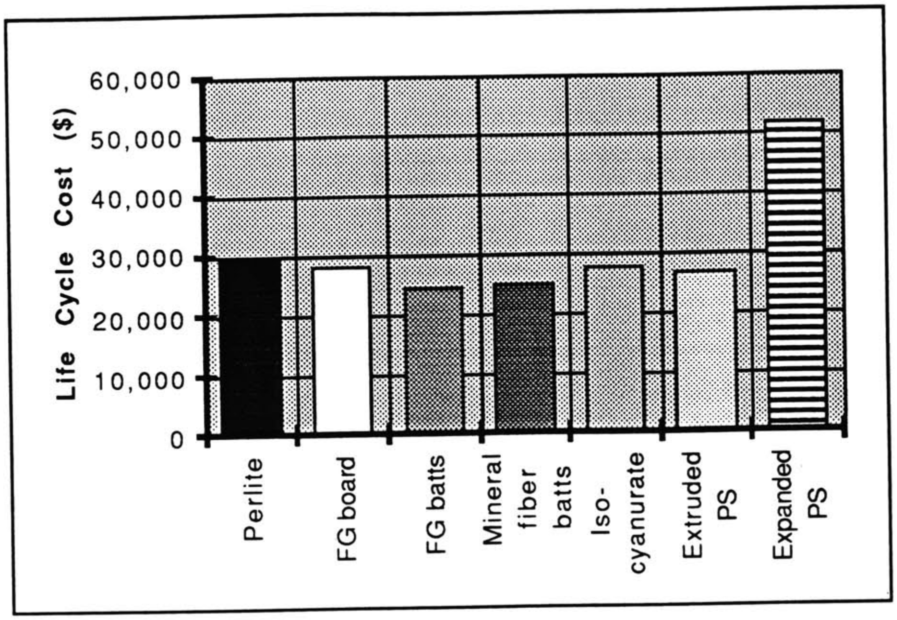


Chart 2.1-7: Chart for Table 2.1-12

2.1.5 Problems and Expected Solutions

2.1.4.1 Potency of LCC Method

Value

LCC brings the concept of time in the analysis. The results from each analysis have shown a close resemblance in ranking and proportion (Chart 2.1-3, 4, 5 and 7). However the LCC method is the only one which can display the points in time where a large increase of cost occurs or where one option becomes more favorable (or unfavorable) than another.

Limit

Validity of Data

Analyses with multiple variable factors are influenced by the degrees of their validity. In our case the different inflation rates for each material had a predictable impacts on the analysis.

Consideration of Whole System

Batt products from Group II (Fiberglass and Mineral Batt) ended favorably in all of the analyses. Still, other products are also frequently chosen and used in actual construction. This seems to suggest that our analysis lacks certain considerations.

The LCC method, which takes into account the concept of time and use, needs to consider the relation of the subject element or system to the whole building.

2.1.4.2 Factors which need Further Consideration

Inflation Rate

In order to simplify the LCC method, we have used cost data from 1991 to 1996 (Means) to calculate the inflation rate of insulation materials. It turned out that these inflation rates varied significantly from minus 5% to plus 10%. These figures have a substantial impact on future renovation costs in our calculation. However, as these materials are competing in the same small segment of the market, it is highly unlikely that their inflation rates continue to vary for the long term. Also, a negative inflation rate is not viable as a long lasting trend.

The range of data seems to have been insufficient for estimating the inflation trend of the next 45 years. Therefore it will be necessary to use (a) CPI as the inflation rates or (b) use a wider range of historical cost data. Option (a) will be easier to achieve but all materials will have the same inflation rate. Option (b) will have a more accurate inflation rate but requires significant time and difficulty in collecting sufficient information. Therefore, option (a) appears to be the practical choice.

System

Batt products from Group II ended favorably in all analyses. However, those "non-rigid" insulation materials have certain drawbacks when seen in the application level.

One drawback is in actual energy performance. As these materials need to be inserted within the supporting wall, the formed thermal barriers are usually obstructed at regular interval by the structural elements of the wall. As these elements may have very poor R-values, the actual R-value of the wall system becomes significantly lower than the calculated value.

Another disadvantage lies in their physical properties, which prevent them from becoming the base of further finish. Rigid boards, which can be the basis for finishes like stucco or waterproofing, will be often chosen, and may reduce the costs of the enclosure overall.

These indicate that the simplified LCC analysis, as well as all other analyses in this section, lack the consideration of the actual constructed condition of the material. As the interaction among the material is an important factor in construction, even the simplified version of LCC should take it into account. Therefore it will be more practical to start the analysis from the system level.

Thickness

Another factor which could not be included in the analysis, though related to the problem of the system, is the thickness of each material. The thickness of the building envelope is often restricted by the building code which regulates the maximum building size and the owner who wants maximum rentable or lettable space. In an extreme case, the thickness of the wall can be converted to the amount of annual rent income from its occupying space. For example, if the R-value of two materials is identical, it will be necessary to compare the cost and the thickness in terms of the LCC income.

2.1.4.3 Revised LCC Result

Before going to the next case study, the result of a partially revised LCC is presented here.

- The inflation rate is set at 3.9% per annum from change rate of Consumer Price Index of years 1984 to 1994. In this revised analysis ,the same rate is applied to all options.
- The degradation factor of expanded polystyrene is changed from the annual rate of 0.7% to the absolute percentage of 3.7%. This is due to the perception that continuous degradation of performance is unlikely.
- The results are given in Table 2.1-13 and Chart 2.1-8. The Batt products remain the best options as they did in the earlier result. However, the expanded polystyrene is now in the next ranking group with other rigid-board products in Group III.

Table 2.1-13: Revised Life Cycle Cost

Group	ITEMS	LCC ($)
I	Perlite	32,419
II	Fiberglass board	31,717
	Fiberglass batts	25,486
	Mineral fiber batts	25,730
III	Iso-cyanurate	30,526
	Extruded PS	30,096
	Expanded PS	30,138

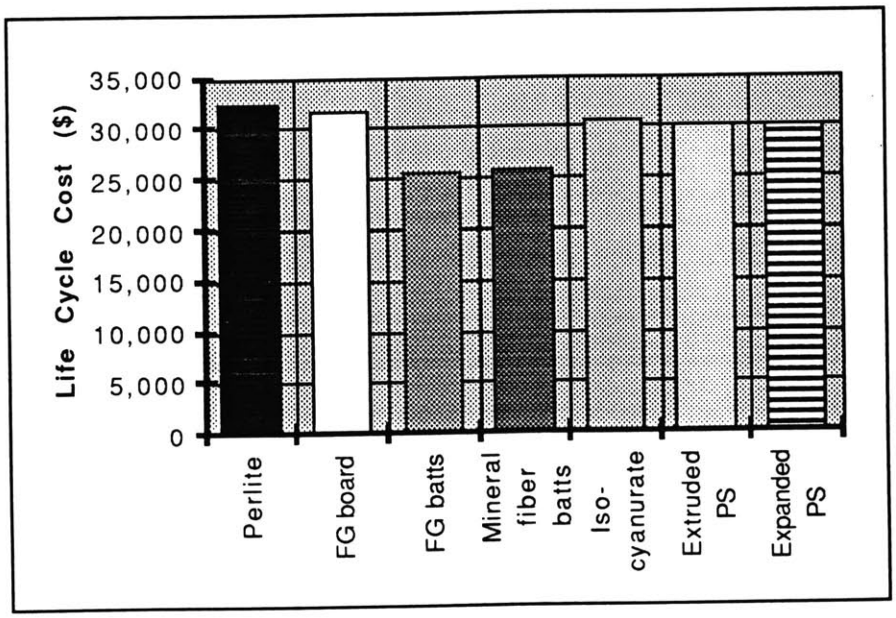


Chart 2.1-8: Chart for Table 2.1-13

2.2 Appendix to Case Study No. 1: Energy Model Calculations

Energy Consumption of a Single-family Detached House

Adaptation from "ASHRAE Handbook of Fundamentals 1993"

Chapter 25 Residential Cooling and Heating Load Calculations

Example 1 page 25.5

CONDITIONS

Geography

	Selection	
Location	Chicago, Illinois	
latitude	41.8	(°N)
cooling DD (65°F)	713	(°F day)
heating DD (65°F)	6127	(°F day)

Geometry

Section	Size	unit
E/W wall	74	(ft)
N/W wall	36	(ft)
ceiling	8	(ft)
Area	2664	(sqft)
Volume	21312	(cft)

Roof construction

Item	R summer	U summer	R winter	U winter
outside air film	0.25		0.17	
gypsum roof deck	9.00		9.00	
fibrous batt insul.	19.00		19.00	
vapor retardant	0.12		0.12	
inside air film	0.76		0.61	
total	29.13	0.03	28.90	0.03

Wall construction

Item	R summer	U summer	R winter	U winter
outside air film	0.25		0.17	
face brick	1.00		1.00	
fibrous batt insul.	13.00		13.00	
polystyrene sheath.	1.88		1.88	
gypsum board	0.45		0.45	
inside air film	0.68		0.68	
total	17.26	0.06	17.18	0.06

Floor construction

4-in concrete slab on ground

Fenestration

Clear double glass, 0.125 in thick
Assume closed, medium color venetian blinds
The window glass has a 2 ft overhang
Assume outdoor storm sash, 1 in air space

U winter
0.25

Doors

Item	R summer	U summer	R winter	U winter
outside air film	0.25		0.17	
all-glass storm door	0.50		0.50	
solid core flush	1.70		1.70	
inside air film	0.68		0.68	
total	3.13	0.32	3.05	0.33

Design conditions

Item		summer	winter	unit
outdoor	dry-bulb	91	2	(°F)
	d. range	15		(°F)
	wet-bulb	77		(°F)
indoor	dry-bulb	75	70	(°F)
	rh	50		(%)
occupancy		4		(person)
appliances	kitchen	1600		(Btu/h)
	utility	1600		(Btu/h)
construction		average grade		(N/A)

COOLING LOAD

Procedure

Basic formula are:

Walls, roof and doors

q= UA*(CLTD)

Windows

q= A*(GLF)

Air Change Rate:

ACH= 0.48

Cooling loads for the living room:

Infiltration

Q= ACH*(room volume)/60
= ACH*(3840)/60
= 31

q= 1.1*Q*(outside T-inside T)
= 541 (Btu/h)

Occupants

q= 230*(persons)
= 920 (Btu/h)

Appliances

q= 50%*(kitchen appliance load)

= 800 (Btu/h)

Cooling loads for the kitchen:

Infiltration

Q= ACH*(room volume)/60

= ACH*(1920)/60

= 15

q= 1.1*Q*(outside T-inside T)

= 270 (Btu/h)

Appliances

q= 50%*(kitchen appliance)+25%*(utility appliance)

= 1200 (Btu/h)

Transmission Cooling Load: Table 10

Item	Net Area (sqft)	GLF (B/hsqft)	U-value	CLTD (°F)	Load (Btu/h)
Living Room					
west wall	91		0.06	23	121
partition	192		0.07	12	161
roof	480		0.03	47	774
west door	21		0.32	23	154
west glass	35	41			1443
shaded gl.	13	16			205
Kitchen					
east wall	138		0.06	23	184
roof	240		0.03	47	387
east glass	11	41			443
shaded gl.	11	16			179

Summary of Sensible Cooling Load Estimate: Table 11

Room	Walls	Glass	Internal	Infilt.	Total (Btu/h)	Room (cfm)
living	1211	1648	1720	541	5120	300
kitchen	571	622	1200	270	2664	170
utility	1100	0	1200	338	2638	150
BR #1	441	496		211	1148	75
BR #2	515	752		211	1479	70
Master BR	1268	744		620	2632	175
Bath	400	96		225	721	60
TOTAL	5507	4358	4120	2416	16401	1000

Duct loss and ventilation

Item	Load (Btu/h)
Duct loss (10%)	1640
Ventilation	1200
TOTAL	19241

HEATING LOAD

Procedure

Basic formula are:

Walls, windows, roof and doors

q= UA*dT

Floors

q= FP*dT

Air Change Rate:

ACH= 0.89

Infiltration

q= 0.018*Q*dT

Summary of Heating Load Estimate:

Walls & Roof	Doors & Partition	Glass	Floors	Infilt.	Total (Btu/h)
9743	2764	2516	11968	18693	45684

ANNUAL ENERGY COST

a) Annual cooling energy

Cooling load coefficient is:

CLC= q(cooling load)*24/dT

= 28,862 (Btu/DD)

Annual cooling energy, Qc:

Qc= CLC*DD

= 20,578 (kBtu/year)

Energy consumed using heat pump unit is:

Ec= Qc*0.000293/2.5

= 2,412 (kWh)

Annual cooling cost is:

Cc= Ec * 0.0834

= 201 ($)

b) Annual Heating Energy

Total(UA)= q(heating load)/(DD base T - outside T)

= 725 (Btu/Dh)

TLC= Total(UA)*24

= 17,404 (Btu/DD)

Annual heating energy, Q:

Q(heating)= TLC*DD

= <u>106,632</u> (kBtu/year)

Energy consumed using an oil boiler is:

Eh= Q(heating)/0.65

= 164,049 (kBtu)

Fuel of oil consumed is:

F= Eh / 144000

= 1,139 (gallon)

<u>Annual Heating Cost is:</u>

Ch= F * 0.60

= <u>684</u> ($)

c) Annual Energy Cost

C(total)= Cc + Ch

= <u>885</u> ($)

3. APPLICATION OF LIFE CYCLE COSTING TO CONSTRUCTION

3.1 Running Costs

3.1.1 Annual Cost

The first category of the life cycle cost are the annual costs. This category can be divided further into two sub-categories: the annual energy costs and the annual maintenance costs.

3.1.1.1 Energy Cost

This is the cost of HVAC, or heating and cooling, which is needed annually to maintain the environment of the project. The annual energy requirement is computed following the established method of ASHRAE, then converted to the annual cost using the energy cost data from other sources.

In order to keep the interior environment of a building within the range defined as the "comfort zone," energy must be consumed. The requirements for energy will differ, according to the material and systems chosen for each option. Some of energy factors will be neglected if they are uniform across cases, hence having no effect on the decision points examined by the LCC analysis.

3.1.1.2 Maintenance Cost Data

Unlike the calculation of energy costs, there is no widely accepted method to estimate the annual maintenance requirement. Also it is widely accepted that the lack of the historic maintenance cost information is one of the weakness of the LCC method (Ashworth, Spedding, ed., 1987). It is suggested that the lack of an established cost-estimating method is because "maintenance is budget-oriented rather than needs-oriented." (Holmes, 1982) Most of the manufacturers can supply the maintenance data for their own products. However, there are very few documents which aggregate the data for an entire building (Dell'Isola, 1983, NBA Construction Consultants, 1985).

3.1.1.3 Estimate from Construction Cost Data Handbook

Another method of obtaining the annual maintenance cost is to sum up estimated costs of actual work. *'Life Cycle Cost Data'* (Dell'Isola, ibid.) supplies us the descriptions and cycles of ordinary maintenance work. By conventional cost estimating methods, it is possible to obtain the cost for maintenance. The cost divided by the maintenance cycle generates the estimated annual cost.

3.1.2 Renovation Costs

The last of the life cycle costs are the renovation costs which occur intermittently. Unlike costs of energy or maintenance, which are applied annually to all options, the cycle of renovation differs among various building options. Some options may not even need renovation during the analysis period.

3.1.2.1 Finish Life Method

This is the method used to compare options which have different replacement lives, like a comparison between finish materials. Each option is renovated at the end of its finish life to restore it to its initial condition. For this reason, the renovation cost is computed from its initial cost, adjusting for the percentage of replacement and the time value of money. As the initial costs are the primary source for information about renovation costs, their equal reliability is crucial to the accurate result of the analysis. Therefore, the analysis of options for new construction will be well suited to this method.

The concept of the renovation cost for this method is shown in the following Chart 3.1-1. In this, one option which costs $200,000 has a finish life of 9 years. Another costs only $100,000, but has a finish life of 3 years. The option with a higher initial cost will have a lower LCC after 12 years.

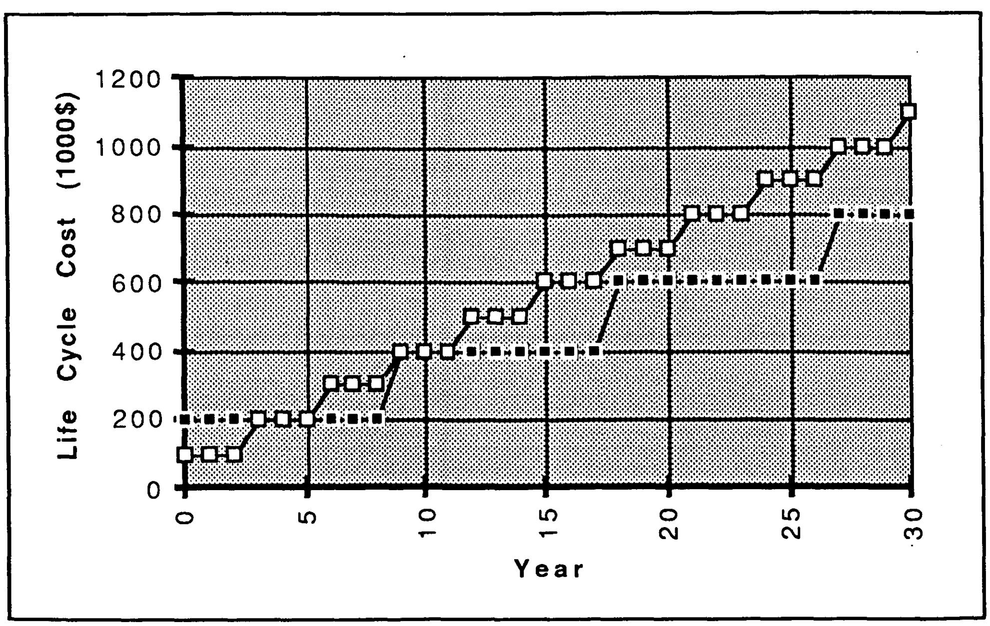


Chart 3.1-1: Diagram of Finish Life Renovation

3.1.2.2 Repair and Replacement

The LCC analysis may be conducted for options having the same construction method or the same material. The difference between these options lies in the extent or the quality of the work done. If the concepts in the Finish Life Method were followed, options with higher initial cost will have a higher replacement cost. This seems to be unlikely, because the low quality option will likely need total renovation sooner than the better quality option with higher cost.

Unlike the preceding method where the initial costs were the governing factors, assessment of the length of the useful life for each option will be the point of importance for this method. The method will be best fit to a comparison of retrofit work where the extent of work to an existing system is the main subject of comparison.

The conceptual diagram for this method is shown in Chart 3.1-2. An existing system costs $150,000 to replace and $50,000 to repair. The system will last 25 years if replaced, but will last only 10 years if only repaired. The replacement option will have a lower LCC for analysis period of 10 to 25 years, but this ranking may change for other analysis periods.

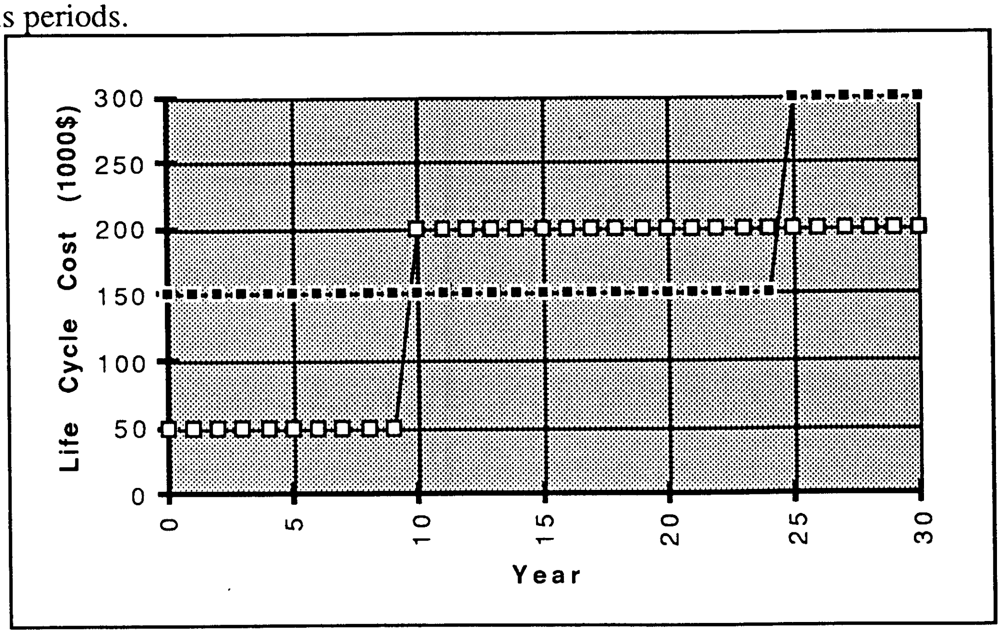


Chart 3.1-2: Diagram of Repair and Replacement

3.1.3 Conclusion for Running Costs

As seen in this section, the life cycle costs may be categorized as;

- Annual costs
  - — 1. Energy cost

- 2. Maintenance costs according to Life Cycle Cost Data
- 3. Maintenance costs according to Means Cost Data

- Renovation costs
  - 1. Finish Life Method
  - 2. Repair and Upgrade

Of these costs the basic combinations should be;

- Annual costs
  - 1.

  AND
  - 2. OR 3.

  AND
- Renovation costs
  - 1. OR 2.

3.2 Sensitivity Analysis

3.2.1 Definitions of Sensitivity Analysis

A sensitivity analysis is a simple approach to risk analysis. It identifies the scale of impact from a change in a single parameter value, or variables, to total LCC. (Flanagan, 1989, Magee, 1988) Some scholars prefer the probabilistic approach over the sensitivity analysis. The sensitivity analysis, which changes only a single variable, is criticized for being oversimplified and unrealistic due to its neglect of the interaction among variables. (Brandon, Spedding, ed., 1987)

In this thesis, where a simple version of the LCC is examined, the single sensitivity analysis is adequate. Also, it should be noted that the probability distribution necessary for a statistical analysis is another requirement for which it is difficult to find complete agreement. (Dell'Isola, ibid.)

3.2.2 Parameters

The sensitivity analysis is conducted by varying slightly, or in some cases extremely, a single parameter within the LCC analysis. The influential parameters can often be inferred from the result of the basic LCC analysis. As many of the parameters are results of some kind of assumption, an agency (design team or developers), which has the authority to change parameters, may consider different concepts or design scenarios. The parameters which are often subject to the sensitivity analysis are:

- the period of analysis
- the discount rate
- the life expectancy of the options
- the various cost estimates
- the rate of inflation

3.2.3 A Further Possibility

Although this is outside the scope of this thesis, it should be noted that the sensitivity analysis is thought to be a useful tool to assess the intangible factors of the LCC analysis. (Flanagan, ibid.) In the building industry, there are more factors apart from cost which are influential to the final judgment. This analysis may be used to assess aesthetic factors, like design or impression, which are usually treated as intangible.

3.3 Case Study No.2: LCC Analysis of Curtain Wall System

3.3.1 Scope of the Case Study

The scope of this study is, again, to conduct a simplified version of Life Cycle Cost (LCC) Analysis. It attempts to limit the input data to those available to a practicing construction engineer. Further possibilities of the LCC method are examined by conducting a sensitivity analysis.

3.3.2 Selection of the Analysis Subject

Following our first "small scale" LCC study, we are now conducting an analysis on a larger system. The subject in this case study is the combined curtain walls of two adjoining institutional buildings in New England, referred to here as buildings A and B. (Figure 3.3-1)

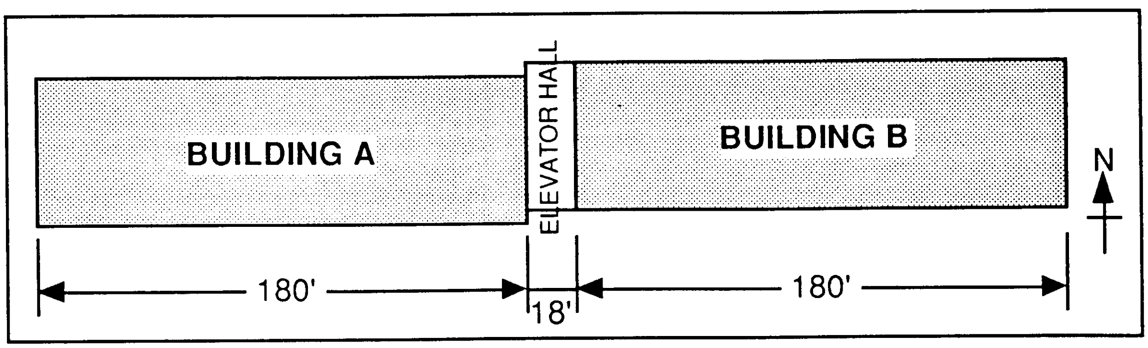


Figure 3.3-1: Site Plan of Buildings A & B

3.3.2.1 Renovation of Buildings A and B

The client of the project is a university in New England. Its Department of Biology has recently completed the construction of its new department building, and has relocated its laboratories and offices from buildings A and B (Figure C1-2), which are respectively 40 and 30 years old. The administration wants to renovate these now-empty buildings, and has hired a construction firm to assess several options. The firm submits three renovation options: I, II and III.

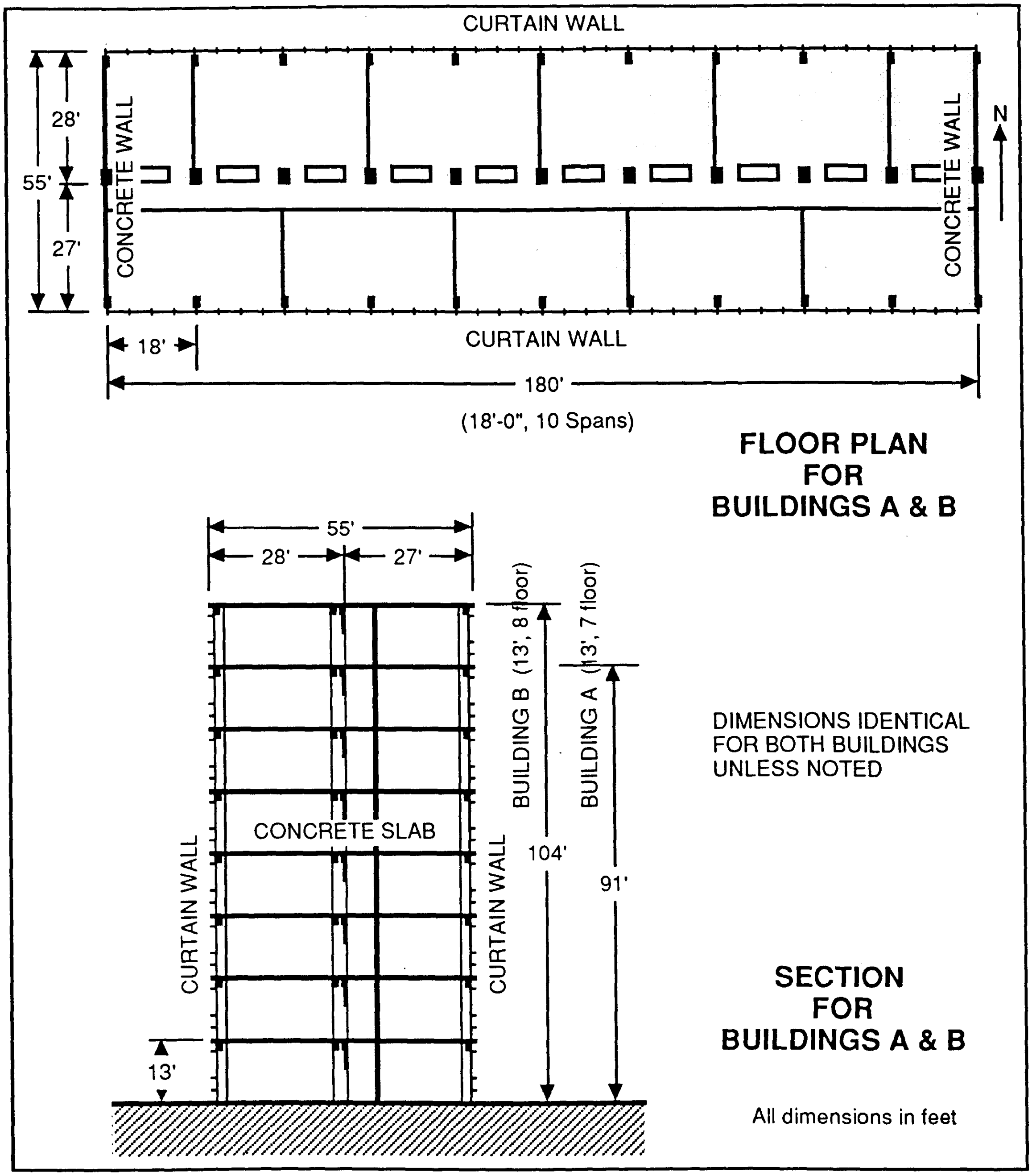


Figure 3.3-2: Typical Floor Plan and Building Section

- Option I (Minor Renovation) is a correction of physical deficiencies, retaining existing systems and applying cosmetic repair. This option represents the work required to maintain a level of service similar to the current operations while repairing the existing systems. However, no significant extension of useful life will be achieved which means that most of the systems within the buildings will reach the end of their useful lives after 5 years.

- Option II (Moderate Renovation) is also a correction of physical deficiencies, but it will feature new service systems and new interior finishes. This option represents the work required to create a level of operations enhanced to modern laboratory standards. The useful life will generally be extended 20 or more years.
- Option III (Major Renovation) is similar to the Option II, but this replaces the curtain wall and reconfigures the main corridor as well.

3.3.2.2 Curtain Wall Renovation

The exterior enclosures of both buildings are almost identical aluminum curtain wall systems. The vertical frame is attached to concrete slabs and supports horizontal frames. Glass window and Spandrel panels are inserted within these frames. (Figure 3.2-3 and 3.2-4)

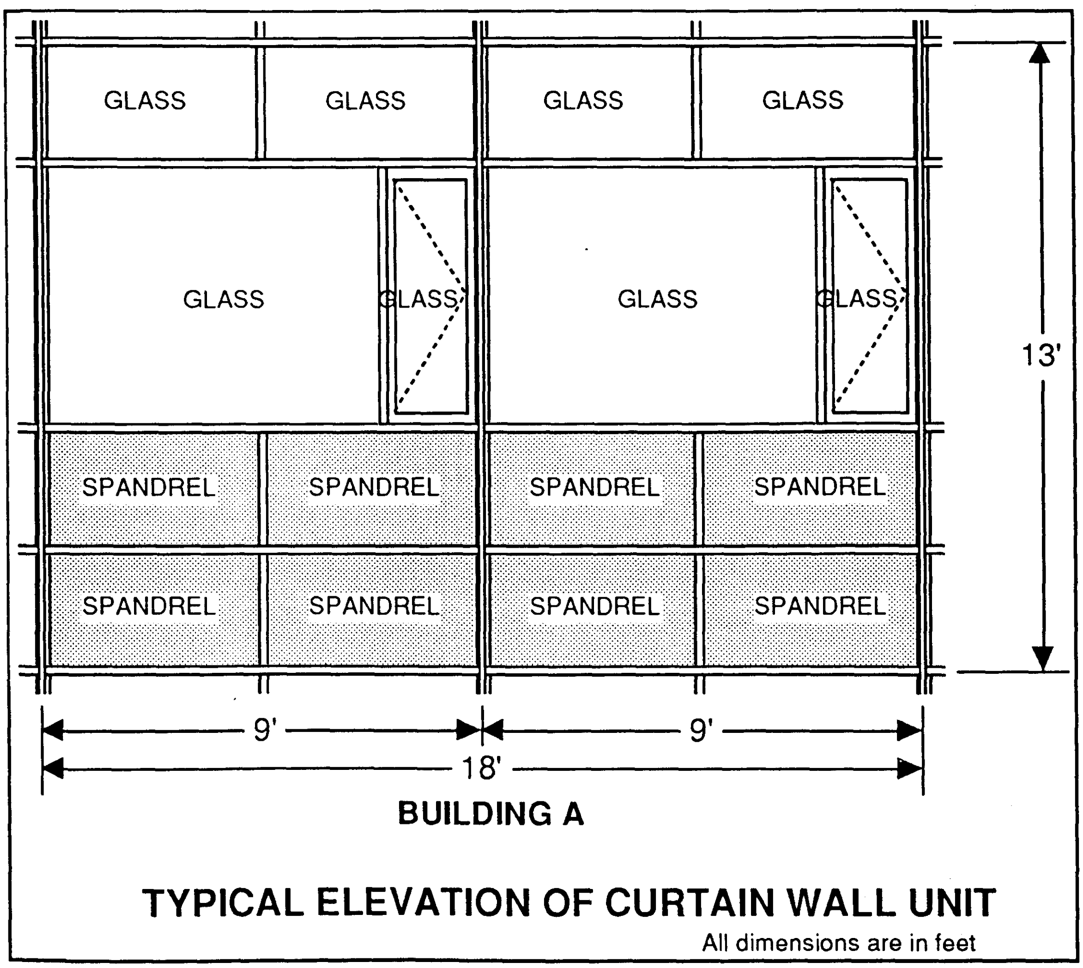


Figure 3.2-3: Typical Curtain Wall Unit for Building A

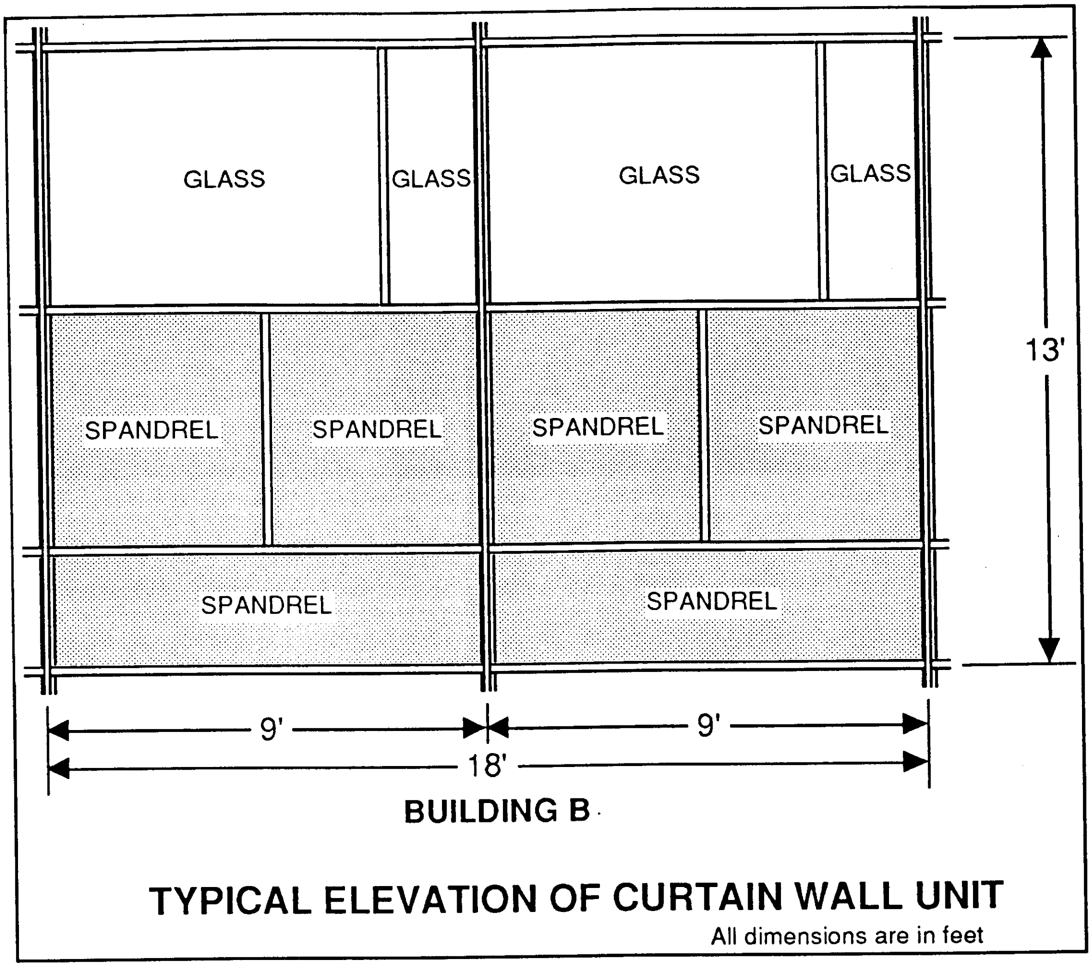


Figure 3.2-4: Typical Curtain Wall Unit for Building B

University authorities have found that the curtain wall system needs special consideration. They do not want the renovation work, though not yet clearly defined, to be disruptive nor very visible on the quiet campus. If the system could be kept intact during the work, it would serve as an ideal screening device.

For the curtain wall, the construction consulting firm proposes four options based on the extent of the initial renovation work. Though still part of the larger scheme, the curtain wall system ends up having its own renovation alternatives which are explained in the report by the firm. These are explained further as follows, and summarized in Table 3.3-1:

- **Option 1: Repair.** This option attempts to repair and to maintain the existing system by resealing all joints and repainting all metal elements. Although the initial cost is the lowest, the problems with water and air infiltration will remain, resulting in a high energy cost.

- **Option 2: Reglaze.** This attempts to improve the energy performance of the system by installing new insulated glass. The problem with this solution is that water trapped in the window channel will accelerate deterioration and fogging of the double-pane insulated glass. As all metal elements are to be retained, a new drainage device will not be installed.
- **Option 3: New Windows.** This option installs new aluminum windows within the existing curtain wall frame. The new windows are supplied with through-wall flashing devices to prevent water infiltration. The addition of a sub-frame will result in bulkier mullions and frames, approximately twice the original sizes.
- **Option 4: Full Replacement.** This replaces the curtain wall with an up-to-date system. This will result in minimal maintenance, low energy consumption and improved user comfort. It will also attain full compliance with the current building code on energy consumption.

In this case study, we are going to compare these four options using the LCC analysis.

Table 3.3-1: Curtain Wall Renovation Options

	Option 1	Option 2	Option 3	Option 4
Basic concept	Repair	Reglaze	New Windows	New Curtain Wall
Description	Repair, seal and repaint the existing system	Install new glazing, repair seal and repaint the existing frames & spandrel	Install new windows within the existing sub-frame. Seal and repaint the sub-frame & spandrel	Replace the entire curtain wall system
Advantages	-small cost	-improved energy performance	-weep holes for drainage -improved energy performance	-code compliance -highest energy performance
Dis-advantages	-poor energy performance -possibility of leakage	-damaging insulation -no drainage	-"bulky" frames	-large cost -open bldg. during construction

3.3.3 Data for the Analysis

3.3.3.1 Economic Data

Initial Costs

The cost estimate data supplied from the consulting firm is used for the initial capital costs. (Table 3.3-2) It includes contractor's general requirements, its fee and soft costs. Contingencies of 5% are added to each of them.

Table 3.3-2: Initial Cost

	Option 1	Option 2	Option 3	Option 4
Building A	$203,905	$942,565	$1,304,297	$1,917,074
Building B	$281,425	$845,883	$1,159,178	$2,660,340
Sub-Total	$485,330	$1,788,448	$2,463,475	$4,577;414

Inflation Rate

Since the subject is renovation work of buildings, the major components of the cost are purchase and construction. Therefore, the inflation rate of the capital and replacement costs are calculated from the historical cost index in the building cost data handbook (Means, 1995). The cost index from 1960 to 1995 was used to compute an average estimated annual inflation rate of 5.85%.

The inflation rate for energy cost is calculated from the CPI (Consumer Price Index) data from *'The Statistical Abstract of the United States 1995'* (U.S. Department of Commerce, 1995). The index from 1960 to 1994 yields the estimated annual inflation rate of 6.19%.

Interest Rate

The interest rate figures are taken also from *'The Statistical Abstract of the United States 1995'* (U.S. Department of Commerce, 1995). The interest rate for the calculation is set at 8.95%. It was estimated using the effective rate of the Federal funds from the years 1970 to 1994.

Fuel Price

The average "end-user" fuel price for natural gas was $6.16 per 1000 cubic feet in the year 1993 (U.S. Department of Commerce, 1995). This figure is used within the energy consumption calculations.

3.3.3.2 Energy Data

Basic Approach

Energy loads and requirements are estimated following the steps in the ASHRAE Handbook. The buildings are multi-story, concrete-built and located in New England.

Energy Requirements

The type of HVAC in the buildings is an all-water system with fan coil units. Cooling costs are calculated for a gas heat pump. Heating costs are calculated for a gas boiler.

Cooling loads are calculated using the CLTD (Cooling Load Temperature Difference) and SHGF (Solar Heat Gain Factor), assuming system operation in daytime through summer and shoulder seasons. Heating loads are calculated using the degree day method, judging from the academic usage of 24 hours a day.

3.3.3.3 Running Costs

As the running costs constitute a large proportion of the costs in the LCC analysis, we need extra precautions in doing the assessment.

Annual Cost

Energy Cost

The annual energy requirement is computed following the established method of ASHRAE, then converted to the annual cost using the energy cost data from above. The subject of the analysis is the curtain wall system or the exterior envelope of the buildings. Some of the energy factors (i.e., the internal gain) were neglected as they are uniform for all options. Details of the energy calculations are supplied as an appendix, at the end of section 3. A summary is given in Table 3.3-3.

Table 3.3-3: Energy Costs

		Option 1	Option 2	Option 3	Option 4
Cost	unit				
Bldg A	(1000$/yr)	100.1	79.8	61.6	54.2
Bldg B	(1000$/yr)	74.1	76.9	59.1	50.8
Total	(1000$/yr)	174.2	156.8	120.7	105.0

Maintenance Costs from LCC Data

The following table (Table 3.3-4) is the life cycle cost data for curtain wall systems in the exterior closure section of Dell'Isola (1983)

Table 3.3-4: Life Cycle Cost Data

Item description	Unit	Maintenance description	Maintenance annual cost, $			Ene-rgy	Repl life	% Repl
			Lab	Mat.	Eqp		yrs	%
Exterior Closure								
Curtain Walls								
Aluminum spandrel panel	WSF	Minor repair, cleaning (2.0 min every 6 yr)	.08	.01	.001	n/a	50	100
Stainless steel panel	WSF	Minor repair, cleaning (2.0 min every 6 yr)	.08	.01	.001	n/a	50	100
Porcelain enamel panel	WSF	Minor repair, cleaning (2.0 min every 6 yr)	.08	.01	.001	n/a	50	100
Weathering steel panel	WSF	No maintenance required						
Opaque colored-glass panel	WSF	Window washing (0.18 min every 6 month)	.07	.01	.005	n/a	40	100
	WSF	Repair glazing	.002	.005	.001			

We use the maintenance cost for "Opaque colored glass panel curtain wall". This data must be updated and converted to be used in the LCC analysis with other cost data.

Updating the Cost

First, we have to update the data to current figures using the historical cost index by Means. (Table 3.3-5)

Table 3.3-5: Updated Maintenance Costs

Items	year	Means Cost Index	Unit	Maintenance annual cost, $		
				Mat	Labor	Equip
Washing			WSF	.01	.07	.005
Repair			"	.01	.00	.001
Total	1984	81.8	"	.015	.072	.006
Total	1995	108.0	"	.020	.095	.008

Cost Components of Curtain Wall

Construction costs are usually expressed in "Total incl. O&P" or the cost which includes Overhead and Profit. Thus, to include the updated maintenance costs in the calculation, the proper percentage of "O&P" must be found. From Means Cost Handbook, we tabulate the cost data for curtain walls (Table 3.3-6).

Table 3.3-6: Means Cost Data

CURTAIN WALLS	crew	daily out-put	Labor hours	Unit	1996 Bare Costs, $				Total incl. O&P
					Mat	Lab	Eqp	Total	($)
Aluminum, stock, incl. glazing									
Minimum grade	H-1	205	.156	SF	17.80	4.12		21.92	26.50
Average single glazed	"	195	.164	"	24.00	4.33		28.33	34.00
Average double glazed	"	180	.178	"	35.00	4.69		39.69	46.50
Maximum grade	"	160	.200	"	91.00	5.30		96.30	109.00

In the Means Handbook the "Bare Costs Total" and "Total including Overhead and Profit" are calculated as:

$$\text{Bare Total} = \text{Material} + \text{Labor} + \text{Equipment}$$
$$\text{Total incl O\&P} = 110\% \times \text{Mat} + (100 + m)\% \times \text{Labor} + 110\% \times \text{Equip}$$

The percentage of "O&P" for material and equipment costs are fixed at 10%, however the percentage for the labor cost depends on the crew configuration of each item (expressed here as m%). In our case, the curtain walls with the crew type of H-1, the factor is given in Table 3.3-7.

Table 3.3-7: factor m for Curtain Walls

CURTAIN WALLS	crew	factor m (%)
Alum., stock, incl. glazing		
Minimum grade	H-1	68.0
Average single glazed	"	75.5
Average double glazed	"	70.6
Maximum grade	"	67.9
Average		70.5

As the factor m varies only slightly, we use the average figure of

$$m = 70.5\%$$

Unit Annual Maintenance Cost

Using obtained factor m, we can convert material, labor and equipment costs from *'Life Cycle Cost Data'* to the "Total including Overhead & Profit" format.

$$\text{Total incl O\&P} = 110\% \times \text{Mat} + 170.5\% \times \text{Labor} + 110\% \times \text{Equip}$$

Applying these factors to the updated LCC data, we obtain the unit annual maintenance cost (Table 3.3-8).

Table 3.3-8: Unit Annual Maintenance Cost

Item	Unit	Mat	Labor	Equip	Total
1995 Costs	($/WSF)	0.020	0.095	0.008	0.123
factors	(%)	110.0%	170.5%	110.0%	
Costs incl. O&P	($/WSF)	0.022	0.162	0.009	0.193

Annual Maintenance Cost for the Curtain Wall

Multiplying the unit annual maintenance cost by the area of wall (WSF) generates the total annual maintenance cost for our buildings A and B (Table 3.3-9). Estimated annual maintenance cost is:

$6,759.

Table 3.3-9: Annual Maintenance Cost

	Unit	Build A	Build B	Total
Curtain Wall Area	(WSF)	16,380	18,720	35,100
Annual Maintenance	($)	3,154	3,605	6,759

Estimate from Means Cost Data

Another method of obtaining the annual maintenance cost is to sum up the estimated costs of the actual work. For the curtain wall system the maintenance work includes cleaning and sealing, and, to a lesser magnitude, inspection.

Maintenance Cost

From *'Facilities Maintenance Management'* (Magee, 1988) and cost data handbook (Means, 1995), we can obtain the unit costs. In multiplying those figures by the size of the system, we can compute the cost of the maintenance work (Table 3.3-10).

Table 3.3-10: Cost of Maintenance Work

	Labor hrs	Unit	Unit costs	Size	Costs
Cleaning	0.5	(SF)	$0.159	70,200	$11,162

Annual Maintenance Cost

The cycle of maintenance work governs the annual cost. For a reasonable range of maintenance work cycles, we compute the estimated annual maintenance cost (Table 3.3-11).

Table 3.3-11: Annual Maintenance Cost

Maint. Cycle (yr)	Annual cost ($/yr)
0.5	22,324
1	11,162
2	5,581
3	3,721
4	2,791
5	2,232
6	1,860

If we apply the same maintenance cycle as in the prior method (6 months), the annual maintenance cost is projected to be:

$22,324

which is considerably higher than the prior estimate — $6,759 per year, using LCC Data method. The fact that the higher cost does not even include "minor repair" work which is included in the lower cost estimate, clearly shows the difficulty of assessing the maintenance cost. Assuming that the LCC Data is based upon better researched data, we use the lower cost as the annual maintenance cost in our calculation.

Renovation Costs

Assessing Repair and Renovation Data

Renovation of buildings A and B, as well as renovation of the curtain wall system, are conducted to prolong, where possible, their useful life. The initial cost for each option can be translated as "investment to gain an additional period of the building's useful life." Future renovation work with replacement of major systems is likely to occur at the end of this target period.

Unfortunately the planners of the consulting firm did not specify the target period for the options of the curtain wall, though they did for the total renovation project.

As stated at the beginning of the case study, the work on the curtain wall is loosely related to the total renovation project. The construction consulting firm has already conducted a facility assessment study of the total project. With reasonable assumptions it is possible to infer necessary figures from that study.

Total Project Costs and Renovation Costs

The total project has three options called Minor, Moderate and Major. The names of these options correspond to the extent of attempted work in order to prolong the useful life of the existing buildings (Table 3.3-12).

Table 3.3-12: The Initial Costs of the Total Project

	Option	Minor	Moderate	Major
Building A		8,073	19,090	20,857
Building B		9,430	23,636	27,093
total	(1000$)	17,503	42,726	47,950
ratio	(%)	37%	89%	100%

In the facility assessment study no repair or renovation is set for the Moderate and Major renovation options over the study period. For the Major option (with concept word "replace"), all major systems within the buildings are initially replaced. Therefore, we assume that this option does not need further repair nor replacement for the next 30 years.. The Moderate option (with concept "renovate"), has a project cost which is far closer to the Major than to the Minor. This must be the reason why the firm has concluded the same renovation profile as for the Major option. For the Minor renovation option, the consulting firm has estimated quite differently with:

a) Substantial repair

at the end of year 4 which costs

$2,000,000 for Building A

$2,500,000 for Building B

or approximately 25% of the initial cost of the Minor renovation option.

b) Major replacement of major systems

at the end of year 10, which is equivalent to the initial cost of the Major renovation option.

As only a minimal investment was made under the assumption of the minor repair, the firm has concluded that the systems within the buildings will need substantial repair at the end of year 4, and that they will come to the end of their useful life at the end of year 10.

Renovation Costs for Curtain Wall System

For the curtain wall system, we have four options and their ratios are tabulated below (Table 3.3-13).

Table 3.3-13: Initial Costs of Curtain Wall Renovation

		Option 1	Option 2	Option 3	Option 4
Cost	(1000$)	485	1,788	2,463	4,577
Ratio	(%)	11%	39%	54%	100%

Here, unlike the case of the overall facility assessment study, the first three options have considerably smaller cost ratios compared to the highest option. Option 2 with ratio of 39% is comparable to the Minor option with ratio of 37%, and for this reason I assume it has an equivalent repair and replacement schedule. We also know that the original curtain wall system did not have adequate drainage which may result in corrosion of the metal frames. Options 1 and 2 do not offer any improvements in drainage. Option 3 offers partial improvement (drainage on horizontal elements), and only Option 4 obtains the highest level of quality (full drainage).

The LCC analysis requires careful consideration of repair and replacement intervals. Here, this information is inferred from the consultant's study, but in practice, this data must come from manufacturers' specifications and building experience. Another renovation schedule is set proportionally based on this assumption. These assumptions and manipulations lead to the schedules for the LCC analysis of Table 3.3-14. Likewise, the cost of renovation work can be proportionally assumed from the example in the assessment study as:

a) Substantial repair

25% of the initial cost of option 2

b) Major replacement

100% of the initial cost of option 4

Table 3.3-14: Schedule of Renovation

		Option 1	Option 2	Option 3	Option 4
Substantial repair	(year)	2	4	8	n/a
Major Replacement	(year)	8	10	15	30

Conclusion

Upon calculating the life cycle costs of the curtain wall renovation, which is a retrofit project, the appropriate combination will be:

A) 1) annual energy cost

and A) 2) annual maintenance cost from LCC Data

and B) repair and upgrade cost

3.3.3.4 Sensitivity Analysis

After the basic analysis, we conducted a sensitivity analysis. As mentioned earlier in the paper, it is one of the simplest approaches to risk analysis, which changes only a single parameter value within the LCC comparison. The parameters for the sensitivity analysis include:

- the interest rate
- the inflation rate
- the initial cost estimate
- the annual maintenance cost estimate
- the renovation cost estimate
- the life expectancy of the options

From the results of this analysis we assess the scale of impact that each parameter has on the total cost and on the ranking of options. The parameters used in the basic case are summarized in Table 3.3-15. These parameters were increased and decreased by 5% and then by 25% in the sensitivity analysis. As an example, the change in parameters for Option 2 is summarized in Table 3.3-16.

Table 3.3-15: Parameters for Basic Case

		Unit	Option 1	Option 2	Option 3	Option 4
Parameter 1: Interest rate		(%)	8.95%			
Parameter 2: Inflation rate	const.	(%)	5.85%			
	energy	(%)	6.19%			
Parameter 3: Initial cost		(1000$)	485	1,788	2,463	4,577
Parameter 4: Annual cost	maint.	(1000$)	6.76			
	energy	(1000$)	180	163	124	107
Parameter 5: Renovation cost	repair	(1000$)	616			
	repl.	(1000$)	4,577			
Parameter 6: Life expectancy	repair	(year)	2	4	8	n/a
	repl.	(year)	8	10	15	30
Parameter 7: Analysis period		(year)	30			

Table 3.3-16: Parameters Change for Sensitivity Analysis

		Unit	Option 2			
Change		(%)	+5%	-5%	+25%	-25%
Parameter 1: Interest rate		(%)	9.40%	8.50%	11.20%	6.71%
Parameter 2: Inflation rate	const.	(%)	6.14%	5.56%	7.31%	4.39%
	energy	(%)	6.50%	5.88%	7.74%	4.64%
Parameter 3: Initial cost		(1000$)	1,878	1,699	2,347	1,341
Parameter 4: Annual cost	maint.	(1000$)	7.10	6.42	8.45	5.07
	energy	(1000$)	165	149	196	118
Parameter 5: Renovation cost	repair	(1000$)	647	585	770	462
	repl.	(1000$)	4,806	4,349	5,722	3,433
Parameter 6: Life expectancy	repair	(year)	4	4	5	3
	repl.	(year)	11	10	13	8
Parameter 7: Analysis period		(year)	32	29	38	23

3.3.4 Analysis Results

3.3.4.1 Basic Case

Table 3.3-17: LCC Analysis Result of Basic Case

			Option 1 Repaint		Option 2 Reglaze		Option 3 New Windows		Option 4 New Curtainwall	
Analysis Years		30	Infl.	5.85%	Infl.	5.85%	Infl.	5.85%	Infl.	5.85%
Interest Rate		8.95%	Disc.	2.93%	Disc.	2.93%	Disc.	2.93%	Disc.	2.93%
COSTS			Est.	PV	Est.	PV	Est.	PV	Est.	PV
Capitals			(1000$)		(1000$)		(1000$)		(1000$)	
Initial Cost				485		1,788		2,463		4,577
Contingencies		5.00%		24		89		123		229
Total Capital Costs				510		1,878		2,587		4,806
Annual Costs			(1000$)		(1000$)		(1000$)		(1000$)	
Maint.	Infl.	5.85%								
	Disc.	2.93%								
	PVCF	19.78	6.76	134	6.76	134	6.76	134	6.76	134
Energy	Infl.	6.19%								
	Disc.	2.60%								
	PVCF	20.66	174	3,598	157	3,238	121	2,494	105	2,169
Total of Annual Costs				3,732		3,372		2,627		2,302
Repair/Replacement (intermittent) Costs			Repair	25%	of	Initial Cost of Option 3		616		
			Repl.	100%	of	Initial Cost of Option 4		4,577		
	(year)	(PVf)	Est.	PV	Est.	PV	Est.	PV	Est.	PV
Option 1			(1000$)		(1000$)		(1000$)		(1000$)	
Repair	2	0.917	616	565						
Repl.	8	0.771	4,577	3,530						
Option 2										
Repair	4	0.866			616	533				
Repl.	10	0.728			4,577	3,332				
Option 3										
Repair	8	0.771					616	475		
Repl.	15	0.630					4,577	2,884		
Option 4										
Repair	0	0.000							616	0
Repl.	30	0.000							4,577	0
Total NPV of LCC				4,095		3,865		3,359		0
Total Costs in 1000 $				8,337		9,115		8,573		7,109

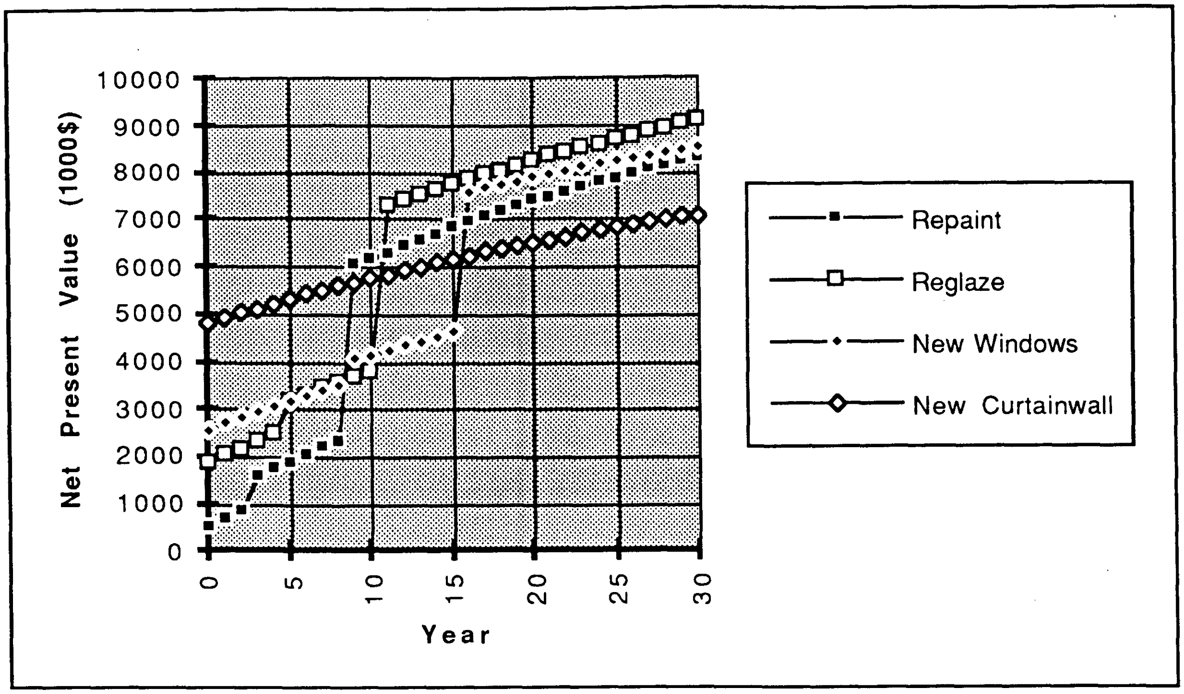


Chart 3.3-1: LCC Profile of the Basic Case

Remark

As can be seen clearly from Chart 3.3-1, Option 4, or the replacement of the curtain wall system, becomes the best option after year 15. Option 4 has the substantial advantage that it does not need any repair or renovation during this analysis period.

Table 3.3-18: Ranking of Basic Case

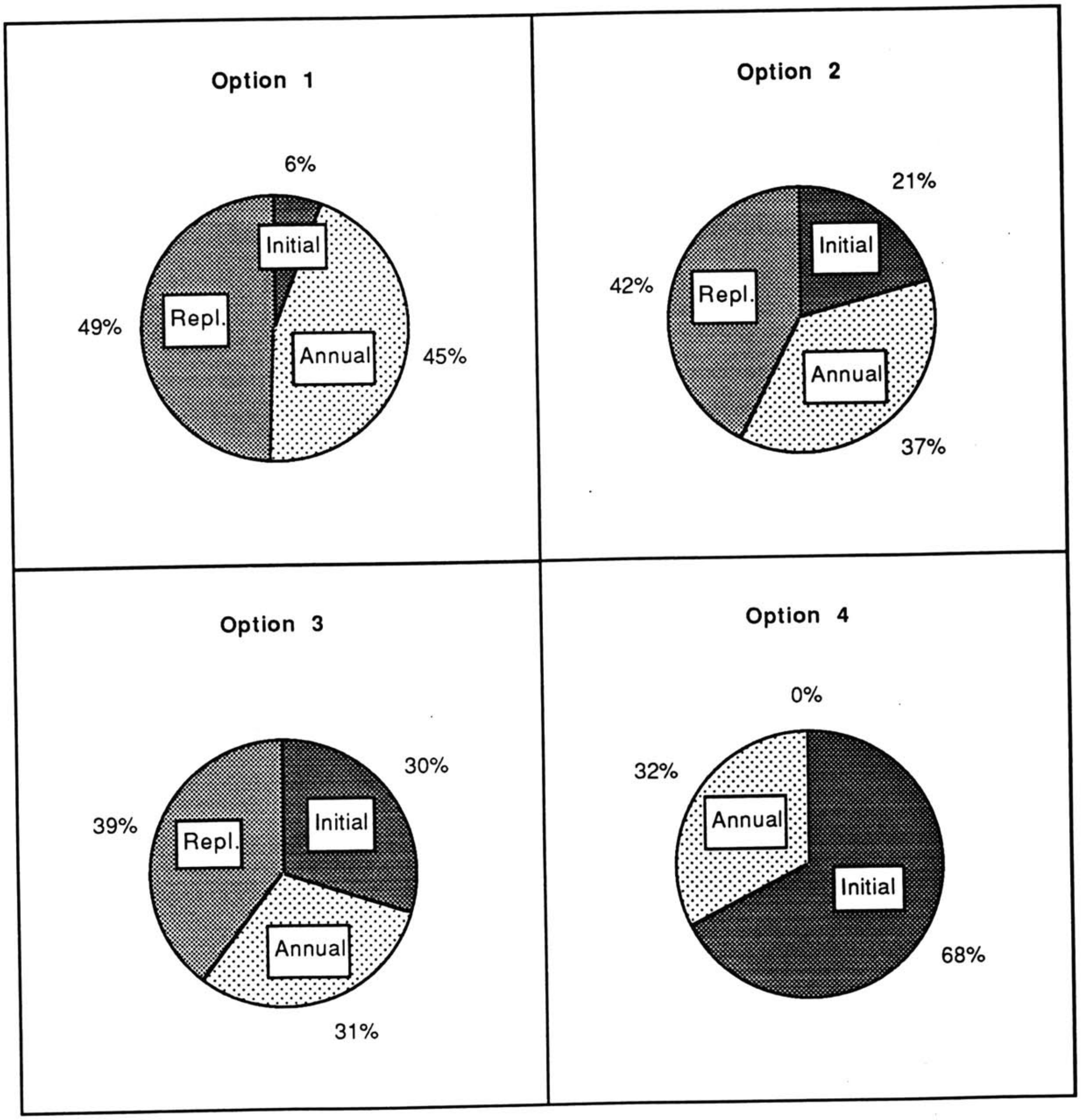
		Option 1	Option 2	Option 3	Option 4
Total LCC	(1000$)	8,337	9,115	8,573	7,109
Ranking		2	4	3	1

If the scope of the analysis period by the owner is shorter, the ranking result will be different. A period under 8 years will make Option 1 preferable, while a period between 10 and 15 years will make Option 3 preferable. Option 2 seems to be an unlikely candidate being the most economical option only at years 9 and 10. Each option loses its economical advantage at the end of its system life expectancy.

The distribution of costs' segments within the total LCC is shown in Table 3.3-19.

Table 3.3-19/Charts 3.3-2a to 3.3-2d: Cost Segments within LCC

Cost (1000$)	Option 1 Repaint	Option 2 Reglaze	Option 3 New Windows	Option 4 New Curtainwall
Initial	510	1,878	2,587	4,806
Annual	3,732	3,372	2,627	2,302
Repl.	4,095	3,865	3,359	0
Total	8,337	9,115	8,573	7,109



As can be seen from the charts, although the total life cycle costs range from $7.1 million to $9.2 million, there are substantial differences in their components.

3.3.4.2 Sensitivity Analysis

Sensitivity Analysis with Parameters Increased or Decreased 5%

Table 3.3-20/Chart 3.3-3: LCC Summary with 5% Increase

Cost (1000$)	Option 1 Repaint	Option 2 Reglaze	Option 3 New Windows	Option 4 New Curtainwall	Average*
Basic	8,337	9,115	8,573	7,109	8,283
Interest rate	8,002	8,776	8,232	6,985	7,999
Inflation rate	8,581	9,362	8,822	7,202	8,492
Constr. costs	8,567	9,402	8,871	7,349	8,547
Annual costs	8,523	9,283	8,705	7,224	8,434
Repl. costs	8,541	9,308	8,741	7,109	8,425
Life	8,337	9,020	8,491	7,109	8,239
Analysis period	8,497	9,260	8,686	9,078	8,880

*The Average forms the basis for Chart 3.3-5

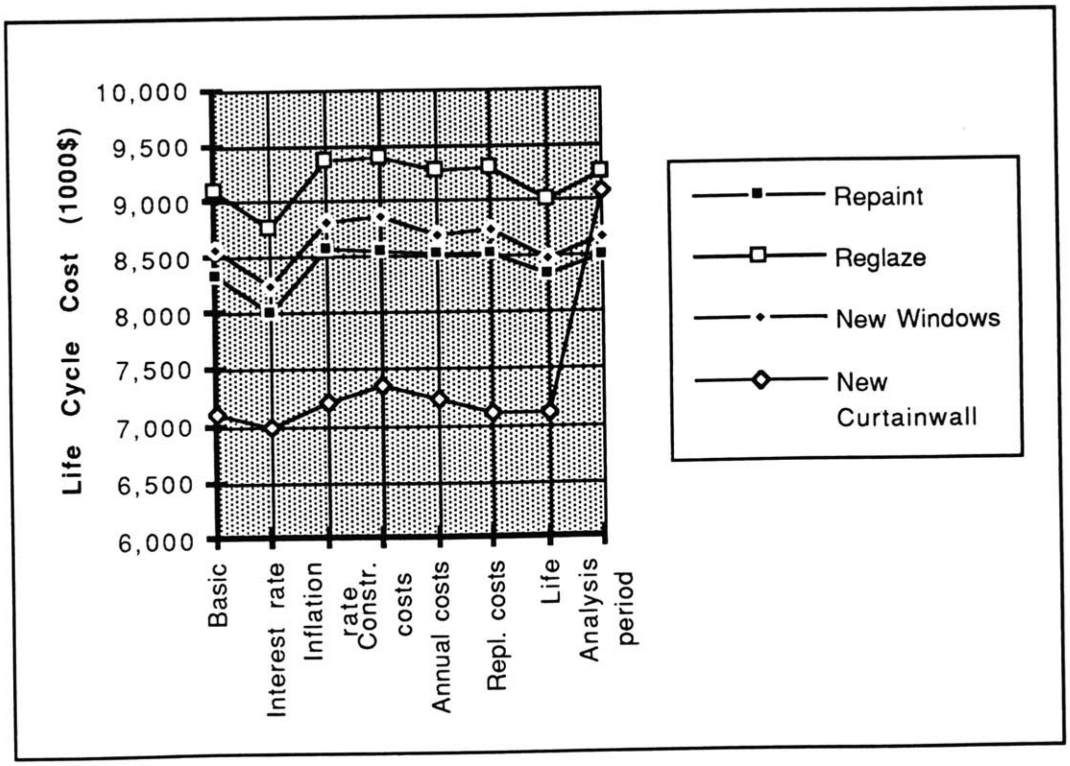
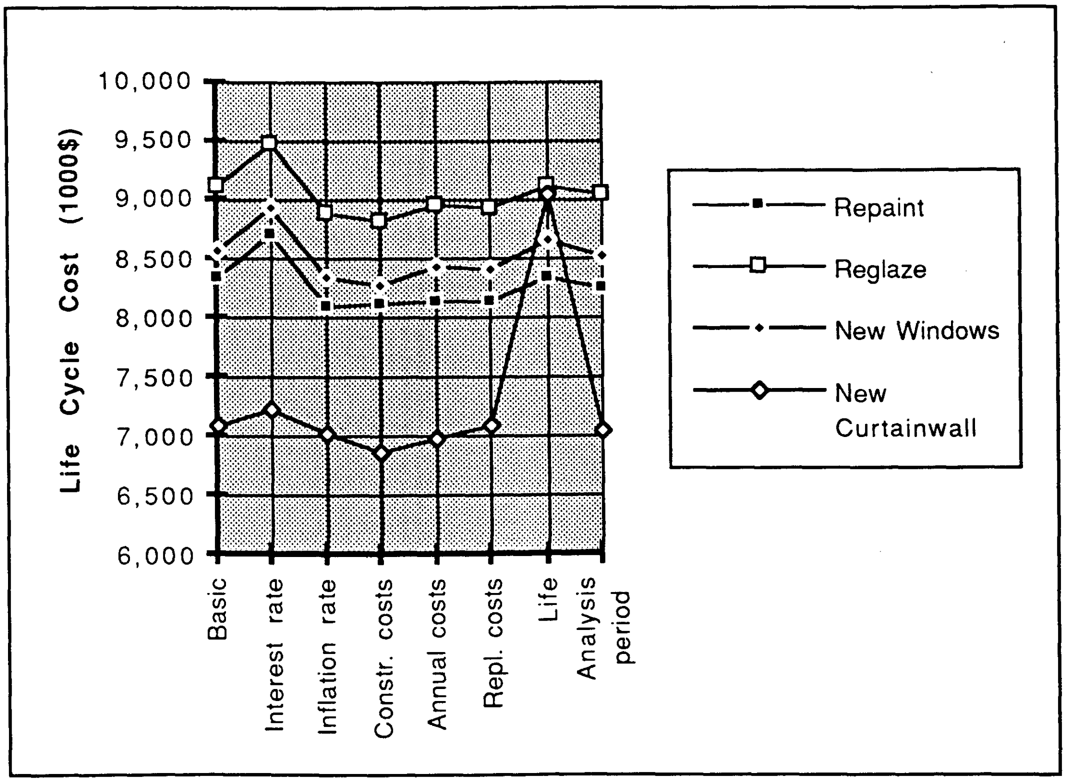


Table 3.3-21/Chart 3.3-4: LCC Summary with 5% Decrease

	Option 1	Option 2	Option 3	Option 4	
Cost (1000$)	Repaint	Reglaze	New Windows	New Curtainwall	Average*
Basic	8,337	9,115	8,573	7,109	8,283
Interest rate	8,694	9,476	8,940	7,243	8,588
Inflation rate	8,101	8,878	8,336	7,020	8,084
Constr. costs	8,106	8,828	8,276	6,868	8,020
Annual costs	8,150	8,946	8,442	6,994	8,133
Repl. costs	8,132	8,922	8,405	7,109	8,142
Life	8,337	9,115	8,658	9,034	8,786
Analysis period	8,253	9,039	8,514	7,057	8,216

*The Average forms the basis for Chart 3.3-5



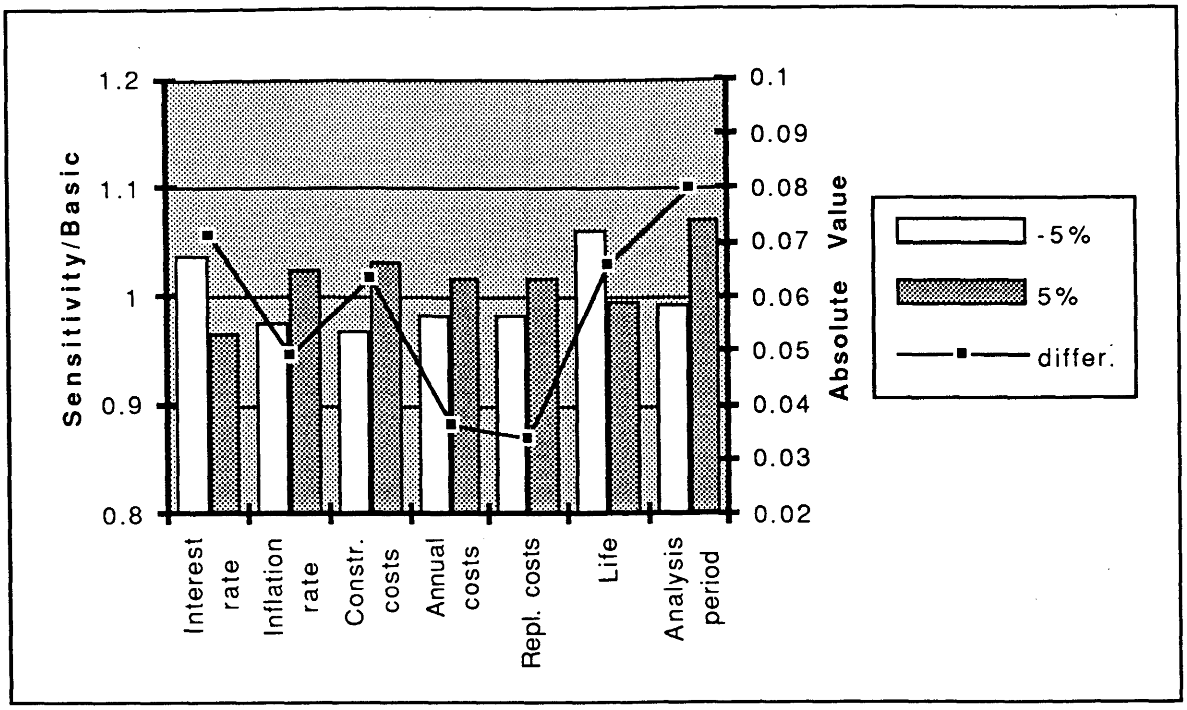


Chart 3.3-5: Impact of Changes in Parameters

Chart 3.3-5 shows the scale of impact that changing each of the parameters has on the total LCC. The bars represent the ratio of the sensitivity analysis results over the basic ones. The dots labeled "differ." represent the absolute value of difference between 5% and -5% results for each parameter.

From the chart, it can be seen that the parameter 7 (period of analysis) has the largest impact on the LCC. It is followed by parameters 1, 6 and 3 (interest rate, life expectancy and construction costs). However, when Charts 3.3-3 and 3.3-4 are considered together, it can be seen that the changes in parameters have very few effects on the order of the LCC ranking among options. Even though the cost components in four options differ substantially, the changes can almost never alter their ranking. Changes in ranking occur only as the result of the end of the useful life in Option 4.

Sensitivity Analysis with Parameters Increased or Decreased 25%

Table 3.3-22/Chart 3.3-6: LCC Summary with 25% Increase

Cost (1000$)	Option 1 Repaint	Option 2 Reglaze	Option 3 New Windows	Option 4 New Curtainwall	Average*
Basic	8,337	9,115	8,573	7,109	8,283
Interest rate	6,854	7,620	7,089	6,579	7,035
Inflation rate	9,668	10,458	9,937	7,629	9,423
Constr. costs	9,488	10,551	10,060	8,310	9,602
Annual costs	9,270	9,958	9,230	7,684	9,035
Repl. costs	9,360	10,081	9,413	7,109	8,991
Life	8,122	8,823	8,232	7,109	8,072
Analysis period	8,723	9,464	8,845	9,218	9,063

*The Average forms the basis for Chart 3.3-8

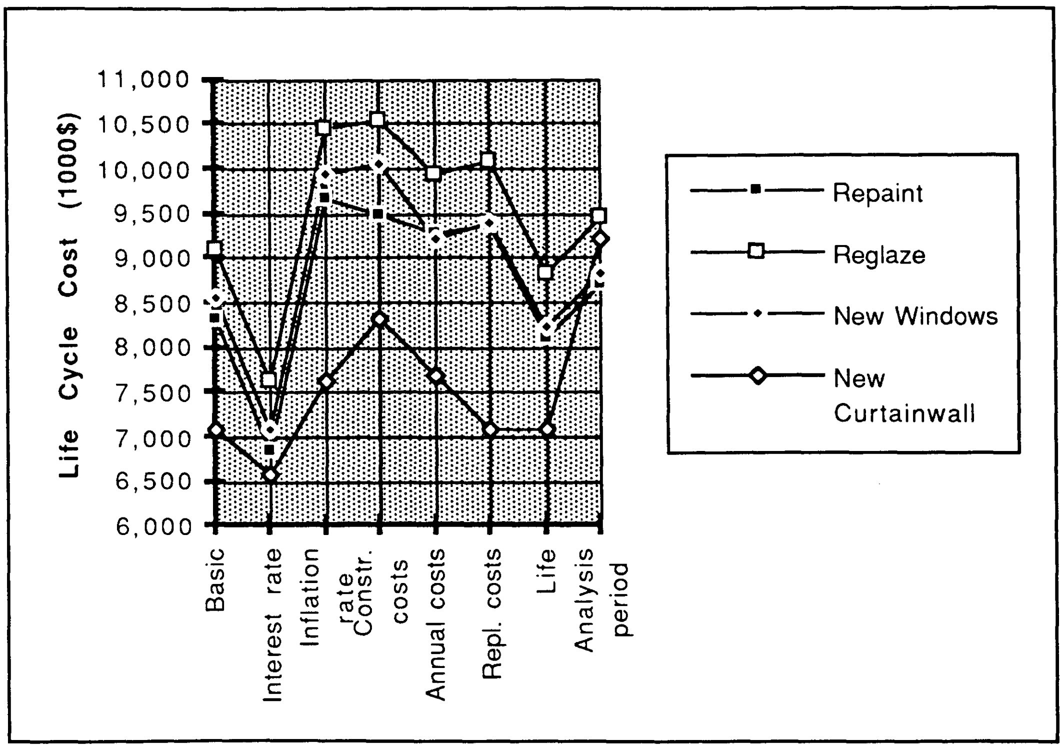
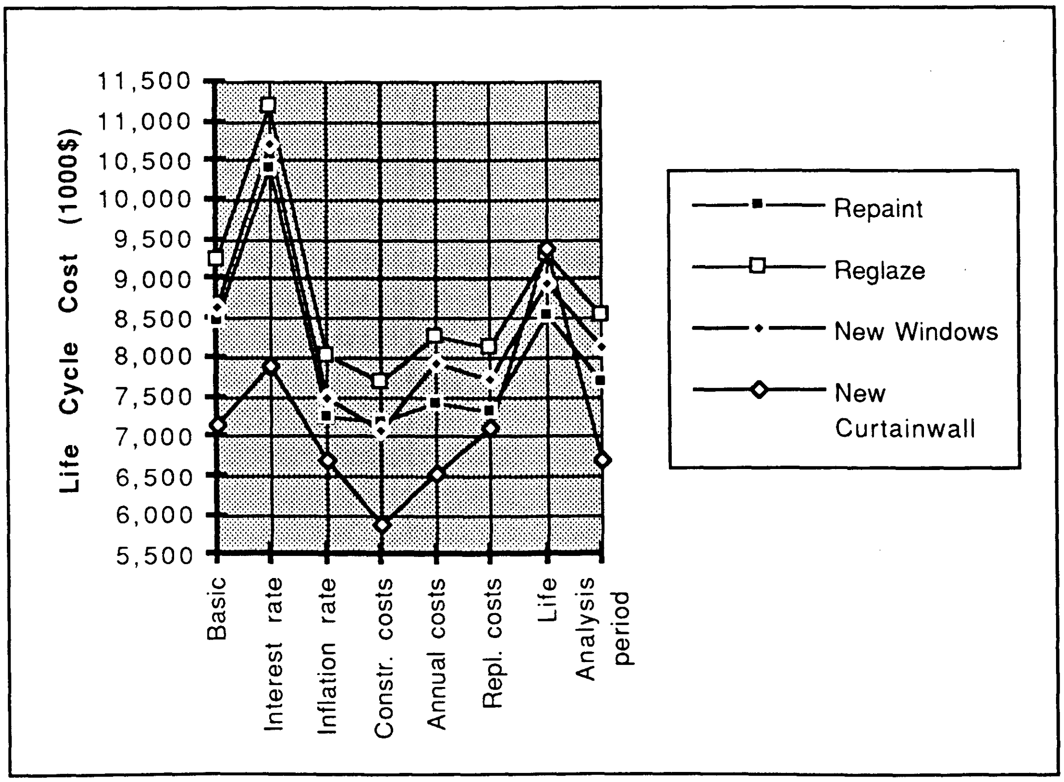


Table 3.3-23/Chart 3.3-7: LCC Summary with 25% Decrease

Cost (1000$)	Option 1 Repaint	Option 2 Reglaze	Option 3 New Windows	Option 4 New Curtainwall	Average*
Basic	8,459	9,246	8,643	7,153	8,375
Interest rate	10,392	11,197	10,718	7,907	10,054
Inflation rate	7,248	8,019	7,484	6,708	7,365
Constr. costs	7,185	7,679	7,087	5,907	6,965
Annual costs	7,404	8,272	7,916	6,533	7,531
Repl. costs	7,313	8,149	7,733	7,109	7,576
Life	8,546	9,329	8,954	9,398	9,057
Analysis period	7,704	8,544	8,128	6,719	7,774

*The Average forms the basis for Chart 3.3-8



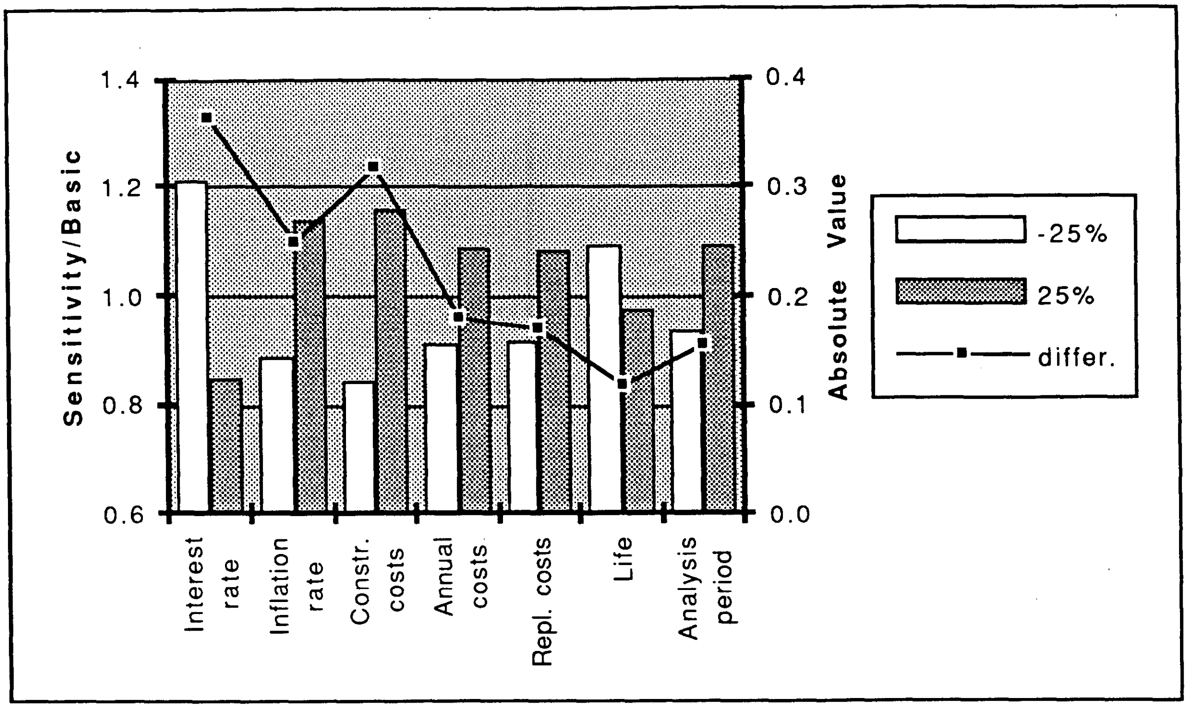


Chart 3.3-8: Impact of Changes in Parameters

As above, Chart 3.3-8 shows the scale of impact that a change each of the parameters has on the total LCC. Parameter 1 (interest rate) has the largest impact on the LCC, followed by parameters 3 and 2 (Initial construction cost and inflation rate). However, as was the case in the analysis with 5% change, the ranking of LCC is rarely influenced by these parameter changes. The largest shifts in ranking occur for parameters 6 and 7 (life expectancy and period of analysis).

Summary of Sensitivity Analysis

From these analyses, we can deduce that 1) the relationship between the period of analysis and the life expectancy of a system should be checked and verified. 2) Parameters that are equally applied to every option (interest and inflation rates) have little effect on the final rankings of the options. The rates have substantial effects on rankings when each of the options have different rates (as seen in Section 2.1).

3.3.5 Conclusions

The results of LCC analysis meet our expectations. The data of input are from the sources readily available to practicing professionals. The charts of LCC depict possible future profiles for each option.

The largest difficulty encountered is the lack of established maintenance cost data. We have tried several approaches to overcome this obstacle, but there will always remain the problem of reliability on this subject. The integrated company that both designs new buildings and manages existing ones, their ability to perform reliable LCC can be enhanced by developing their own database.

Also we attempted to identify the impacts of changing the parameters. The timing of the renovation work seems to have the largest effect on the ranking among the options. This is examined further in the next case study.

3.4 Appendix for Case Study No.2: Energy Model Calculations

3.4.1 Configurations of Curtain Wall Units

Building A

Unit Size and Number in One Wall

Section		Horizontal	Vertical	Subtotal	Total Area
Unit Size	(ft)	18	13		234
Unit Qty.	(module)	10	7	70	16380

Area per Unit

Item	Size on Center		Net Size		Total Area
	Horizontal	Vertical	Horizontal	Vertical	
	(ft)	(ft)	(ft)	(ft)	(sqft)
Glazing	18	8	17.33	7.67	132.89
Spandrel	18	5	17.33	4.67	80.89
Steel frame	0.17	0.17			20.22
Total	18	13			234.00

R & U value: N/S Wall

Item	Option	1	2	3	4
Spandrel	R-value	4.5	4.5	4.5	6.0
	U-value	0.2	0.2	0.2	0.2
	U*A	18.0	18.0	18.0	13.5
Steel frame	R-value	0.2	0.2	0.5	1.0
	U-value	5.0	5.0	2.0	1.0
	U*A	101.1	101.1	40.4	20.2
UA/Unit	(Btu/'F)	119.1	119.1	58.4	33.7
UA Total	(Btu/'F)	8336.0	8336.0	4089.4	2359.3

R & U value: N/S Glazing

Item	Option	1	2	3	4
Glazing	R-value	1.0	2.0	2.0	2.0
	U-value	1.0	0.5	0.5	0.5
	U*A	132.9	66.4	66.4	66.4
UA/Unit	(Btu/'F)	132.9	66.4	66.4	66.4
UA Total	(Btu/'F)	9302.2	4651.1	4651.1	4651.1

Building B

Unit Size and Number in One Wall

Section		Horizontal	Vertical	Subtotal	Total Area
Unit Size	(ft)	18	13		234
Unit Qty.	(module)	10	8	80	18720

Area per Unit

Item	Size on Center		Net Size		Total Area
	Horizontal	Vertical	Horizontal	Vertical	
	(ft)	(ft)	(ft)	(ft)	(sqft)
Glazing	18	5.5	17.33	5.33	92.44
Spandrel	18	7.5	17.33	7.17	124.22
Steel frame	0.17	0.17			17.33
Total	18	13			234.00

R & U value: N/S Wall

Item	Option	1	2	3	4
Spandrel	R-value	4.5	4.5	4.5	6.0
	U-value	0.2	0.2	0.2	0.2
	U*A	27.6	27.6	27.6	20.7
Steel frame	R-value	0.2	0.2	0.5	1.0
	U-value	5.0	5.0	2.0	1.0
	U*A	86.7	86.7	34.7	17.3
UA/Unit	(Btu/'F)	114.3	114.3	62.3	38.0
UA Total	(Btu/'F)	9141.7	9141.7	4981.7	3043.0

R & U value: N/S Glazing

Item	Option	1	2	3	4
Glazing	R-value	2.0	2.0	2.0	2.0
	U-value	0.5	0.5	0.5	0.5
	U*A	46.2	46.2	46.2	46.2
UA/Unit	(Btu/'F)	46.2	46.2	46.2	46.2
UA Total	(Btu/'F)	3697.8	3697.8	3697.8	3697.8

3.4.2 CLTD and SHGF

CLTD: Cooling Load Temperature Difference

CLTD: For 40' N latitude, July 21, T out 95°F, T in 78°F

Average for day-time (9 to 17 hrs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	AVE.
Roof																									
	19	14	10	7	4	2	0	0	4	10	19	29	39	48	56	62	65	64	61	54	46	38	30	24	43.6
Wall---Group G: Metal Curtain Wall																									
N	3	2	1	0	-1	2	7	8	9	12	15	18	21	23	24	24	25	26	22	15	11	9	7	5	20.9
S	4	2	1	0	-1	0	1	5	12	22	31	39	45	46	43	37	31	25	20	15	12	10	8	5	35.4
Wall---Group D: 4" Concrete + 1" Insulation																									
E	19	17	15	13	11	9	8	9	12	17	22	27	30	32	33	33	32	32	31	30	28	26	24	22	28.7
W	31	27	24	21	18	15	13	11	10	9	9	9	10	11	14	18	24	30	36	40	41	40	38	34	14.9
Glass and Doors																									
	1	0	-1	-2	-2	-2	-2	0	2	4	7	9	12	13	14	14	13	12	10	8	6	4	3	2	10.9

LM: CLTD Correction for Latitude and Month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Horizontal												
	-19	-14	-8	-3	1	2	1	-3	-8	-14	-19	-21
Wall												
N	-5	-5	-4	-2	0	1	0	-2	-4	-5	-5	-6
S	11	12	10	4	1	-1	1	4	10	12	11	10
Wall												
E	-9	-6	-3	0	0	1	0	0	-3	-6	-9	-10
W	-9	-6	-3	0	0	1	0	0	-3	-6	-9	-10

T: CLTD Correction for design Temperature

item		(°F)	(dF)
ti	room design temperature	75	3
to	outdoor temperature	88	
DR	daily range	16	
tom	outdoor mean temperature	80	-5
T	correction factor		-2

CLTD(cor): Corrected CLTD = CLTD + LM + T

Annual Daily Average

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVE.
Roof													
	22.6	27.6	33.6	38.6	42.6	43.6	42.6	38.6	33.6	27.6	22.6	20.6	32.8
Wall---Group G: Metal Curtain Wall													
N	13.9	13.9	14.9	16.9	18.9	19.9	18.9	16.9	14.9	13.9	13.9	12.9	15.8
S	44.4	45.4	43.4	37.4	34.4	32.4	34.4	37.4	43.4	45.4	44.4	43.4	40.5
Wall---Group D: 4" Concrete + 1" Insulation													
E	17.7	20.7	23.7	26.7	26.7	27.7	26.7	26.7	23.7	20.7	17.7	16.7	22.9
W	3.9	6.9	9.9	12.9	12.9	13.9	12.9	12.9	9.9	6.9	3.9	2.9	9.1
Glass and Doors													
	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9

SHGF: Solar Heat Gain Factor

SC: Shading Coefficients

Glass		thick.	Shading		SC
pane	type	thick.	indoor	class	coeffic.
Single	clear	1/8"	venet.	med.	0.64
Double	clear	1/4"	venet.	med.	0.48

SHGF: Max Solar Heat Gain Factor, for Sunlit Glass, (Btu/(hr sqft))

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVE.
N	24	27	32	36	38	44	40	37	33	28	24	22	32
S	246	221	176	115	74	60	72	111	171	215	243	252	163

CLF: Cooling Load Factors for Glass with Interior Shading

Average for day-time (9 to 17 hrs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	AVE.
N	8	7	6	6	7	73	66	65	73	80	86	89	89	86	82	75	78	91	24	18	15	13	11	10	0.84
S	4	4	3	3	3	9	16	23	38	58	75	83	80	68	50	35	27	19	11	9	8	7	6	5	0.55

3.4.3 Energy Cost of Building A

Conditions

An office building in New England (latitude 42'N)

Geometry

Item	Dimension	unit
E/W	180	(ft)
N/S	55	(ft)
Height	91	(ft)

Area and Volume

Item	Glazing	Wall	Total	unit
N wall	9302	7078	16380	(sqft)
S wall	9302	7078	16380	(sqft)
E wall			5005	(sqft)
W wall			5005	(sqft)
Roof			9900	(sqft)
Volume			900900	(cb ft)

Climatic conditions

outdoor	summer	dry-bulb	88	(°F)
		daily range	16	(°F)
		wet-bulb	71	(°F)
	winter		9	(°F)
indoor		dry-bulb	75	(°F)
		wet-bulb	60	(°F)
Degree-day			5634	(°F-day)

Construction

Roof construction

	Option	1	2	3	4
concrete		0.76	0.76	0.76	0.76
insul.		5.00	5.00	5.00	5.00
R total		5.76	5.76	5.76	5.76
U-value		0.17	0.17	0.17	0.17
U*A(roof)		1719	1719	1719	1719

North and South wall construction

	Option	1	2	3	4
U*A(nrth)		8336	8336	4089	2359
U*A(south)		8336	8336	4089	2359

East wall construction

	Option	1	2	3	4
concrete		0.57	0.57	0.57	0.57
Insul.		5.00	5.00	5.00	5.00
plaster		0.32	0.32	0.32	0.32
R total		5.89	5.89	5.89	5.89
U-value		0.17	0.17	0.17	0.17
U*A(east)		850	850	850	850

West wall construction

	Option	1	2	3	4
concrete		0.57	0.57	0.57	0.57
Insul.		5.00	5.00	5.00	5.00
plaster		0.32	0.32	0.32	0.32
R total		5.89	5.89	5.89	5.89
U-value		0.17	0.17	0.17	0.17
U*A(west)		850	850	850	850

Glazing

	Option	1	2	3	4
U*A(nrth)	(Btu/h)	9302	4651	4651	4651
U*A(south)	(Btu/h)	9302	4651	4651	4651

Infiltration

	Option	1	2	3	4
crack/unit	(in)	168	134	134	134
crack total	(in)	23520	18816	18816	18816
	(ft)	1960	1568	1568	1568

Cooling Loads

Conduction Thru Envelope

Formula; q = U*A*CLTD

	Option	1	2	3	4
Item	CLTD (°F)				
Roof	32.8	56375	56375	56375	56375
North wall	15.8	131710	131710	64612	37276
South wall	40.5	337610	337610	165620	95550
East wall	0.0	0	0	0	0
West wall	9.1	7733	7733	7733	7733
Glazing	8.9	165580	82790	82790	82790
TOTAL	(Btu/h)	699007	616217	377130	279724
	(MBtu/h)	0.70	0.62	0.38	0.28

Radiation Thru Envelope

Formula; q = A*SC*SHGF*CLF

	Option	1	2	3	4
Coefficients					
SC		0.64	0.48	0.48	0.48
SHGF	North	32	32	32	32
	South	163	163	163	163
CLF	North	0.84	0.84	0.84	0.84
	South	0.55	0.55	0.55	0.55

	Option	1	2	3	4
Item					
North wall		160445	120334	120334	120334
South wall		533724	400293	400293	400293
TOTAL	(Btu/h)	694169	520627	520627	520627
	(MBtu/h)	0.69	0.52	0.52	0.52

Cooling Load Summary

	Option	1	2	3	4
Item					
Conduction		0.70	0.62	0.38	0.28
Radiation		0.69	0.52	0.52	0.52
Sensible	sub total	1.39	1.14	0.90	0.80
Latent	30%	0.42	0.34	0.27	0.24
TOTAL	(MBtu/h)	1.81	1.48	1.17	1.04

Cooling Cost due to the Envelope
Assume Engine-driven Heat Pumps

Factor	unit	
COP		1.45
Natural Gas	(Btu/cbft)	1000
	($/k cbft)	6.16

	Option	1	2	3	4
Item	unit				
Load	(MBtu/h)	1.81	1.48	1.17	1.04
	(MBtu/yr)	15865	12946	10224	9114
Fuel	(Mcft/yr)	11	9	7	6
Cost	(k $/yr)	67	55	43	39

Heating Loads

Conduction Thru Envelope
Formula; q = U*A*dT

	Option	1	2	3	4
Item	dT (°F)				
Roof	66.0	113438	113438	113438	113438
North wall	66.0	550179	550179	269899	155711
South wall	66.0	550179	550179	269899	155711
East wall	0.0	0	0	0	0
West wall	66.0	56083	56083	56083	56083
Glazing	66.0	1227893	613947	613947	613947
TOTAL	(Btu/h)	2497773	1883826	1323266	1094890
	(MBtu/h)	2.50	1.88	1.32	1.09

Due to Infiltration

Formula; $q = m*Cp*dT$

	Option	1	2	3	4
air volume	(cbft/min)	3528	2822	2822	2822
	(cbft/h)	211680	169344	169344	169344
spec heat	(Btu/lb°F)	0.24	0.24	0.24	0.24
spec vol	(cbft/lb)	12.7	12.7	12.7	12.7
dT	(°F)	66.0	66.0	66.0	66.0
Load	(Btu/h)	264017	211213	211213	211213
	(MBtu/h)	0.26	0.21	0.21	0.21

Heating Load Summary

	Option	1	2	3	4
Item					
Conduction		2.50	1.88	1.32	1.09
Infiltration		0.26	0.21	0.21	0.21
TOTAL	(MBtu/h)	2.76	2.10	1.53	1.31

Heating Cost due to the Envelope

Factor	unit	
DD	(°F-day)	5634
Efficiency		0.65
Correction		0.61
Natural Gas	(Btu/cbft)	1000
	($/k cbft)	6.16

$F=24*DD*q*Cor/(Eff*HV*dT)$

	Option	1	2	3	4
Item	unit				
Load	(MBtu/h)	2.76	2.10	1.53	1.31
	(MBtu/yr)	3451	2618	1918	1632
Fuel	(Mcft/yr)	5	4	3	3
Cost	(k $/yr)	33	25	18	15

Cost Summary for Building A

	Option	1	2	3	4
Cost	unit				
Cooling	(k $/yr)	67	55	43	39
Heating	(k $/yr)	33	25	18	15
Total	(k $/yr)	100	80	62	54

3.4.4 Energy Cost of Building B

Conditions

An office building in New England (latitude 42°N)

Geometry

Item	Dimension	unit
E/W	180	(ft)
N/S	55	(ft)
Height	104	(ft)

Area and Volume

Item	Glazing	Wall	Total	unit
N wall	7396	11324	18720	(sqft)
S wall	7396	11324	18720	(sqft)
E wall			5720	(sqft)
W wall			5720	(sqft)
Roof			9900	(sqft)
Volume			1029600	(cb ft)

Climatic conditions

outdoor	summer	dry-bulb	88	(°F)
		daily range	16	(°F)
		wet-bulb	71	(°F)
	winter		9	(°F)
indoor		dry-bulb	75	(°F)
		wet-bulb	60	(°F)
Degree-day			5634	(°F-day)

Construction

Roof construction

	Option	1	2	3	4
concrete		0.76	0.76	0.76	0.76
insul.		5.00	5.00	5.00	5.00
R total		5.76	5.76	5.76	5.76
U-value		0.17	0.17	0.17	0.17
U*A(roof)		1719	1719	1719	1719

North and South wall construction

	Option	1	2	3	4
U*A(nrth)		9142	9142	4982	3043
U*A(south)		9142	9142	4982	3043

East wall construction

	Option	1	2	3	4
concrete		0.57	0.57	0.57	0.57
Insul.		5.00	5.00	5.00	5.00
plaster		0.32	0.32	0.32	0.32
R total		5.89	5.89	5.89	5.89
U-value		0.17	0.17	0.17	0.17
U*A(east)		971	971	971	971

West wall construction

	Option	1	2	3	4
concrete		0.57	0.57	0.57	0.57
Insul.		5.00	5.00	5.00	5.00
plaster		0.32	0.32	0.32	0.32
R total		5.89	5.89	5.89	5.89
U-value		0.17	0.17	0.17	0.17
U*A(west)		971	971	971	971

Glazing

	Option	1	2	3	4
U*A(nrth)	(Btu/h)	3698	3698	3698	3698
U*A(south)	(Btu/h)	3698	3698	3698	3698

Infiltration

	Option	1	2	3	4
crack/unit	(in)	0	134	134	134
crack total	(in)	0	21504	21504	21504
	(ft)	0	1792	1792	1792

Cooling Loads

Conduction Thru Envelope

Formula; q = U*A*CLTD

	Option	1	2	3	4
Item	CLTD (°F)				
Roof	32.8	56375	56375	56375	56375
North wall	15.8	144439	144439	78711	48079
South wall	40.5	370240	370240	201760	123240
East wall	22.9	22239	22239	22239	22239
West wall	0.0	0	0	0	0
Glazing	8.9	65820	65820	65820	65820
TOTAL	(Btu/h)	659114	659114	424906	315753
	(MBtu/h)	0.66	0.66	0.42	0.32

Radiation Thru Envelope

Formula; q = A*SC*SHGF*CLF

	Option	1	2	3	4
Coefficients					
SC		0.48	0.48	0.48	0.48
SHGF	North	32	32	32	32
	South	163	163	163	163
CLF	North	0.84	0.84	0.84	0.84
	South	0.55	0.55	0.55	0.55

	Option	1	2	3	4
North wall		95669	95669	95669	95669
South wall		318246	318246	318246	318246
TOTAL	(Btu/h)	413914	413914	413914	413914
	(MBtu/h)	0.41	0.41	0.41	0.41

Cooling Load Summary

	Option	1	2	3	4
Conduction		0.66	0.66	0.42	0.32
Radiation		0.41	0.41	0.41	0.41
Sensible	sub total	1.07	1.07	0.84	0.73
Latent	30%	0.32	0.32	0.25	0.22
TOTAL	(MBtu/h)	1.39	1.39	1.09	0.95

Cooling Cost due to the Envelope
Assume Engine-driven Heat Pumps

Factor	unit	
COP		1.45
Natural Gas	(Btu/cbft)	1000
	($/k cbft)	6.16

	Option	1	2	3	4
Load	(MBtu/h)	1.39	1.39	1.09	0.95
	(MBtu/yr)	12220	12220	9552	8309
Fuel	(Mcft/yr)	8	8	7	6
Cost	(k $/yr)	52	52	41	35

Heating Loads

Conduction Thru Envelope
Formula; $q = U*A*dT$

	Option	1	2	3	4
Item	dT (°F)				
Roof	66.0	113438	113438	113438	113438
North wall	66.0	603354	603354	328794	200836
South wall	66.0	603354	603354	328794	200836
East wall	66.0	64095	64095	64095	64095
West wall	0.0	0	0	0	0
Glazing	66.0	488107	488107	488107	488107
TOTAL	(Btu/h)	1872347	1872347	1323227	1067310
	(MBtu/h)	1.87	1.87	1.32	1.07

Due to Infiltration
Formula; q = m*Cp*dT

	Option	1	2	3	4
air volume	(cbft/min)	0	3226	3226	3226
	(cbft/h)	0	193536	193536	193536
spec heat	(Btu/lb°F)	0.24	0.24	0.24	0.24
spec vol	(cbft/lb)	12.7	12.7	12.7	12.7
dT	(°F)	66.0	66.0	66.0	66.0
Load	(Btu/h)	0	241387	241387	241387
	(MBtu/h)	0.00	0.24	0.24	0.24

Heating Load Summary

	Option	1	2	3	4
Conduction		1.87	1.87	1.32	1.07
Infiltration		0.00	0.24	0.24	0.24
TOTAL	(MBtu/h)	1.87	2.11	1.56	1.31

Heating Cost due to the Envelope

Factor	unit	
DD	(°F-day)	5634
Efficiency		0.65
Correction		0.61
Natural Gas	(Btu/cbft)	1000
	($/k cbft)	6.16

F=24*DD*q*Cor/(Eff*HV*dT)

	Option	1	2	3	4
Load	(MBtu/h)	1.87	2.11	1.56	1.31
	(MBtu/yr)	2340	2642	1955	1636
Fuel	(Mcft/yr)	4	4	3	3
Cost	(k $/yr)	22	25	19	15

Cost Summary for Building B

	Option	1	2	3	4
Cost	unit				
Cooling	(k $/yr)	52	52	41	35
Heating	(k $/yr)	22	25	19	15
Total	(k $/yr)	74	77	59	51

4. LIFE CYCLE COSTING AS A VALUE ASSESSMENT TOOL

4.1 Residual Value

4.1.1 Retrofit Approach

4.1.1.1 "Retrofit" LCC

We present here, the "Retrofit LCC", another approach to simplify and employ the LCC method. Unlike the attempts in the two preceding case studies which are basically "down-sizing" of the existing method, this is an LCC with a different objective. The main concept is to apply the LCC method to appraise the remaining value of existing buildings. The method will be unconventional in two ways:

1) It sets building models with preset LCC profile
2) It uses the LCC method "downstream" in a project's time scale

4.1.1.2 LCC Models

The notion that LCC takes into account "all" or "total" costs (Section 1.1) seems to force painful compilation of cost data. However, for the ordinary cost estimating, there are multiple methods of appraisal. One major method, or "detailed" method, quantifies all materials and labor of a project. The "area" method, or square-foot method, applies the cost per square-foot which is already defined for the type and size of the proposed project.

As there are different data needs for these two methods to estimate capital cost, there are different needs as well for the LCC. Currently, LCC analysis resembles the detailed method in many ways. However, an LCC version of the square-foot method, which has preset building types, might have its own advantages and disadvantages.

4.1.1.3 Objective of LCC

As already stated in Section 1.3, we could not find any proper reason to limit application of the LCC method to the design and concept stages of a building's life. The LCC analysis conducted at later stages will not have the ability to dramatically change the total costs of a project, especially as some are already spent, or "sunken", costs. However, it can still influence decision making and change the remaining LCC profile of that project.

Also, as the LCC method is, after all, just another appraisal technique, it can be conducted to evaluate an existing system or an entire building. We think that many mistakenly evaluate a building from its superficial systems, like exterior enclosure or interior finish. This may end to an unexpected expenditure in short future due to some system failure which could not be perceived. By applying the LCC method, one can assess the remaining value of a building, estimate the current and future conditions of each system. It is hoped that this LCC method might discourage construction of low quality buildings by offering an accurate tool to assess their residual value.

4.1.2 Assessing the Residual Value

4.1.2.1 Depreciation

In Means handbook (Means Square-foot Cost, 1994), depreciation is defined as "the loss of value due to any cause" as well as "the cost to cure." The cause may be physical, functional and/or external. As an example, it gives a table to estimate the percentage of residual value of the building's exterior system. The data from the table can be interpreted as shown in Chart 4.1-1.

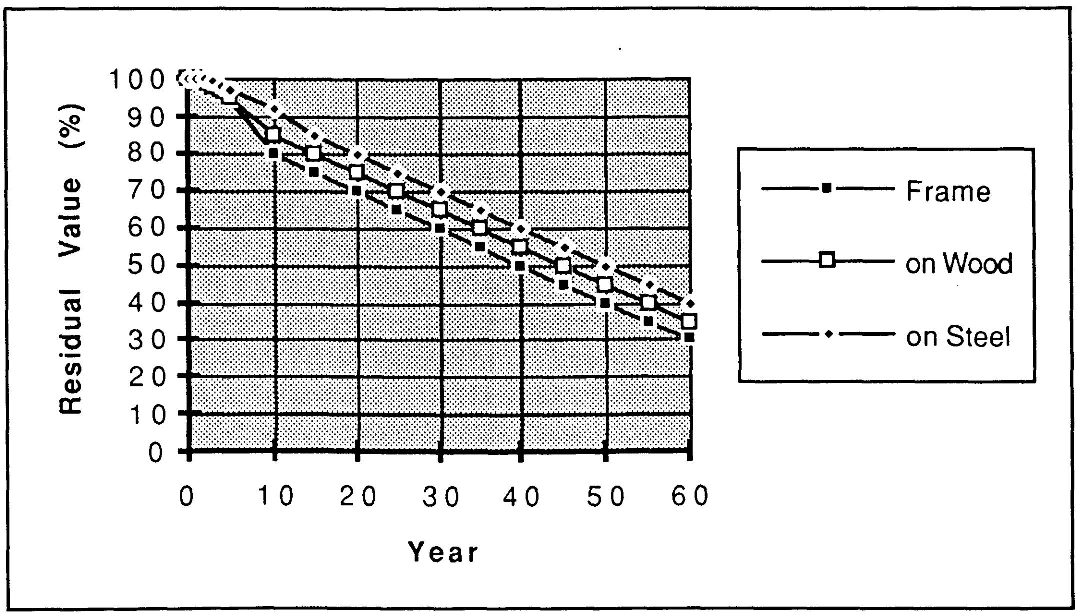


Chart 4.1-1: Residual Value of Exterior Closure

It can be seen from the chart that the concept of depreciation is "straight-line" in the long analysis period. We will use the same concept of depreciation using the "Percentage of the

Replacement" and "Life Expectancy until Replacement" figures from *'Life Cycle Cost Data'* (Dell'Isola, 1983).

Each system within the building has its specific rate of depreciation that can be defined as an annual depreciation rate;

$$dp = \frac{r}{L}$$

where

$dp =$ annual depreciation rate

$r =$ percentage of replacement

$L =$ Life expectancy until replacement

For example, a system that has a 20 year life and 100% replacement requirement and another with a10 year life and 50% replacement requirement both have the same straight depreciation rate of 5% per annum.

4.1.2.2 Residual Value

In Means (ibid.), the deterioration expressed by depreciation is divided into two categories: Curable and incurable. Curable deterioration can be remedied either by maintenance, repair or replacement. Incurable deterioration makes repair or replacement not economically feasible.

We will treat all deterioration as curable in the belief that it is not our task to make the economic decision but to present a different view point to help make a reasonable decision. Therefore the depreciation is defined as "the cost to cure." This cost for a specific year can be defined as:

$$C_n = V_0 \cdot (dp \times n)$$

where

$C_n =$ Cost to cure

$V_0 =$ initial Value

$dp =$ annual depreciation rate

$n =$ number of years

The residual value of a system can be obtained by subtracting the cost to cure from the initial cost:

$$V_n = V_0 - C_n$$

$$= V_0 \cdot [1 - (dp \times n)]$$

where

$V_n =$ residual Value

$V_0 =$ initial Value

A simple example of residual value calculation will be shown in Table 4.1-1. In this section, the system life expectancy and percentage requirement for replacement will be set at these figures.

Table 4.1-1: Residual Value

Code	Categories	Items	Repl. years	% Repl.	Depr. rate	0	1	2
010	Structure	Foundation	75	100%	1.3%	100%	99%	97%
020		Substructure	50	50%	1.0%	100%	99%	98%
030		Superstructure	50	100%	2.0%	100%	98%	96%
040	Architecture	Exterior Closure	40	100%	2.5%	100%	98%	95%
050		Roofing	20	100%	5.0%	100%	95%	90%
060		Interior Construction	20	100%	5.0%	100%	95%	90%
070		Conveying System	20	100%	5.0%	100%	95%	90%
081	MEP	Plumbing	20	50%	2.5%	100%	98%	95%
082		HVAC	20	50%	2.5%	100%	98%	95%
083		Fire Protection	25	100%	4.0%	100%	96%	92%
090		Electrical	30	100%	3.3%	100%	97%	93%
110	Other	Equipment	7	100%	14.3%	100%	86%	71%

4.1.2.3 Actual and Observed Age

The residual value is based on the age of a system. However, the age can be divided to the actual age and the observed age. The observed age of a system refers to the age that the system appears to be. Periodic maintenance, remodeling and renovation all tend to reduce the amount of deterioration that remains visible, thereby decreasing the observed age. Actual age on the other hand relates solely to the year that the system was built.

Ideally every system should be examined and have its age assessed before the analysis. The depreciation rate and the residual value are all based on the observed age. However for obvious reasons of limits in time and resources, many of the analyses will be forced to be done with only limited information of the actual age (or even less).

The lack of precise observed age may well cause a 10% or more fluctuation in the expected life expectancy of a system. However, as noted earlier, physical deterioration is only one of the factors in the actual loss of value. It should be emphasized that precision is not the primary objective in this method.

4.1.2.4 System Hierarchy

One should consider systems interaction, because a building is not merely a collection of many systems but of systems which rely upon and support each other. It is assumed that all sub-systems which rely on a larger main system must be replaced when the main system is replaced. For example, sub-systems "Interior Construction" and "Electrical" are renewed when the main system, "Superstructure", is replaced. An example of system hierarchy is given as Figure 4.1-1. The numbers correspond to the codes in Table 4.1-1, which conform to Construction Specifications Institute (CSI) Codes.

Of course, in actual renovation, there will be many exceptions that do not follow this assumption. However, as a general rule, the hierarchy shall hold.

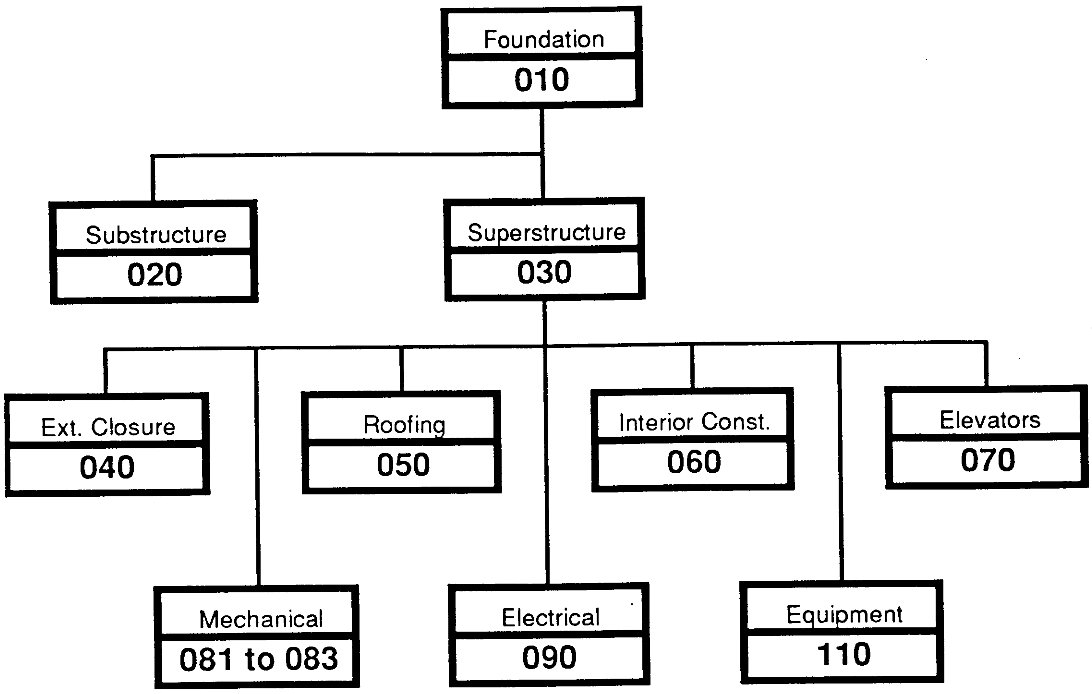


Figure 4.1-1: Diagram of System Hierarchy

4.1.2.5 Residual Value of Building

We define that a system must be cured before it reaches the designated point of replacement. Using the same examples, a system with 100% replacement requirement and a 5% annual depreciation rate must be cured after the year when its residual value is less than 5%. The one with a 50% requirement must be cured after the year it becomes less than 55%. The residual value of 0% or less is thought to cause additional damage to adjacent systems and thus should be avoided.

The conceptual diagram of the depreciation of building systems will be seen in the following chart (Chart 4.1-2). Because of the system hierarchy, values of all systems return to 100% at year 75.

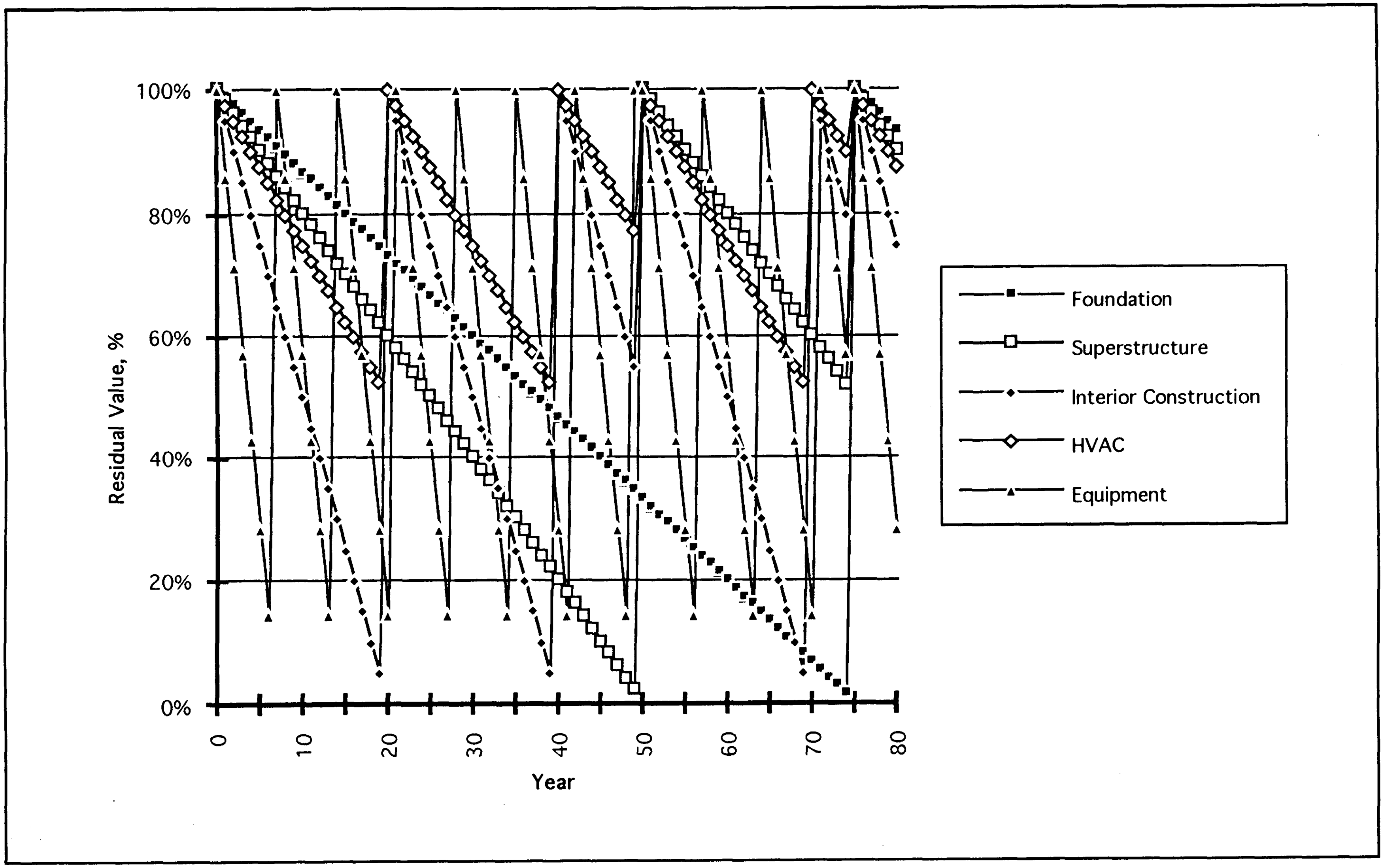


Chart 4.1-2: Residual Value of Building Systems

The residual value of each system can be obtained by multiplying the obtained rate of depreciation by the initial cost. The sum of the individual systems costs should generate the residual value of the entire building. A new building should generate a figure that begins to depreciate from 100% at year 0, or year of completion. We will show here a very simple example of a building with the initial value of $3,000,000, completed in the year 2000. The residual value for a new building is shown in Chart 4.1-3.

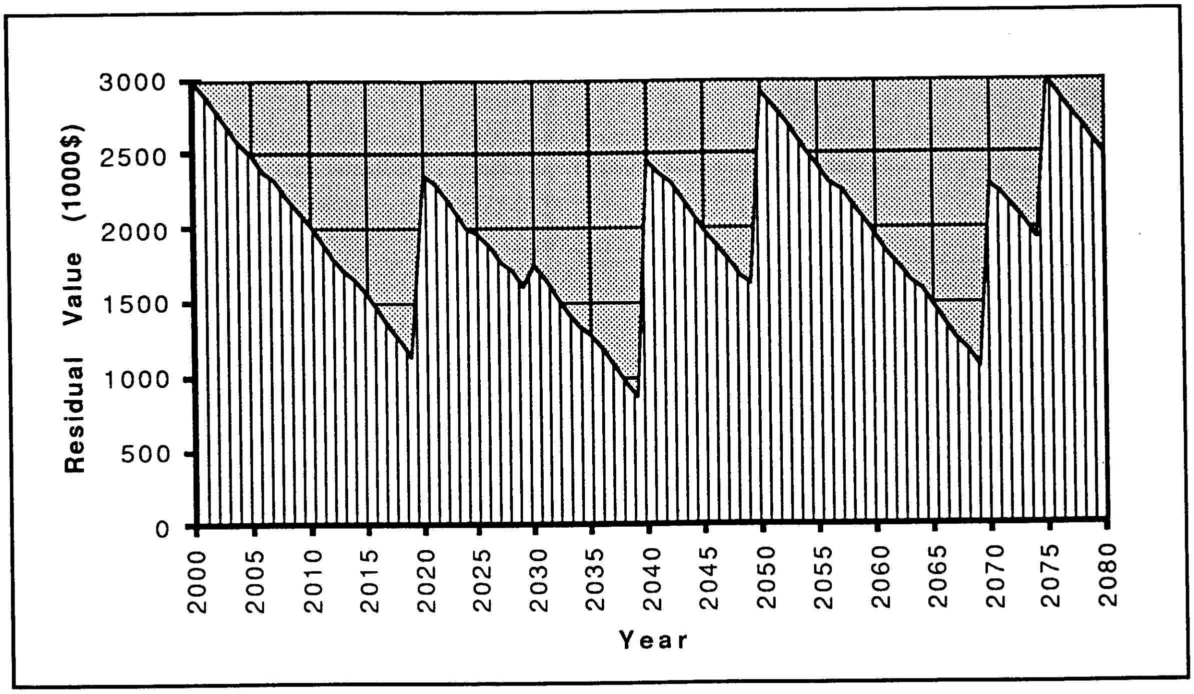


Chart 4.1-3: Residual Value: New Building

It can be seen from the chart that the value of the building approaches $3,000,000 at year 2050, when all systems except the foundation have been replaced (refer Chart 4.1-2). It actually reaches the original value at year 2075, when the building is virtually built anew. The owner must accept (or try to avoid) large expenditures at these two points in time.

Next, we assume another building with the same design and cost but constructed 30 years earlier, at year 1970. We assess its value and expected change in residual value at year 2000. To make the case more realistic, roof, interior, plumbing, HVAC and equipment systems are set to have been renovated 10 years earlier, at year 1990. This analysis is summarized in Charts 4.1-4 and 4.1-5.

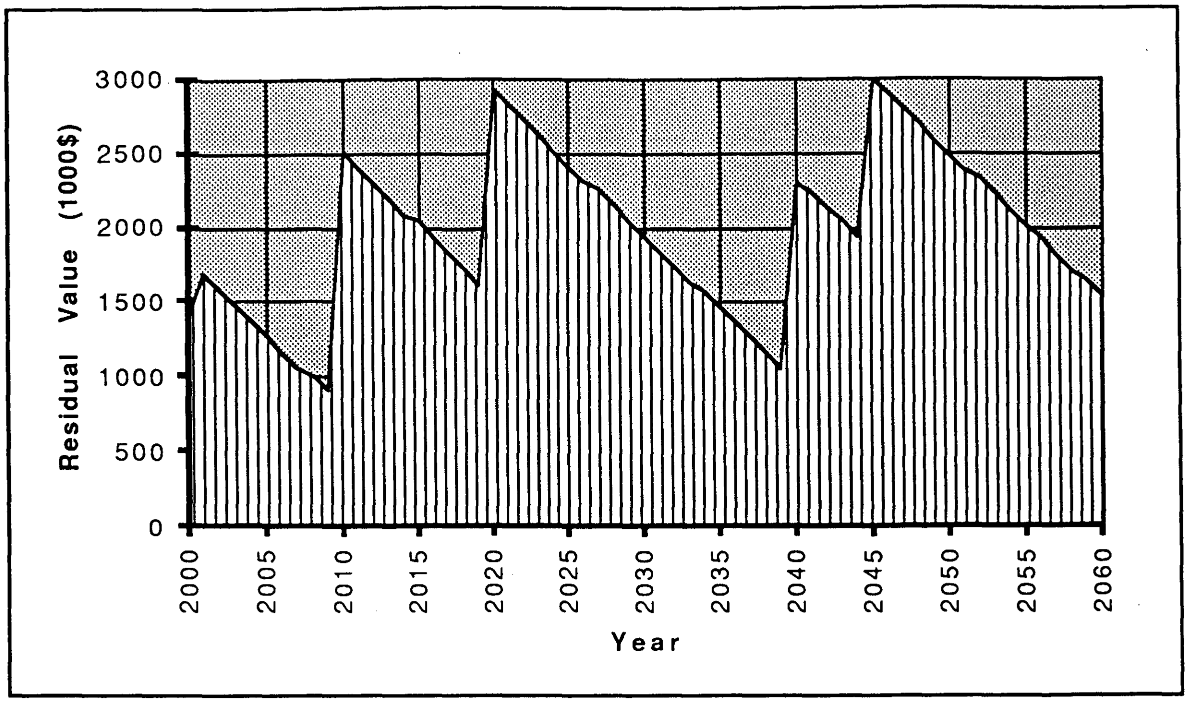


Chart 4.1-4: Residual Value: Retrofit

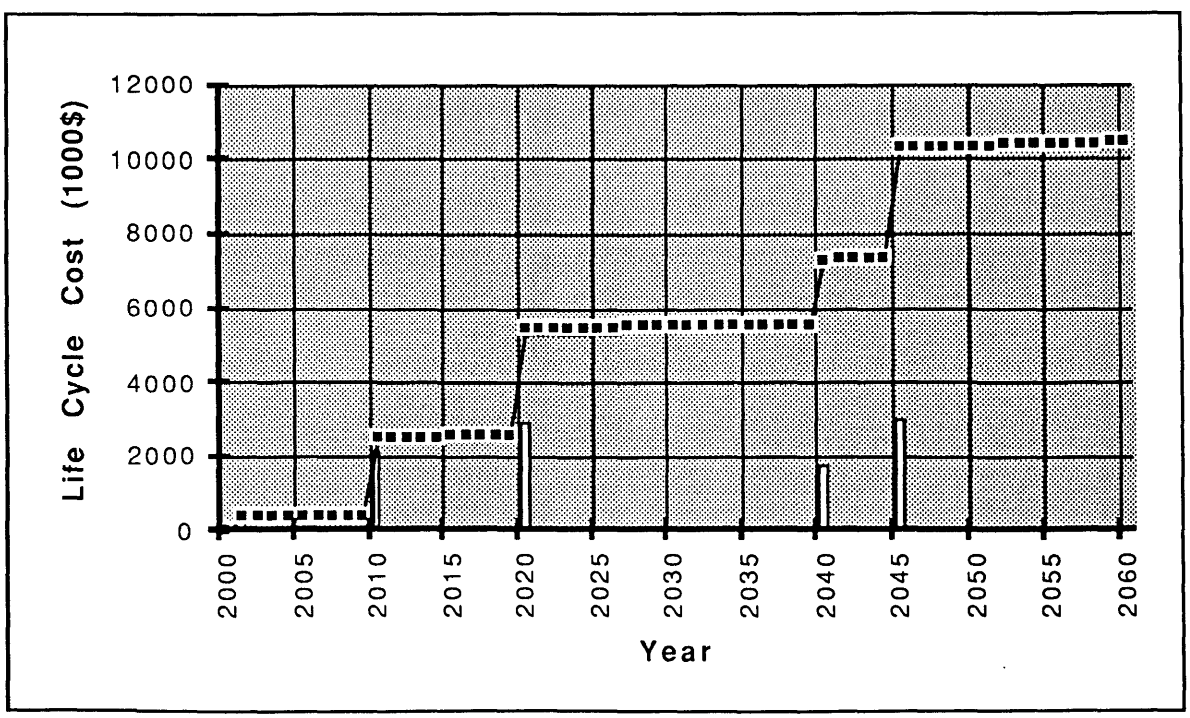


Chart 4.1-5: Life Cycle Cost: Retrofit

The value of the building at year 2000 is $1,410,000 — less than half of the construction cost of a new building. This may serve as an index to consider acquisition. Also it should be noted that the profile of the chart closely resembles the section from the year 2030 of Chart 4.1-3.

Each of the jumps in Chart 4.1-4 indicates a large renovation expense due to some major system which has reached an unacceptable level of deterioration and has been repaired or replaced. The cost of renovation and its cumulative sum can be seen in Chart 4.1-5. Chart 4.1-5 shows large expenditures at years 2010, 2020, 2040 and 2045. The low price of an old building may not be as attractive as before. This LCC profile, along with the residual value index, explains the actual consequences of the building acquisition.

4.2 Case study No.3: Retrofit LCC

4.2.1 Scope of the Case Study

This case study attempts to establish a new and simplified version of the LCC method, by applying it to the "square-foot" estimate format. During the study, we show that this new method can be used in a later stage of a project where the LCC method is currently thought to be inapplicable.

4.2.2 Establishing a Case

Assume a client is considering an acquisition of an existing building. What will be 1) the residual value per square foot of the building 2) the running costs for the coming 30 years?

We establish a fictional project to be used in this study. The project is a 5 story office building with 50,000 square feet of total floor area. The building is 25 years old, and has deteriorated accordingly in an average way. Some systems have been renovated more recently; the exterior window and the roof systems are 10 years old, while all of the interior construction is only 5 years old. As the structural components within a building are assumed to have a life expectancy of 75 years, we consider the running costs of the next 50 years.

4.2.3 Information Sources

We use *'Means Square-foot Costs'* (Means, 1995) as the source of cost data for the building models. It also provides the capital costs per square foot and their distribution among the systems. An example of the Means format is given in Table 4.2-1.

We use *'Life Cycle Cost Data'* (Dell'Isola, 1983) as the source of the LCC information. As already seen in Section 3-2, it provides considerable information on life cycle cost: maintenance cycle, annual maintenance cost, energy consideration, life expectancy and required percentage of replacement. Of these we use the last two items. An example of Dell'Isola's format is given in Table 4.2-2.

To set up building models, we limit the source of information to these two documents. Once the models are set, additional information must be supplied according to the actual buildings for which the LCC analysis is conducted.

Table 4.2-1: Format Example of Means Square Foot Costs

Model: 3 story building; story height 10'; 22,500 SF floor area

No.	System/ Component	Specifications	Unit	Unit Cost	Cost /SF	% / Sub-Tot
1.0	**FOUNDATIONS**					
.1	Footings/Foundations	Concrete footings and wall	SF Ground	6.15	2.05	
:		:	:	:	:	:
9.0	**ELECTRICAL**	:	:	:	:	:
.1	Service/Distribution	400 A	SF Floor	0.74	0.74	
.2	Lighting/Power	Incandescent fixtures	SF Floor	3.77	3.77	
.4	Special Electrical	Alarm systems & emergency light	SF Floor	0.56	0.56	7.9%
			SUB-TOTAL		64.52	100%
	GENERAL CONDITIONS (Overhead & Profit)			15%	9.68	
	ARCHITECT FEES			8%	5.94	
			TOTAL BUILDING COST		80.1	

Table 4.2-2: Format Example of Life Cycle Cost Data

	Item description	Unit	Maintenance description	Maintenance annual cost, $			Ene-rgy	Repl life	% Repl
				Lab	Mat	Eqp		yrs	%
04	*Exterior Closure*								
0422	*Curtain Walls*								
	Aluminum spandrel panel	WSF	Minor repair, cleaning (2.0 min every 6 yr)	.08	.01	.001	n/a	50	100
	Stainless steel panel	WSF	Minor repair, cleaning (2.0 min every 6 yr)	.08	.01	.001	n/a	50	100

4.2.4 LCC Retrofit Procedure

4.2.4.1 Understanding Systems

To the format by Means, we needed to add information on (1) the system life expectancy and (2) required percentage of replacement. However, the degree of detail does not necessarily match between our two sources. For example, the HVAC system is expressed in one line in Means book, but is described over several pages in *'Life Cycle Cost Data'*. For these cases, we have weighed the importance of system items with cost and function, then assigned figures considered to be appropriate.

Also, there was a need to consider systems' hierarchy, because a building is a collection of many systems which rely upon each other. It is more natural to assume that all sub-systems which rely on a larger main system would be replaced when the main system is replaced. For example, sub-systems "interior doors" and "wall finishes" should be renewed when the main system, "partitions", is replaced. It takes knowledge and experience to assign item weights and system hierarchy, both of which are crucial to set up the format of the "cost per square foot" LCC.

4.2.4.2 Format

For this example, we selected "apartment and office buildings" out of over 100 models from Means book. Each building type has three different models based on its size. Six models are set and shown here. Remaining models in Means book can easily be converted to this format. So, even for a different building type, the format can be set and an LCC analysis done easily.

Table 4.2-3: M010 Apartment, 1-3 Story

Model: 3 story building; story height 10'; 22,500 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl.	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	2.05	3.2%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.29	0.4%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.95	1.5%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Gypsum fireproofing, steel	0.79	1.2%	75	100%	
.5	Elevated Floors	Steel joists, concrete slab	5.23	8.1%	50	100%	
.7	Roof	Steel joists, metal deck	1.27	2.0%	30	100%	
.9	Stairs	Concrete filled metal pan	1.02	1.6%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	Face brick, concrete	6.55	10.2%	75	100%	
.6	Doors	Aluminum and glass	0.18	0.3%	40	100%	
.7	Window, Glasswall	Aluminum horiz. sliding	1.08	1.7%	35	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.76	1.2%	20	100%	
.7	Insulation	Perlite/EPS composite	0.35	0.5%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	2.80	4.3%	25	100%	
.4	Interior Doors	15% solid core, 85% hollow	4.30	6.7%	20	100%	
.5	Wall Finishes	70% paint, 25% vinyl, 5% tile	1.64	2.5%	12	100%	
.6	Floor Finishes	60% carp., 30% vinyl, 10% tile	3.51	5.4%	12	100%	
.7	Ceiling Finishes	Paint. gypsum board on channels	2.56	4.0%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	1.17	1.8%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	One hydraulic passenger elev.	2.90	4.5%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Kitchen, bathroom and fixtures	7.98	12.4%	35	100%	
.2	Fire Protection	Wet pipe sprinkler system	1.51	2.3%	25	100%	
.3	Heating	Oil fired hot water, baseboard	4.13	6.4%	20	100%	
.4	Cooling	Chill. water, air cool. condenser	5.31	8.2%	20	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	400 A	0.74	1.1%	75	100%	
.2	Lighting & Power	Incandescent fixtures	3.77	5.8%	20	100%	
.4	Special Electrical	Alarm systems & emerg. light	0.56	0.9%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	Kitchen cabinets	1.12	1.7%	30	100%	
		SUB-TOTAL	64.52	100%			
	General Conditions	15%	9.68				
	Architect Fees	8%	5.95				
		TOTAL BUILDING COST	80.15				

Table 4.2-4: M020 Apartment, 4-7 Story

Model: 6 story building; story height 10'-4"; 60,000 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl.	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	1.04	1.6%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.14	0.2%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.47	0.7%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Gypsum fireproofing, steel	1.31	2.0%	75	100%	
.5	Elevated Floors	Steel joists, concrete slab	8.53	12.8%	50	100%	
.7	Roof	Steel joists, metal deck	0.71	1.1%	30	100%	
.9	Stairs	Concrete filled metal pan	1.01	1.5%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	Face brick, concrete	6.00	9.0%	75	100%	
.6	Doors	Aluminum and glass	0.19	0.3%	40	100%	
.7	Window, Glasswall	Aluminum horiz. sliding	1.18	1.8%	35	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.37	0.6%	20	100%	
.7	Insulation	Perlite/EPS composite	0.17	0.3%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	3.56	5.3%	25	100%	
.4	Interior Doors	15% solid core, 85% hollow	5.13	7.7%	20	100%	
.5	Wall Finishes	70% paint, 25% vinyl, 5% tile	2.01	3.0%	12	100%	
.6	Floor Finishes	60% carp., 30% vinyl, 10% tile	3.51	5.3%	12	100%	
.7	Ceiling Finishes	Paint. gypsum board on channels	2.42	3.6%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	1.10	1.6%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	Two geared passenger elev.	4.10	6.1%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Kitchen, bathroom and fixtures	7.30	10.9%	35	100%	
.2	Fire Protection	Stand + wet pipe sprinkler	1.55	2.3%	20	100%	
.3	Heating	Oil fired hot water, baseboard	3.63	5.4%	20	100%	
.4	Cooling	Chilled water, air cooled condens	5.16	7.7%	20	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	1000 A	0.80	1.2%	75	100%	
.2	Lighting & Power	Incandescent fixtures	3.75	5.6%	20	100%	
.4	Special Electrical	Alarm, emerg. light + intercom	0.32	0.5%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	Kitchen cabinets	1.34	2.0%	30	100%	
		SUB-TOTAL	66.80	100%			
	General Conditions	15%	10.02				
	Architect Fees	7%	5.38				
		TOTAL BUILDING COST	82.20				

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Table 4.2-5: M030 Apartment, 8-24 Story

Model: 15 story building; story height 10'-6"; 162,000 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl.	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	0.67	0.9%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.05	0.1%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.19	0.3%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Gypsum fireproofing, steel	2.22	3.1%	75	100%	
.5	Elevated Floors	Steel joists, concrete slab	7.07	9.7%	50	100%	
.7	Roof	Steel joists, metal deck	0.22	0.3%	30	100%	
.9	Stairs	Concrete filled metal pan	1.01	1.4%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	Ribbed precast concrete panel	6.04	8.3%	75	100%	
.6	Doors	Aluminum and glass	1.28	1.8%	40	100%	
.7	Window, Glasswall	Aluminum horiz. sliding	0.97	1.3%	35	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.14	0.2%	20	100%	
.7	Insulation	Perlite/EPS composite	0.07	0.1%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	7.56	10.4%	25	100%	
.4	Interior Doors	15% solid core, 85% hollow	5.13	7.0%	20	100%	
.5	Wall Finishes	70% paint, 25% vinyl, 5% tile	1.99	2.7%	12	100%	
.6	Floor Finishes	60% carp, 30% vinyl, 10% tile	3.51	4.8%	12	100%	
.7	Ceiling Finishes	Paint. gypsum board on channels	2.42	3.3%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	0.98	1.3%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	Four geared passenger elev.	6.21	8.5%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Kitchen, bathroom and fixtures	7.45	10.2%	35	100%	
.2	Fire Protection	Stand + wet pipe sprinkler	1.85	2.5%	20	100%	
.3	Heating	Oil fired hot water, baseboard	3.63	5.0%	20	100%	
.4	Cooling	Chill. water, air cool. condenser	5.16	7.1%	20	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	1200 A	0.41	0.6%	75	100%	
.2	Lighting & Power	Incandescent fixtures	4.03	5.5%	20	100%	
.4	Special Electrical	Alarm, em. lite, antna., intcom	1.28	1.8%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	Kitchen cabinets	1.24	1.7%	30	100%	
		SUB-TOTAL	72.78	100%			
	General Conditions	15%	10.92				
	Architect Fees	6%	5.05				
		TOTAL BUILDING COST	88.75				

Table 4.2-6: M460 Office, 2-4 Story

Model: 3 story building; story height 12'; 58,000 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl.	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	1.02	2.0%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.29	0.6%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.95	1.9%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Fireproofing, steel	0.57	1.1%	75	100%	
.5	Elevated Floors	Steel joists, concrete slab	4.39	8.6%	50	100%	
.7	Roof	Steel joists, metal deck	1.02	2.0%	30	100%	
.9	Stairs	Concrete filled metal pan	0.56	1.1%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	Face brick, concrete	5.01	9.8%	75	100%	
.6	Doors	Aluminum and glass	0.21	0.4%	40	100%	
.7	Window, Glasswall	Steel outward projecting	1.24	2.4%	35	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.61	1.2%	20	100%	
.7	Insulation	Perlite/EPS composite	0.35	0.7%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	1.46	2.9%	25	100%	
.4	Interior Doors	Single leaf hollow metal	2.51	4.9%	30	100%	
.5	Wall Finishes	60% vinyl, 40% paint	0.83	1.6%	12	100%	
.6	Floor Finishes	60% carp, 30% vinyl, 10% tile	4.23	8.3%	12	100%	
.7	Ceiling Finishes	Mineral fiber tile on zee bars	3.15	6.2%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	0.77	1.5%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	Two hydraulic passenger elev.	2.37	4.6%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Toilet and service fixtures	1.36	2.7%	35	100%	
.2	Fire Protection	Stand pipe + hose system	0.20	0.4%	20	100%	
.3	Heating	Included in 8.4	0.00	0.0%	0	0%	
.4	Cooling	Gas heating, electric cooling	10.17	20.0%	15	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	1000 A	0.82	1.6%	75	100%	
.2	Lighting & Power	Fluorescent fixtures	6.70	13.1%	20	100%	
.4	Special Electrical	Alarm & emergency light	0.18	0.4%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	N/A	0.00	0.0%	0	0%	
		SUB-TOTAL	50.97	100%			
	General Conditions	15%	7.65				
	Architect Fees	7%	4.13				
		TOTAL BUILDING COST	62.75				

Table 4.2-7: M470 Office, 5-10 Story

Model: 8 story building; story height 12'; 100,000 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	0.91	1.6%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.12	0.2%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.36	0.6%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Steel columns w/ fireproofing	1.61	2.8%	75	100%	
.5	Elevated Floors	Concr. slab w/ metal deck/beam	7.72	13.5%	50	100%	
.7	Roof	Steel joists, metal deck	0.41	0.7%	30	100%	
.9	Stairs	Concrete filled metal pan	0.78	1.4%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	Precast concrete panels	5.58	9.8%	75	100%	
.6	Doors	Double alum./glass w/ transoms	0.12	0.2%	40	100%	
.7	Window, Glasswall	Vertical pivoted steel	1.83	3.2%	35	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.24	0.4%	20	100%	
.7	Insulation	Perlite/EPS composite	0.13	0.2%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	1.43	2.5%	25	100%	
.4	Interior Doors	Single leaf hollow metal	1.25	2.2%	30	100%	
.5	Wall Finishes	60% vinyl, 40% paint	0.69	1.2%	12	100%	
.6	Floor Finishes	60% carp, 30% vinyl, 10% tile	4.23	7.4%	12	100%	
.7	Ceiling Finishes	Mineral fiber tile on zee bars	3.15	5.5%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	0.95	1.7%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	Four geared passenger elev.	6.21	10.9%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Toilet and service fixtures	0.98	1.7%	35	100%	
.2	Fire Protection	Stand pipe + hose system	0.14	0.2%	20	100%	
.3	Heating	Included in 8.4	0.00	0.0%	0	0%	
.4	Cooling	Gas heating, electric cooling	10.17	17.8%	15	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	1600 A	0.72	1.3%	75	100%	
.2	Lighting & Power	Fluorescent fixtures	6.72	11.8%	20	100%	
.4	Special Electrical	Alarm & emergency light	0.65	1.1%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	N/A	0.00	0.0%	0	0%	
		SUB-TOTAL	57.10	100%			
	General Conditions	15%	8.57				
	Architect Fees	6%	3.93				
		TOTAL BUILDING COST	69.60				

Table 4.2-8: M480 Office, 11-20 Story

Model: 15 story building; story height 10'; 140,000 SF floor area

No.	System/ Components	Specifications	$/SF	% of Sub-T	Repl. yrs	% Repl.	Age
1.0	**FOUNDATIONS**						
.1	Footings + Found.	Concrete footings and wall	1.17	1.7%	75	100%	
.9	Excav. + Backfill	Site preparation and trench	0.06	0.1%	75	100%	
2.0	**SUB-STRUCTURE**						
.1	Slab on Grade	4" Concrete	0.19	0.3%	50	50%	
3.0	**SUPER-STRUCTURE**						
.1	Columns + Beams	Steel columns w/ fireproofing	2.38	3.4%	75	100%	
.5	Elevated Floors	Concr. slab w/ metal deck/beam	11.11	15.8%	50	100%	
.7	Roof	Steel joists, metal deck	0.25	0.4%	30	100%	
.9	Stairs	Concrete filled metal pan	1.35	1.9%	40	100%	
4.0	**EXTERIOR CLOSURE**						
.1	Walls	N/A	0.00	0.0%	0	100%	
.6	Doors	Double aluminum & glass	0.79	1.1%	40	100%	
.7	Window, Glasswall	Dbl., heat-absorb., tinted pane	10.59	15.1%	40	100%	
5.0	**ROOFING**						
.1	Roof Coverings	Built-up tar and gravel	0.25	0.4%	20	100%	
.7	Insulation	Perlite/EPS composite	0.07	0.1%	40	100%	
6.0	**INTERIOR CONSTRUCTION**						
.1	Partitions	Gypsum board on metal studs	1.38	2.0%	25	100%	
.4	Interior Doors	Single leaf hollow metal	1.25	1.8%	30	100%	
.5	Wall Finishes	60% vinyl, 40% paint	0.55	0.8%	12	100%	
.6	Floor Finishes	60% carp., 30% vinyl, 10% tile	4.23	6.0%	12	100%	
.7	Ceiling Finishes	Mineral fiber tile on zee bars	3.15	4.5%	10	100%	
.9	Int Surf./Ext Wall	Painted gypsum board on furring	0.93	1.3%	25	100%	
7.0	**CONVEYING**						
.1	Elevators	Four geared passenger elev.	7.19	10.2%	20	100%	
8.0	**MECHANICAL**						
.1	Plumbing	Toilet and service fixtures	1.33	1.9%	35	100%	
.2	Fire Protection	Standpipe/hose + sprinkler	2.68	3.8%	20	100%	
.3	Heating	Oil fired hot water	2.76	3.9%	25	100%	
.4	Cooling	Chilled water, fan coil units	8.33	11.8%	20	100%	
9.0	**ELECTRICAL**						
.1	Service & Distr.	2400 A	1.02	1.5%	75	100%	
.2	Lighting & Power	Fluorescent fixtures	6.70	9.5%	20	100%	
.4	Special Electrical	Alarm & emergency light	0.63	0.9%	15	100%	
11.0	**SPECIAL CONSTRUCTION**						
.1	Specialties	N/A	0.00	0.0%	0	0%	
		SUB-TOTAL	70.34	100%			
	General Conditions	15%	10.55				
	Architect Fees	6%	4.86				
		TOTAL BUILDING COST	85.75				

4.2.4.3 System Hierarchy

All systems categorized in the building models must be assigned an appropriate order of hierarchy. Because of the increased number of system entries, the diagrams will be more complex than the example in Section 4.1. However, basically it is still the same. The systems in the lower level will be replaced simultaneously when the system directly above is replaced. For example, the exterior windows and doors will be replaced when the exterior wall system, which is the system directly above them, is replaced.

The system diagrams for our two building types, apartment and office, are given in Figures 4.2-1 and 4.2-2.

4.2.4.4 Calculation

Now, the information for our case must be interpreted to fit into a building model. The project was established to be a 5 story office building, thus the model "M470 Office, 5-10 Story", which is given in Table 4.2-7, is used. The age of each system should be assessed.

Summing the residual value for each system, the sub-total of the residual value of the building is obtained. The original value of the building certainly included "General Conditions" and "Architect Fees." Therefore, the same percentage increase should be accounted accordingly for the sub-total. Thus, the total residual value of the project at the point of acquisition (year 0) is obtained.

The expected "cost to cure" is calculated from year 1. At year 0, some of the systems may have a residual value of 0% or less (though expressed 0%). These systems must be cured to the fully functional condition, thus the "cost to cure" is calculated and added up. This method is summarized in Table 4.2-9, and calculation examples from year 0 to 5 are shown.

As already explained, the deterioration below designated level is avoided. If the expected replacement percentage of a system is 100%, we assume renovation work to occur before it reaches the residual value of 0%; if the replacement percentage is 25%, renovation should occur before residual value reaches 75%. Each intermittent "cost to cure" is added cumulatively to give a "life cycle cost to cure." They are also expressed in the average annual cost. Table 4.2-10 shows the calculation examples from year 0 to 5.

The running cost is estimated using the format of the square-foot LCC. Table 4.2-11 shows the calculation examples of running costs results.

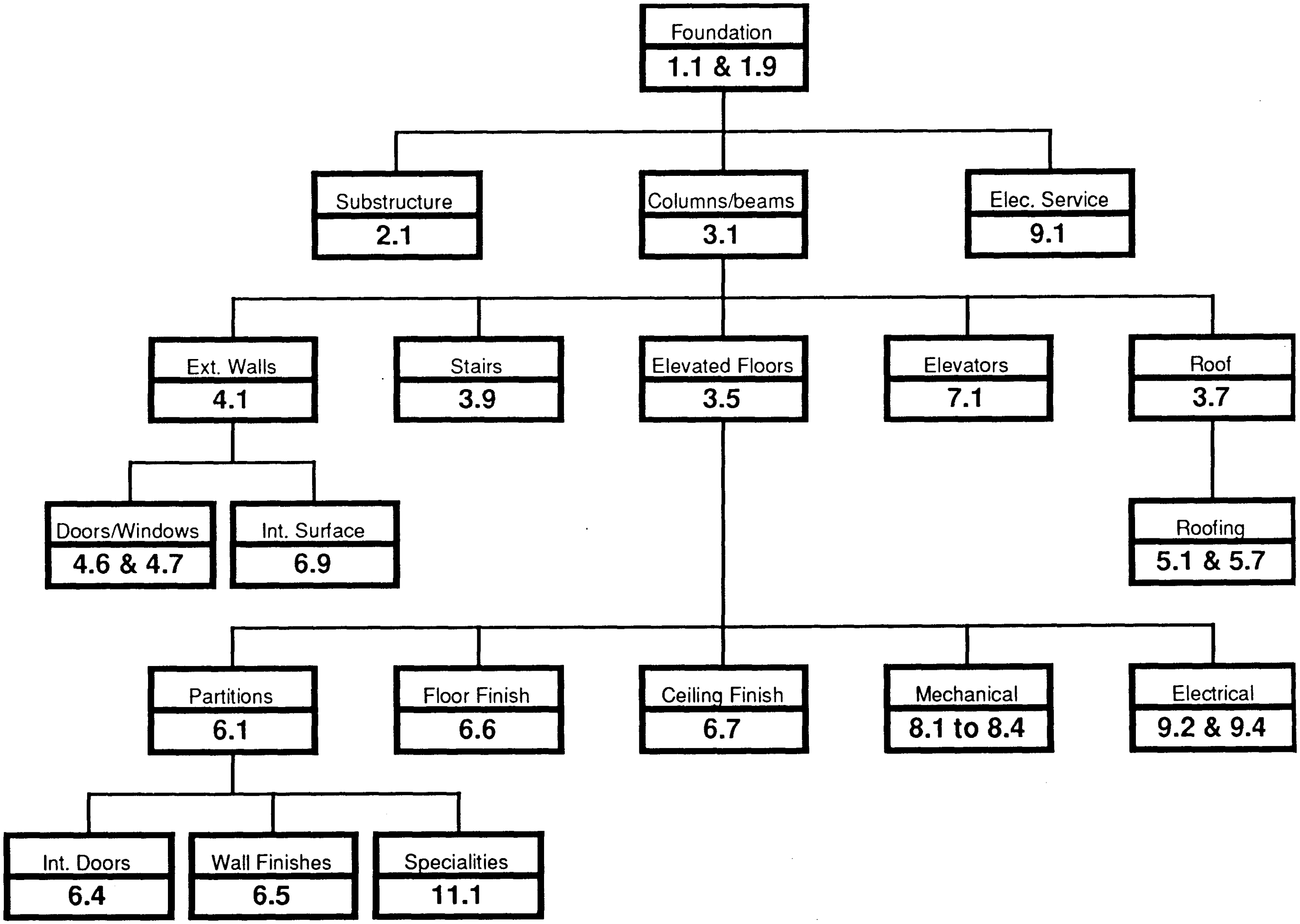

Figure 4.2-1: System Hierarchy: Apartment

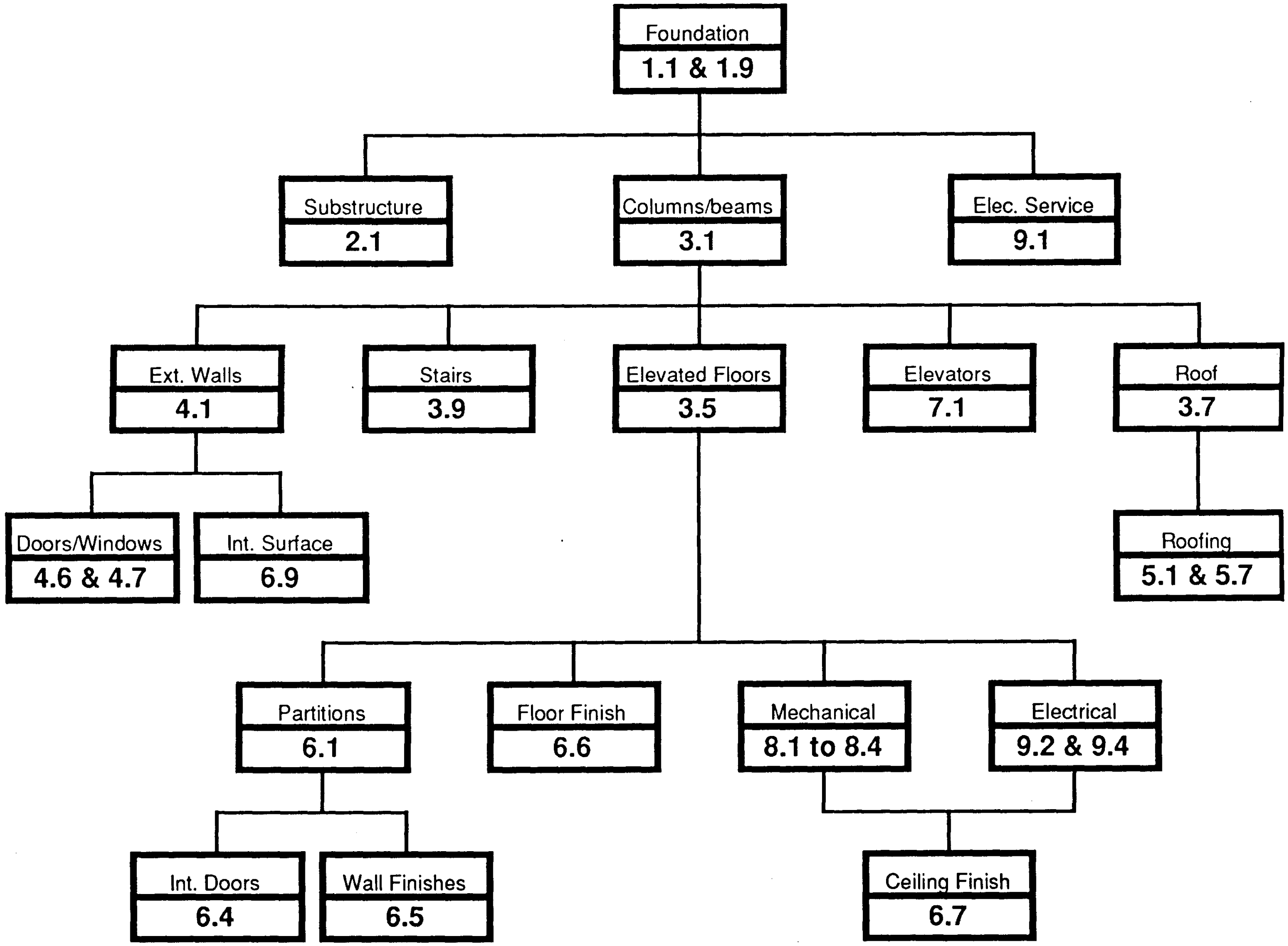

Figure 4.2-2: System Hierarchy: Offic

Table 4.2-9: Example of Sum of Residual Value

No.	System/ Components	Year	0	1	2	3	4	5
1.0	**FOUNDATIONS**							
.1	Footings + Foundations		.61	.59	.58	.57	.56	.55
"	"	"	"	"	"	"	"	"
11.0	**SPECIAL CONSTRUCTION**		"	"	"	"	"	"
.1	Specialties		.00	.00	.00	.00	.00	.00
	SUB TOTAL	($/SF)	20.18	42.81	40.17	37.54	34.90	35.42
	TOTAL	($/SF)	24.60	52.18	48.97	45.75	42.54	43.17
	Residual Value	(%)	35%	75%	70%	66%	61%	62%

Table 4.2-10: Example of LCC to Cure

No.	System/ Components	Year	0	1	2	3	4	5
1.0	**FOUNDATIONS**							
.1	Footings + Foundations		.0	.0	.0	.0	.0	.0
"	"	"	"	"	"	"	"	"
11.0	**SPECIAL CONSTRUCTION**		"	"	"	"	"	"
.1	Specialties		.0	.0	.0	.0	.0	.0
	Cost to Cure	($/SF)	.0	23.9	.0	.0	.0	4.7
	Cost to Cure with Fees	($/SF)	.0	29.1	.0	.0	.0	5.7
	Life Cycle Cost	($/SF)	.0	29.1	29.1	29.1	29.1	34.8
	Average Annual Cost	($/SF)	.0	29.1	14.6	9.7	7.3	7.0

Table 4.2-11: Example of Running Cost Results

Cost	Year	1	2	3	"	48	49	50
Cost to Cure	($/SF)	23.9	.0	.0	"	.0	4.9	52.0
Cost to Cure with Fees	($/SF)	29.1	.0	.0	"	.0	6.0	63.4
Life Cycle Cost	($/SF)	29.1	29.1	29.1	"	181.7	187.7	251.0
Average Annual Cost	($/SF)	29.1	14.6	9.7	"	3.8	3.8	5.0

4.2.4.5 Time Value of Money

This particular analysis has omitted several aspects of the ordinary LCC method. The analysis has omitted the annual maintenance and energy costs. Probably the largest omission lies in ignoring the "time value of money". It does not use interest, inflation or discount rates. Also all the costs are computed at the current value.

These omissions may seem to be surprising, however there are scholars like Brandon (Spedding, ed., 1987) who advocates separation of LCC and "time value of money" concept. Additionally, it should be noted that the result of the sensitivity analysis from case study No.2 indicated that the parameter changes in inflation rate do not affect the ranking result of the LCC comparisons. Instead, it indicated the importance of the "analysis period" and "life expectancy" or the "timing of renovation" for each system. The omission of the "time value of money" comes from the concept of renovation work. Renovation is treated as an attempt to remedy the depreciation.

Application of the Present Value factor to the final figures of the obtained table can be done easily. However, one addition to the parameter will necessitate another to maintain consistency. Instead, we preferred to maintain simplicity. Just an example may not serve as proof, but even if we had eliminated parameters 1, 2 and 4 (interest rate, inflation rate and annual cost) in Case Study No. 2, the rank of the LCC remains almost unchanged with a similar LCC profile. This is easily perceived by comparing Chart 4.2-1 (basic LCC) and Chart 4.2-2 (LCC with parameters 1, 2 & 4 eliminated).

4.2.5 Results

For this analysis, the value of the project at the purchase date, year 0, is $24.31 per square foot. Therefore its appropriate value should be $1,215,500. Of course, the market price will be different, and we will not discuss further about the difference between value and market price. However, those who know the market well will be able to assess the price from this value index. The profile of residual value is expressed in Chart 4.2-3, and from the chart we estimate substantial renovation work at years 20, 25 and 50.

For the 50-year analysis period, the cost of renovation totals to $251.04 per square foot or $12,552,000 for the entire building. This can also be expressed as an annual average expense of $5.02 per square foot or $251,000 per annum for the entire building. Chart 4.2-4 describes the profile of the running cost.

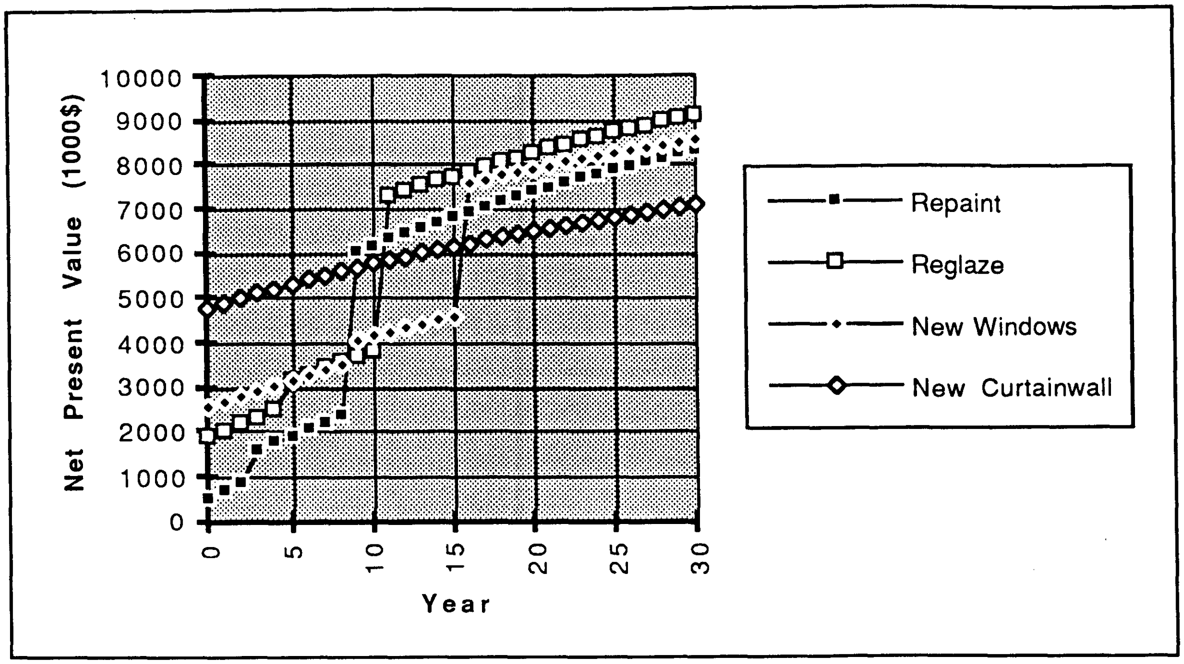

Chart 4.2-1: Basic LCC Profile

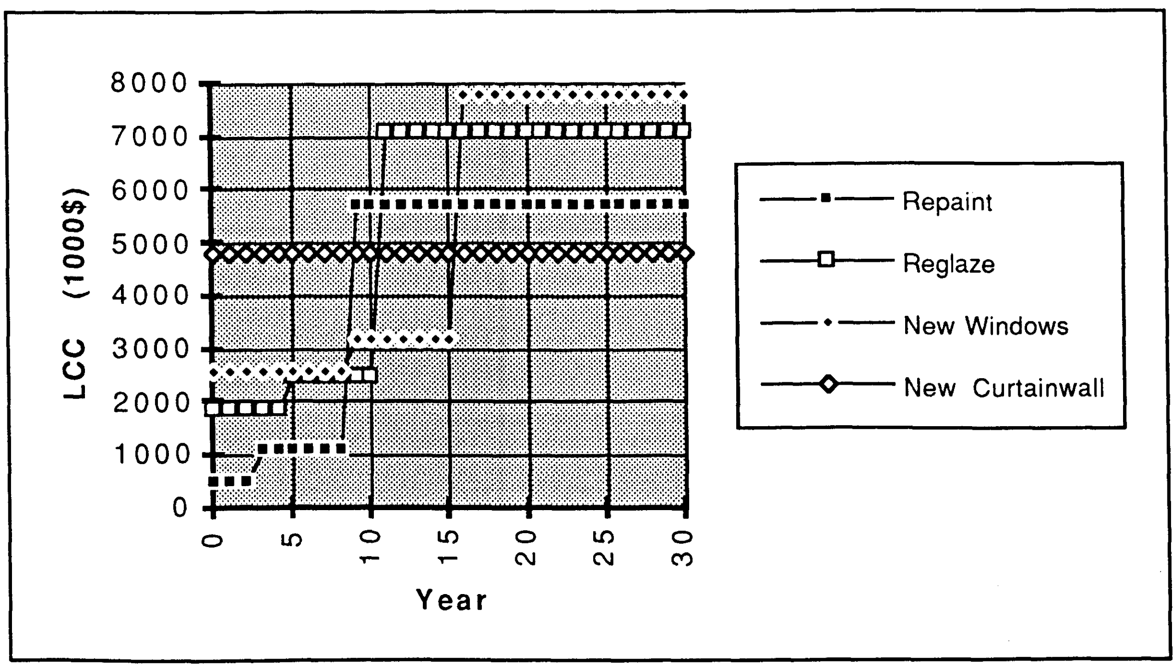

Chart 4.2-2: Arranged LCC Profile

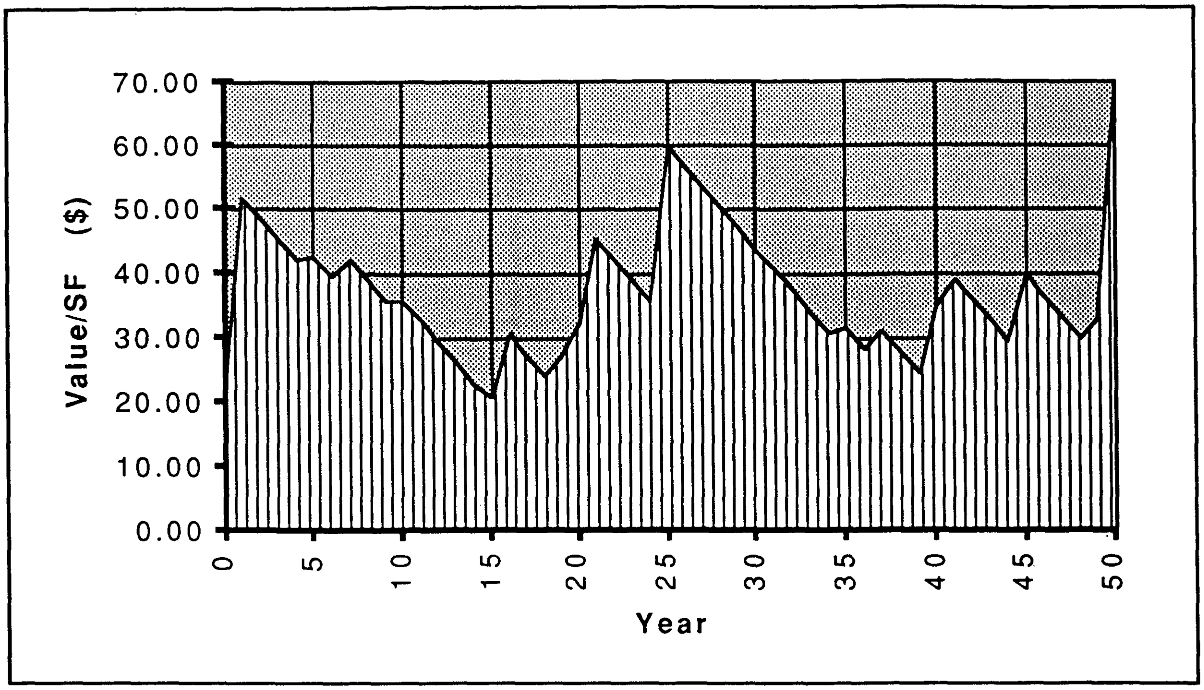

Chart 4.2-3: Residual Value of the Project

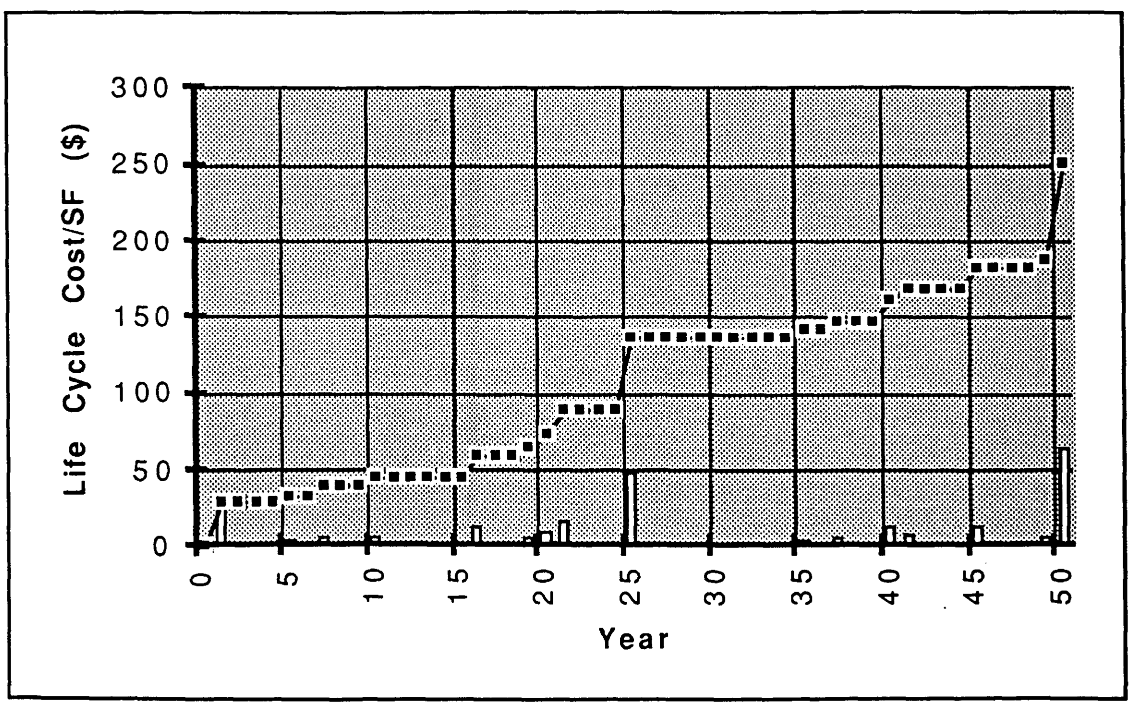

Chart 4.2-4: Running Cost Profile

4.2.6 Conclusion:

We have examined the possibility of using the LCC concept to estimate both the cost of an existing building and the running costs which will be needed after acquisition. We have found that setting up the LCC models in advance requires knowledge and experience of building construction. Without knowing actual system interaction, the model will not function correctly.

The proposed format enables an LCC analysis in a very short time. The results are given in the "costs per square foot", a term familiar to many practitioners and already known to be a fast (if not so precise) type of estimated cost. Still, the results enable one to envision the approximate life cycle cost profiles of the building, and serve as an effective tool to help decision making.

5. CONCLUSION

The LCC analysis can be conducted at later stages of a building's life.

The LCC method is the most effective tool to understand the future cost profile of a building. In the design stage, where there is a wide range of flexibility in directing decisions, LCC provides a powerful tool for understanding their cost implications. However, even when there is a limited range of possible dicisions, LCC provides an excellent opportunity to inform those decisions. Also, the LCC method can be used to analyze the historical value profile of an existing building, to provide an estimate of its residual value, and to estimate possible future expenses.

As the purpose of the analyses proposed here differ slightly from the current LCC, their method and style will be different as well. We propose applications of the simplified and the square-foot versions of the LCC analysis, but further refinements will be necessary.

In order to execute an accurate LCC analysis, extensive knowledge of building systems is essential. In addition to information about initial and operating costs, the accuracy of LCC analysis requires reliable data on maintenance costs. Further, the interaction among the systems and their life expectancy both have substantial impacts on the LCC analysis result.

Finally, we think that the application of the LCC method to later stages of building life is necessary:

- 1. to enable fully understanding and implementation of any existing life cycle conscious design
- 2. to induce proper information feedback of maintenance costs and cycles from later stages of building life to provide important data for use in design
- 3. to enable control over any coming costs

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