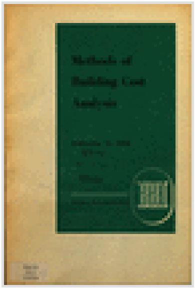

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Inquiries concerning Methods of Building Cost Analysis or other publications resulting from the BRI 1961 Fall Conferences may be directed to the Building Research Institute, 1725 De Sales Street, N.W., Washington 6, D. C. The other publications are:

Design for the Nuclear Age, No. 992
Prefinishing of Exterior Building Components, No. 993
Identification of Colors for Building, No. 1001
Mechanical Fasteners for Wood, No. 1003
Performance of Plastics in Building, No. 1004

The list of conference participants appears in Design for the Nuclear Age.

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The Building Research Institute gratefully acknowledges the contributions to building science made by the participants in the program on Methods of Building Cost Analysis.

MILTON C. COON, JR.
Executive Vice President

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Introduction

By Charles A. Bogert, Western Electric Company

EVERYONE CONNECTED WITH BUILDINGS today realizes the need for sound, economic studies for comparing the cost of buildings and building components. Many studies have been made that are not sound. In some cases, the author tried to prove his point by distorting the figures or by using misleading figures. Even more unfortunate are the studies in which the author worked conscientiously and honestly to find the more economical solution to a problem but, through lack of experience, left out factors or made incorrect assumptions. Important decisions have been reached based on such studies and, doubtless, much money has been misspent.

There are two parts to a sound economic study of the cost of buildings and building components. One is the accumulation of the necessary cost data. This may be easy, or it may be extremely time-consuming. The other part consists of setting up the economic study; making use of the accumulated data. The BRI Planning Committee on Methods of Building Cost Analysis, as the name implies, has confined itself strictly to methods, and the papers in this report will thus deal only with methods of setting up economic studies.

Are good, sound studies something that an engineer or architect should be willing to tackle, or are these studies outside of their fields? This Committee feels that every architect and engineer is capable of preparing a good economic study, and should not hesitate to make such a study when the need arises. Most of us were exposed to engineering economics or its equivalent when in school. However, the majority of us haven't made use of it, and apparently have forgotten what we learned.

The Committee originally started out by advising the BRI membership of its aims and requesting samples of studies. At first, there appeared to be an endless number of types, and review showed that some were not sound. Some for example, considered only the initial cost, and neglected the maintenance and operating costs. We narrowed the remaining studies down to

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several basic types. These were presented at a committee meeting this spring, in an effort to find out whether the Committee as a whole felt that they represented good conference program material. During this meeting, one of the members of the Committee pointed out that the several basic types of studies we were considering were really exactly the same, the only difference being the way in which the results were presented -- as annual costs, or as present worth of annual charges. The first paper in this conference will further amplify this concept.

Through the presentation of the papers and case studies, the Committee hopes that it can accomplish the following things:

1. Take some of the mystery out of economic studies.
2. Show that certain commonly used types of studies are fallacious and misleading.
3. Show that the same basic ideas can be used for any economic study.

We hope to encourage people in the building industry to make wider use of this valuable tool. If we can accomplish these things, we will feel that this conference has been worthwhile.

Techniques for Economic Analysis of Building Designs

By J. W. Griffith, Southern Methodist University

Abstract: The usefulness of various types of economic cost analysis techniques in the solution of building design problems by the designer is discussed. Methods considered are those based on present worth, uniform annual cost, and rate of return on investment. Six different interest-computing formulas are given, and the merits of each are explored. Examples of the various methods are presented and evaluated. Five tables are included, based on compound interest factors ranging from 4% to 8%.

THERE IS NO SUCH THING as the one perfect building type for all conditions. Consequently, a building must be designed for the owner. When a building is designed for the owner, economy becomes a prime factor. Even in prestige buildings, the owner is interested in obtaining the best possible design for the least amount of money.

The designer must determine the various alternative types of building designs and equipment that will satisfy the desires and needs of the owner. Many of the alternatives can be eliminated either by cursory inspection or by past experience of the designer. However, it must be remembered that a less desirable alternative will be chosen if the better alternative is not being considered.

Decision-making is one of the biggest problems a building designer faces. There are various tools available to aid him in making proper decisions. One of the most helpful tools is the Economic Cost Model, which is simply an equation that represents the total cost involved in constructing, owning, and operating a building. If properly used, it will give the owner and the designer a true picture of the over-all economy of the building. The Cost Model can be constructed to give the actual cost involved in each alternative being considered, or it can be simplified to making a comparison between two or more alternates. When the Cost Model uses actual costs involved, it can be used by the financial department for decision-making. Where the architect or engineer is using the Cost Model for decisions between alternates, it is only necessary to work with cost differences between alternates.

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CONSTRUCTING AN ECONOMIC COST MODEL

To construct an Economic Cost Model, all significant facts, advantages, and disadvantages of alternates should be reduced to monetary values. Some factors, such as prestige, personal desires, etc., are irreducible to monetary values. These factors will be used in the final decision on alternates, after the Cost Model has been used for economic comparison.

The second step in setting up an Economic Cost Model is to determine the "time value" of money. Plato once said that money does not breed money. This was probably true in his day when interest was an unknown quantity. However, today everyone is quite aware that money has a time value. If $1,000 is invested at 6% today, it will be worth $1,790 in 10 years.

To recognize this time value of money in a Cost Model, the interest rate applicable to the particular owner must be established. If the owner operates on any borrowed capital, the interest rate may be determined by the rate he pays for this borrowed capital. If the owner operates on his own money, the interest rate may be established by determining the interest rate he could obtain by investing his money in a venture having a risk equal to the one under study. Some companies have a minimum attractive rate of return already established for new ventures. If this rate of return is realistic, it can be used in the Cost Model. After the designer has reduced all possible factors to a dollar value and established the time at which these costs occur, as well as the minimum attractive rate of return, he is ready to construct an Economic Cost Model.

There are many variations of Cost Models and so-called Cost Models in use today. If properly applied, all of the true Cost Models will give an equivalent answer for decision-making. The most popular form of the so-called Cost Models is the First Cost method. The First Cost is not a valid technique for economic comparison, as it is not a model at all, but a part of all Cost Models. The usual arguments for using a First Cost as a decision-making tool are not valid. It is true that it is easier to obtain and understand than most true Cost Models. However, if this is the criterion of decision-making tools, the old method of flipping a coin to determine the alternative to be used is much quicker and more easily understood.

Another argument for using the First Cost occurs in those cases where the owner has a limited amount of capital, and little or no credit available. It would appear in this case that the owner must take the low First Cost building, as he does not have the funds to take advantage of long-range economics. In such a case as this, the owner should run a true Economic Cost Model of the proposed construction, as he still has the problem of deciding whether to build the building, rent the space, or invest his money in a more advantageous venture.

The fallacy of using the First Cost as an Economic Cost Model can be seen in the following simplified example, comparing two alternate types of buildings with the following cost characteristics:

Cost Consideration	Alternate A	Alternate B
Useful Life	20 years	30 years
First Cost	\$80,000	\$100,000
Annual Operation & Maintenance Cost	\$ 6,000	\$ 2,000
Annual Property Taxes & Insurance (5% of First Cost)	\$ 4,000	\$ 5,000
Income Tax Depreciation Allowance (Straight-Line with 50% Corporation Tax)	-\$ 1,800	-\$ 1,500
Salvage Value	-\$ 8,000	-\$ 10,000

If the First Cost consideration alone is used to choose between Alternates A and B, Alternate A appears to have a \$20,000 advantage over B. However, it will be shown that this is not necessarily true when other cost considerations are taken into account.

SIX BASIC FORMULAS

The more common and acceptable cost analysis techniques are the Present Worth, the Uniform Annual Cost, and the Rate of Return on the Investment. There are several variations of these techniques, such as the Rate of Return of the Extra Investment and various types of break-even formulas.

In setting up an Economic Cost Model for studying alternate types of building designs, there are six basic interest formulas used, as listed below. The symbols in these formulas are:

i = a compound interest rate per year

y = a number of years

P = a present sum of money

F = a future sum of money, y years from the present

A = a uniform annual payment at the end of each year

1. Single Payment Present Worth Factor (SPPWF)

Given a sum of money (F), (y) years in the future, find its present worth (P) today.

$$P = F\left[\frac{1}{(1+i)^y}\right]$$

2. Single Payment Compound Amount Factor (SPCAF)

Given a sum of money (P) today, find its future worth (F), (y) years in the future.

$$F = P\left[(1+i)^y\right]$$

3. Uniform Annual Present Worth Factor (UAPWF)

Given the uniform annual payments (A), find the present worth (P) of these payments over a period of (y) years.

$$P = A\left[\frac{(1+i)^y - 1}{i(1+i)^y}\right]$$

4. Uniform Annual Capital Recovery Factor (UACRF)

Given a sum of money (P) today, find the uniform annual payments (A) to recover this capital over the next (y) years.

$$A = P\left[\frac{i(1+i)^y}{(1+i)^y - 1}\right]$$

5. Uniform Annual Sinking Fund Factor (UASFF)

Given a sum of money (F),(y) years in the future, find the annual payment (A) necessary to provide this money.

$$A = F\left[\frac{i}{(1+i)^y - 1}\right]$$

6. Uniform Annual Compound Amount Factor (UACAF)

Given the annual payments (A) for (y) years, find the future sum of money (F) they will provide.

$$F = A\left[\frac{(1+i)^y - 1}{i}\right]$$

The derivation for these interest formulas can be found in any textbook on engineering economics and in some textbooks on finance. The formulas are unique in that for any given interest (i) and years(y) the factors inside the bracket for each formula are constant. It is not necessary to calculate these factors, as they can be found in tabular form for various interest rates and numbers of years in all engineering economics books and most mathematical handbooks.

In applying these interest formulas to some Economic Models, it is necessary to establish the interest rate to be used, and the life of the building and its equipment. All costs involved, including the First Cost of the building, its equipment and all disbursements for the life of the building, must be determined. The time at which each cost or disbursement, such as maintenance, upkeep, and replacement of equipment accrues, must also be determined. All negative disbursements or receipts, such as salvage value or tax write-off, must also be included. After this information has been collected, the Cost Model can then be constructed.

PRESENT WORTH MODEL

The Present Worth technique is simply a matter of adding the Present Worth of all future costs to the First Costs, using interest Formula 1 to bring single costs back to the Present Worth, and Formula 3 to bring annual costs back to the Present Worth. To apply this model to the example, a 60-year study period must be used to give equivalent useful lives for buildings A and B.

PRESENT WORTH MODEL

Minimum attractive rate of return, 6%
(All Factors obtained from Table 3, page 14)

Cost Consideration	Alternate A	Alternate B
Present Worth (PW) of First Cost	$80,000	$100,000
PW of 1st Renewal (First Cost minus Salvage) (SPPWF)	($72,000)(.3118) = $22,450 y=20	($90,000)(.1741) = $15,669 y=30
PW of 2nd Renewal (First Cost minus Salvage) (SPPWF)	($72,000)(.0972) = $6,999 y=40	0
PW of Annual Operation & Maintenance Cost (Annual Cost)(UAPWF)	($6,000)(16.161) = $96,966 y=60	($2,000)(16.161) = $32,322 y=60
PW of Annual Property Taxes & Insurance (Annual Cost)(UAPWF)	($4,000)(16.161) = $64,644 y=60	($5,000)(16.161) = $80,805 y=60
PW of Income From Depreciation Allowance	(-$1,800)(16.161) = -$29,090 y=60	(-$1,500)(16.161) = -$24,242 y=60
PW of Final Salvage Value (Salvage)(SPPWF)	(-$8,000)(.0303) = -$242 y=60	(-$10,000)(.0303) = -$303 y=60
Total PW of 60 years of Service	$241,727	$204,251

Plan B has a $37,476 advantage over Plan A at the end of a 60-year period. This advantage would be proportionately less over a shorter period. Therefore, it can be seen that Plan A does not have the advantage over Plan B which it appeared to have when First Cost alone was considered (see page 5).

There are two primary disadvantages to using the Present Worth technique. The biggest disadvantage is that if the buildings do not have equal lives, the cost study must be extended over a period of years long enough to be a multiple of the number of years in each alternate. This is illustrated in the example which shows two replacements for the 20-year-life building and one replacement for the 30-year-life building.

Generally, a building is considered to be used for an indefinite period of time. If a building is to be used only part of its useful life, then the resale or salvage value at the termination of its use is included in the Cost Model as a negative disbursement. Since this is only a model for comparing costs, the long time period does not detract from its value as a decision-making tool.

The second disadvantage to using the Present Worth Model is that the comparative costs are very large. Most people are not accustomed to evaluating the large differences in Present Worth calculations. Consequently, too much emphasis is sometimes given to a large difference in Present Worth values, which may not be significant.

UNIFORM ANNUAL COST MODEL

Both of the above disadvantages can be overcome by using the Uniform Annual Cost Model. In this Model all values can be brought to a Present Worth and then spread over the life of the building in a uniform annual payment due at the end of each year. This is accomplished by applying Formula 4 to the Present Worth values. If certain costs such as maintenance, utilities, taxes and insurance are already in Uniform Annual Cost terms, they can be added to the other cost after they have been converted to Uniform Annual Costs.

People understand Annual Costs much better than they do Present Worth Costs. They are used to paying for services on an annual or periodic basis, as well as buying homes and buildings with uniform payments. Since the Uniform Annual Cost in a model study is the same whether a building is replaced one or more times, it eliminates the problem of comparing alternates having different lives. The salvage value in the example on the next page could have been accounted for by applying Formula 5 instead of 1 and 4. In fact, most Cost Models can be constructed several different ways and still produce equivalent answers.

If the Uniform Annual Cost technique has been used, it can be converted to the Present Worth technique by applying Formula 3 to the Annual Costs for an equal number of years of life for the two alternates. Likewise, if the Present Worth Cost Model has been used, it can be converted to a Uniform Annual Cost by applying Formula 4 to the Present Worth values.

This Model is applied to the example as follows:

UNIFORM ANNUAL COST MODEL

Minimum attractive rate of return 6%.

(All factors obtained from Table 3, page 14)

Cost Consideration	Alternate A	Alternate B
Uniform Annual Cost of Recovering 1st Cost (1st Cost)(UACRF)	(\$80,000)(.08718) = \$6,974 y=20	(\$100,000)(.07265) = \$7,265 y=30
Annual Operation U Maintenance Cost	\$6,000	\$2,000
Annual Property Taxes & Insurance	\$4,000	\$5,000
Annual Income From Depreciation Allowance	-\$1,800	-\$1,500
Annual Income Due from Salvage (Salvage)(SPPWF) (UACRF)	(\$8,000) (.3318)(.08718) = -\$231 y=20	(\$ 10,000) (.1741)(.07265) = -\$126 y=30
Total Annual Cost	\$14,943	\$12,639

Alternate B has a \$2,304 annual advantage over Alternate A. If plan A and B both had a 20-year life, plan A would still have a \$1,764 annual advantage over plan B.

If the Present Worth of the \$2,304 annual advantage is computed over a 60-year period, it approximates the \$37,476 savings using the Present Worth Model (variation due to rounding off).

($2,304)(16.161)=$37,234
y=60

RATE OF RETURN MODEL

Another type of Cost Model used by people investing in buildings for income purposes is the Rate of Return on Investment. This model can be used with either Present Worth or Annual Cost calculations. The model is set up as previously described using all costs and disbursements, both positive and negative. It is then set equal to zero. Since the interest rate is unknown, the factors are included in the formula in symbol form. After the equation has been established, it is then a trial-and-error procedure of choosing interest rates and inserting the corresponding values of Present Worth and Capital Recovery factors into the equation. When an interest rate makes this equation equal zero, it represents the Rate of Return on the particular investment.

If the particular interest rate lies between two interest rates given in the interest rates tables, straight-line interpolation is usually satisfactory in determining the actual rate. To apply this technique to the example, the income from the building must be forecast. If a rent of $15,000 per year is anticipated, the Rate of Return for each plan can be computed, using the following equation:

Annual Cost Technique for Rate of Return

(First Cost)(UACRF) + $ Annual Operation & Maintenance Costs + Annual Property Taxes & Insurance - Income from Depreciation - Annual Worth of Salvage Value - Rent = 0

Plan A: ($80,000)(UACRF)+$6,000+$4,000-$1,800-($8,000) (SPPWF)(UASCRF)-$15,000=0

By trial and error substitution of Single Payment Present Worth factors and Uniform Annual Capital Recovery factors for 20 years, the interest rate that gives a zero value to the Rate of Return Model is found to be between 6 and 6½%.

Plan A Model at 6% : ($80,000)(.08718)+$6,000+$4,000-$1,800-($8,000)(.3318)(.08718)-$15,000=$14,943

This is, of course, the same Annual Cost found previously. Since the $15,000 rent is practically the same as the Annual Cost of $14,943, the Rate of Return for Plan A is approximately 6%, which was the assumed minimum attractive Rate of Return previously used.

Plan B Model is similar to that of Plan A, but the Rate of Return is found to be 8.8% as follows:

Plan B Model at 8% interest Factors from complete set of interest tables) : ($100,000) (.08883)+$2,000+$5,000-$1,500-($10,000)(.0994) (.08883)-$15,000 = $705

Plan B Model at 10% interest : ($100,000) (.10608)+$2,000+$5,000-$1,500-($10,000) (.0573) (.10608)-$15,000 = $1,047

By straight-line interpolation, the Rate of Return is approximately 8.8%. Plan B produces 2.3% more interest than Plan A.

Another form of the Rate of Return technique is the Rate of Return on the extra investment. If the designer is interested only in the prospective difference between two or more alternates, he can compare them by computing the Rate of Return on the extra investment of the more expensive First Cost building over the less expensive one. This is a very useful tool for the investor who wishes to determine which building type will allow him to make the most money on his investment.

The interest rate that makes the two Rate of Return equations for Plans A and B equal in the previous study is the Rate of Return on the extra investment of $20,000 in Plan B. Again the trial-and-error technique is used to determine the interest rate. Rate of Return on the Extra Investment Model at 15% interest is set up by subtracting the Rate of Return equation for Plan B from that for Plan A and equating this to zero:

$$\text{Plan A}\left[(\$80{,}000)\ (.15976)+\$6{,}000+\$4{,}000-\$1{,}800-(\$8{,}000)\ \underset{y=20}{(.0611)}\ \underset{y=20}{(.15976)} - \$15{,}000\right]$$

minus

$$\text{Plan B}\left[(\$100{,}000)\ (.15230)+\$2{,}000+\$5{,}000-\$1{,}500-(\$10{,}000)\ \underset{y=30}{(.0151)}\ \underset{y=30}{(.15230)} - \$15{,}000\right]=\$195.$$

Rate of Return on the Extra Investment Model at 20% interest:

$$\text{Plan A}\left[(\$80.000\ \underset{y=20}{(.20536)}+\$6{,}000+\$4{,}000-\$1{,}800-(\$8{,}000)\ \underset{y=20}{(.0261)}\ \underset{y=20}{(.20536)} - \$15{,}000\right]$$

minus

$$\text{Plan B}\left[(\$100{,}000)\ \underset{y=30}{(.20085)}+\$2{,}000+\$5{,}000-\$1{,}500-(\$10{,}000)\underset{y=30}{(.0042)}\ \underset{y=30}{(.20085)} - \$15{,}000\right]= -\$991.$$

By straight-line interpolation the Rate of Return on the extra $20,000 invested in Plan B over Plan A would be approximately 15.8%.

The primary advantage of using the Rate of Return on the investment for decision-making is that it allows the investors to know their actual Rates of Return rather than simply that the rate is above or below a minimum attractive one. A disadvantage is its trial-and-error calculation which takes more time than other models that are satisfactory for making decisions between alternates.

Still another type of Cost Model is the Break-even Equation. This is sometimes used in comparing buildings when the forecasted life of a building is not known, but it is desired to know what life would make it the desirable alternate. To set up such a Break-even Equation, the Uniform Annual Cost or Present Worth Models are constructed for both alternates and set equal to each other. Since the expected life of one of the two buildings is the unknown, the Present Worth and Capital Recovery factors are again used in symbol form. The trial-and-error technique of searching for the year in a given interest table that makes the two cost equations equal is used. Once the year has been determined, it is then usually obvious that one alternate should be chosen if the expected life is less than this Break-even life, and the other alternate if the expected life is more.

If Plan A has a 20-year life, and it is desired to know what life Plan B must have to make it desirable, the Annual Cost equation for Plan B is set equal to that of Plan A.

Plan B --

$$(\$100{,}000)(UACRF)_{y=?}+\$2{,}000+\$5{,}000-\$1{,}500-(\$10{,}000)(SPPWF)_{y=?}\,(UACRF)_{y=?} = \$14{,}943$$

For y=16 years, Plan B Annual Cost = $15,003

For y=17 years, Plan B Annual Cost = $14,690

It would, therefore, pay to use Plan B if its expected life was 17 or more years.

EVALUATION

The foregoing Economic Cost Models are the more common types used today. There are many other techniques and variations of these applicable to decision-making. There are also many ways of simplifying economic cost studies so that people unqualified to understand the actual calculations can apply them to specific situations. These may be in the form of Break-even Equations, Graphical Solutions, Nomographs, and tables of various kinds. However, it is usually no more difficult to set up the Actual Cost Model, which allows understanding of the problem, rather than merely providing single answers.

In studying Cost Models the owner should be careful in his analysis of problems dealing with excess capacity that is not usable. This problem usually exists where building costs are quoted as so much per square foot or cubic foot of building space. The owner must realize that certain types of construction will produce lower costs per square or cubic foot, but unless it is usable space, the cost is misleading. This is quite similar to buying a passenger automobile on the basis of cost per passenger mile. If family cars were bought on this basis, most people would probably own buses for family transportation, even though they would not need the extra capacity.

Frequently, a criticism of Economic Cost Models is based on the fact that the assumptions made are not what actually happens. This criticism is made by one who does not understand the use of models for decision-making. The Cost Model is only a tool and synthesizes the actual situation.

The big problem with Economic Cost Models is that of forecasting; the mathematics involved is simple. The Internal Revenue Service has a Bulletin F which gives expected life values for various building types and equipment. Past history is a good source of information from which to establish expected lives and costs. However, this is an area where research is required.

Another problem with Economic Models is the cyclic effect of economic conditions. If these can be forecast, they can be inserted in the Model. If not, it is best to assume that prices will remain the same. Inflation usually has an automatic compensation effect. If a $50,000 building is replaced 20 years from now, its price will probably be inflated above $50,000. However, the money that purchases this building will have an inflation factor applied to it so that it is self-compensating. If it takes a certain number of items to yield enough money to build the building today, it will probably take a similar number to build it in the future.

In evaluating the usefulness of Economic Cost Models, the critic should remember the alternate choice is usually a sales presentation, or a hunch at best. If economic analysis appears to be a time-consuming process, remember that this is part of what is included in fees for engineering. Many dissatisfied owners of poorly engineered buildings are finding their maintenance costs prohibitive. They have only themselves to blame for not demanding cost studies. The extra cost of having good economic analysis techniques used in building design is equally as profitable as having good structural analysis techniques used.

TABLE 1 -- 4% COMPOUND INTEREST FACTORS

	Single Payment		Uniform Annual Cost			
y Years	Present Worth	Compound Amount	Present Worth	Capital Recovery	Compound Amount	Sinking Fund
	$\frac{1}{(1+i)^y}$	$(1+i)^y$	$\frac{(1+i)^y-1}{i(1+i)^y}$	$\frac{i(1+i)^y}{(1+i)^y-1}$	$\frac{(1+i)^y-1}{1}$	$\frac{1}{(1+i)^y-1}$
	F known, find P	P known, find F	A known, find P	P known, find A	A known find F	F known, find A
1	.962	1.04	0.96	1.040	1.00	1.000
2	.925	1.08	1.89	.530	2.04	.490
3	.889	1.13	2.78	.360	3.12	.320
4	.855	1.70	3.63	.275	4.25	.235
5	.822	1.22	4.45	.225	5.42	.185
6	.790	1.27	5.24	.191	6.63	.151
7	.760	1.32	6.00	.166	7.90	.127
8	.731	1.37	6.73	.149	9.21	.109
9	.703	1.42	7.44	.135	10.58	.094
10	.676	1.48	8.11	.123	12.01	.083
15	.555	1.80	11.12	.090	20.02	.050
20	.456	2.19	13.60	.074	29.78	.034
25	.375	2.67	15.62	.064	41.65	.024
30	.308	3.24	17.29	.058	56.09	.018
35	.253	3.95	18.67	.054	73.65	.014
40	.208	4.80	19.79	.051	95.02	.011
45	.171	5.84	20.72	.048	121.00	.008
50	.141	7.11	21.48	.047	152.60	.007
60	.095	10.52	22.62	.044	237.99	.004

TABLE 2 -- 5% COMPOUND INTEREST FACTORS

y Years	Single Payment: Present Worth $\frac{1}{(1+i)^y}$	Single Payment: Compound Amount $(1+i)^y$	Uniform Annual Cost: Present Worth $\frac{(1+i)^y-1}{i(1+i)^y}$	Uniform Annual Cost: Capital Recovery $\frac{i(1+i)^y}{(1+i)^y-1}$	Uniform Annual Cost: Compound Amount $\frac{(1+i)^y-1}{i}$	Uniform Annual Cost: Sinking Fund $\frac{1}{(1+i)^y-1}$
1	.952	1.05	0.95	1.050	1.00	1.000
2	.907	1.10	1.86	.538	2.05	.488
3	.864	1.16	2.72	.367	3.15	.317
4	.823	1.21	3.55	.282	4.31	.232
5	.784	1.28	4.33	.231	5.53	.181
6	.746	1.34	5.08	.197	6.80	.147
7	.711	1.41	5.79	.173	8.14	.123
8	.677	1.48	6.46	.155	9.55	.105
9	.645	1.55	7.11	.141	11.03	.091
10	.614	1.63	7.72	.130	12.58	.080
15	.481	2.08	10.38	.096	21.58	.046
20	.377	2.65	12.46	.080	33.07	.030
25	.295	3.39	14.09	.071	47.73	.021
30	.231	4.32	15.37	.065	66.44	.015
35	.181	5.52	16.37	.061	90.32	.011
40	.142	7.04	17.16	.058	120.80	.008
45	.111	8.99	17.77	.056	159.70	.006
50	.087	11.47	18.26	.055	209.30	.005
60	.054	18.68	18.92	.053	353.58	.003

TABLE 3 -- 6% COMPOUND INTEREST FACTORS

y Years	Single Payment: Present Worth $\frac{1}{(1+i)^y}$	Single Payment: Compound Amount $(1+i)^y$	Uniform Annual Cost: Present Worth $\frac{(1+i)^y-1}{i(1+i)^y}$	Uniform Annual Cost: Capital Recovery $\frac{i(1+i)^y}{(1+i)^y-1}$	Uniform Annual Cost: Compound Amount $\frac{(1+i)^y-1}{i}$	Uniform Annual Cost: Sinking Fund $\frac{1}{(1+i)^y-1}$
1	.943	1.06	0.94	1.060	1.00	1.000
2	.890	1.12	1.83	.545	2.06	.485
3	.840	1.19	2.67	.374	3.18	.314
4	.792	1.26	3.47	.289	4.38	.229
5	.747	1.34	4.21	.237	5.64	.177
6	.705	1.42	4.92	.203	6.98	.143
7	.665	1.50	5.58	.179	8.39	.119
8	.627	1.59	6.21	.161	9.90	.101
9	.592	1.69	6.80	.147	11.49	.087
10	.558	1.79	7.36	.136	13.18	.076
15	.417	2.40	9.71	.103	23.28	.043
20	.312	3.21	11.47	.087	36.79	.027
25	.233	4.29	12.78	.078	54.87	.018
30	.174	5.74	13.77	.073	79.06	.013
35	.130	7.69	14.50	.069	111.40	.009
40	.097	10.69	15.05	.066	154.70	.006
45	.073	13.77	15.46	.065	212.70	.005
50	.054	18.42	15.76	.063	290.40	.003
60	.030	32.99	16.16	.062	533.13	.002

TABLE 4 -- 7% COMPOUND INTEREST FACTORS

y Years	Single Payment: Present Worth $\frac{1}{(1+i)^y}$	Single Payment: Compound Amount $(1+i)^y$	Uniform Annual Cost: Present Worth $\frac{(1+i)^y-1}{i(1+i)^y}$	Uniform Annual Cost: Capital Recovery $\frac{i(1+i)^y}{(1+i)^y-1}$	Uniform Annual Cost: Compound Amount $\frac{(1+i)^y-1}{i}$	Uniform Annual Cost: Sinking Fund $\frac{1}{(1+i)^y-1}$
1	.935	1.07	0.94	1.070	1.00	1.000
2	.873	1.15	1.81	.553	2.07	.483
3	.816	1.23	2.62	.381	3.22	.311
4	.763	1.31	3.39	.295	4.44	.225
5	.713	1.40	4.10	.244	5.75	.174
6	.666	1.50	4.77	.210	7.15	.140
7	.623	1.61	5.39	.186	8.65	.116
8	.582	1.72	5.97	.167	10.26	.097
9	.544	1.84	6.52	.153	11.98	.083
10	.508	1.97	7.02	.142	13.82	.072
15	.362	2.76	9.11	.110	25.13	.040
20	.258	3.87	10.59	.094	41.00	.024
25	.184	5.43	11.65	.086	63.25	.016
30	.131	7.61	12.41	.081	94.46	.011
35	.094	10.68	12.95	.077	138.20	.007
40	.067	14.97	13.33	.075	199.60	.005
45	.048	21.00	13.61	.074	285.70	.004
50	.034	29.46	13.80	.072	406.50	.002
60	.017	57.95	14.04	.071	813.52	.001

TABLE 5 -- 8% COMPOUND INTEREST FACTORS

y Years	Single Payment: Present Worth $\frac{1}{(1+i)^y}$	Single Payment: Compound Amount $(1+i)^y$	Uniform Annual Cost: Present Worth $\frac{(1+i)^y-1}{i(1+i)^y}$	Uniform Annual Cost: Capital Recovery $\frac{i(1+i)^y}{(1+i)^y-1}$	Uniform Annual Cost: Compound Amount $\frac{(1+i)^y-1}{i}$	Uniform Annual Cost: Sinking Fund $\frac{1}{(1+i)^y-1}$
1	.926	1.08	0.93	1.080	1.00	1.000
2	.857	1.17	1.78	.561	2.08	.481
3	.794	1.26	2.58	.388	3.25	.308
4	.735	1.36	3.31	.302	4.51	.222
5	.681	1.47	3.99	.251	5.87	.170
6	.630	1.59	4.62	.216	7.34	.136
7	.584	1.71	5.21	.192	8.92	.112
8	.540	1.85	5.75	.174	10.63	.094
9	.500	2.00	6.25	.160	12.49	.080
10	.463	2.16	6.71	.149	14.49	.069
15	.315	3.17	8.56	.117	27.15	.037
20	.215	4.66	9.82	.102	45.76	.022
25	.146	6.85	10.67	.094	73.11	.014
30	.099	10.06	11.26	.089	113.30	.009
35	.068	14.79	11.66	.086	172.30	.006
40	.046	21.73	11.93	.084	259.10	.004
45	.031	31.92	12.11	.083	386.50	.003
50	.021	46.90	12.23	.082	573.80	.002
60	.010	101.26	12.38	.081	1253.21	.001

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Case Studies of Analysis Techniques

Annual Cost Method

The Thermal Economics of Building Enclosures

By Clayford T. Grimm, Zonolite Company

Abstract: A study to establish a method for the rapid determination of annual fuel costs attributable to heat transfer through building walls and roofs is described. Heating and air conditioning costs are included for masonry walls and lightweight roofs. The study is applicable to smaller projects. It is shown that, aside from reducing operating costs, the addition of insulation can in some cases reduce the size of mechanical equipment by an amount sufficient to pay for the entire cost of insulating. Thermal economic coefficients for heating and cooling are tabulated for 75 cities.

THE ENGINEERING PROPERTIES of most materials are well known, and architects have devoted a substantial amount of study to aesthetics. But economics, once you leave the familiar ground of initial costs, is often a mysterious and uncharted bog.

This is not to say that building industry professionals lack awareness of this condition. No less authoritative document than the AIA Handbook of Architectural Practice demands that a building be designed for "efficient operation and economical maintenance," and the materials employed be "economical for their particular use." This consideration of economics extends to the cost of owning the building rather than simply putting it up. To put it another way, this implies searching for the ultimate cost of buildings over their useful life in contrast to what is sometimes a comparably minor expense of putting a roof over a client's head. Too often, this search is based on hunch and habit rather than careful analysis of the economic parameters.

It is not sufficient that men or buildings be handsome and strong; they must also earn their way in the world, support dependents, stockholders, and families. This can be done with reasonable certainty only by analyzing the economics of alternatives. Profit is the

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prime reason for enclosing rentable space, and lower total cost consistent with the use of the building is always desirable to free funds for other needs.

Insulation of building enclosures affords the designer an excellent opportunity for a study of comparative economics because the monetary saving it provides is the principal reason for the use of insulation, though increased comfort is also a design consideration. In 1961, inadequate insulation cost this nation nearly $2 billion in wasted fuel. In my short lifetime, this fuel waste has cost the United States $50 billion. A greater emphasis on the economic performance of building materials is a necessity not only for the benefit of the building owner, but of the nation as a whole. Hunch and guesswork must be eliminated from the selection of building materials. This will be accomplished only when more emphasis is placed on building economics, and this should begin with the improvement of architectural curriculums in our schools.

The problem of economic analysis in building design is complicated by several factors, including the pressure to reduce initial capital outlay and the requirements of different users who may be short-time owners, lessors or owner-occupants. The tax status of the client can also make a difference in the most economical selection of materials or systems of construction.

Having come to the realization that true economy is concerned not only with initial cost but also with operating and maintenance expenditures throughout the useful life of the structure, and that these cannot be determined by hunch, the question then presents itself as to which method of economic analysis to employ. The principal methods now in use have been described by Mr. Griffith (see pages 3 to 16).

No one method is always best. It may be sufficient in some cases to show that the use of a particular material will produce a 25% saving on its initial cost in the first year. In four years or so, the material will have paid for itself and is, therefore, a good investment. Investigation beyond that point may be academic. In other cases, the difference in annual expenditures between two alternatives may be so small as to justify a meticulous examination of the relative economics over the useful life of the building. In this case, the Present Worth method of economic analysis may be justified, in view of a great aggregate difference in cost.

In any event, the precision of the investigation should be consistent with its purpose. There is no need to tie up a calf with a 2-inch Manila rope when it can be determined with little investigation that a 1/4-inch rope will probably do the trick. Great precision in economic analysis is time-consuming, expensive, and not justified in many cases. When an economic analysis is more precise than it need be, the cost is unnecessarily increased and this, unfortunately, tends to limit the number of studies which are made. This suggestion for less precision, however, is not meant to condone outright incompetence.

A few years ago a book was published which contained economic comparisons of building materials and methods. It suggested that the total cost was equal to the sum of the annual costs. This idea, like Communism, negates the principle of compound interest. Simplification of economic analysis does not require the elimination of compound interest tables.

Several manufacturers and manufacturer's associations have recently prepared economic analyses of particular building elements which designers will find useful. As an example of this, The Ultimate Cost of Building Walls, published by the Structural Clay Products Institute, has found acceptance by the design professions. Our company has recently undertaken a study of the economics of thermal insulation for building enclosures. This report is available on request. It was prepared to be of particular assistance to the smaller architectural offices which, for most of their work, cannot afford to make intricate economic analyses.

Most architects know that annual costs for heating and air conditioning are reduced in proportion to a reduction in U value for building enclosures. Many, however, are not aware of the magnitude of the dollar savings which can accrue. It was the purpose of our report to provide a simple method of determining rapidly the annual fuel cost attributable to heat transfer through building walls and roofs. Heating and air conditioning costs are included for masonry walls and lightweight roofs.

THERMAL ECONOMIC COEFFICIENTS

A thermal economic coefficient has been computed for all regions in the United States. These are presented in Table 1. The product of this coefficient and the U value of the wall or roof provides the annual thermal cost per square foot of surface area. For opaque building enclosures in common use in the United States, the range in annual fuel cost is about 6000%, from about 2/10 of a cent to 12¢ per sq. ft. per year. Even in the same climate, the spread is often more than 300%.

Any architect would be embarrassed at such a divergence in contract bids on the initial cost of his buildings, but such differences in operating costs are often ignored. Yet, for many owners, the operating costs are just as great as the initial cost in terms of capital outlay. For example, the Department of Defense and the New York State school system spend as much each year to maintain buildings as they do to build new ones.

The U value of uninsulated masonry walls is in the .25 to .50 range. The addition of insulation would reduce this by 30 to 60%. The economic effect of this reduction is to save up to 4¢ per sq. ft. of wall area per year, providing an annual return on the insulation investment of up to 40% per year with an annual return of 25% being more usual.

TABLE 1 -- THERMAL ECONOMIC COEFFICIENTS -- HEATING AND COOLING

City & State	Heating, W_w	Cooling, W_s		Heating & Cooling, W	
	Any Wall, Roof or Window	Masonry Walls	Lightweight Roofs	Masonry Walls	Lightweight Roofs
Albany, N. Y.	.180	-	-	-	-
Albuquerque, N. M.	.138	0	0	138	.138
Amarillo, Texas	.134	-	-	-	-
Atlanta, Georgia	.089	.026	.094	.115	.183
Baker, Oregon	.197	-	-	-	-
Bakersfield, California	.072	.044	.134	.116	.206
Birmingham, Alabama	.087	.036	.129	.123	.216
Bishop, California	.132	.024	.073	.156	.205
Bismarck, N. D.	.238	0	0	.238	.238
Boise, Idaho	.171	0	.017	.171	.188
Boston, Massachusetts	.171	0	.014	.171	.185
Burbank, California	.059	.009	.032	.068	.091
Burlington, Vermont	.216	0	0	.216	.216
Charlotte, N. C.	.104	.028	.101	.132	.205
Cheyenne, Wyo.	.208	0	0	.208	.208
Chicago, Illinois	.180	.007	.029	.187	.209
Cincinnati, Ohio	.138	.013	.045	.151	.183
Dallas, Texas	.076	.105	.319	.181	.395
Denver, Colorado	.169	0	.013	.169	.182
Des Moines, Iowa	.178	.009	.041	.187	.219
Detroit, Michigan	.183	0	.014	.183	.197
Duluth, Minnesota	.244	-	-	-	-
Durango, Colorado	.202	-	-	-	-
El Paso, Texas	.085	.042	.152	.127	.237
Flagstaff, Arizona	.209	-	-	-	-
Fresno, California	.085	.036	.110	.121	.195
Greenville, Maine	.239	-	-	-	-
Havre, Montana	.228	0	0	.228	.228
Helena, Montana	.225	0	0	.225	.225
Houston, Texas	.044	.073	.242	.117	.286
Independence, Calif.	.116	-	-	-	-
Jacksonville, Florida	.036	.071	.254	.107	.290
Kansas City, Kansas	.147	.019	.062	.166	.209
Las Vegas, Nevada	.080	.075	.177	.155	.257
Little Rock, Arkansas	.098	.040	.159	.138	.257
Los Angeles, California	.047	0	.005	.047	.052
Miles City, Montana	.222	-	-	-	-
Minneapolis, Minnesota	.217	0	.014	.217	.231
Modena, Utah	.189	-	-	-	-
Montreal, Canada	.218	-	-	-	-
Nashville, Tennessee	.111	.022	.079	.133	.190
Needles, California	.047	-	-	-	-
New Orleans, Louisiana	.038	.078	.279	.116	.317
New York, N. Y.	.152	.013	.046	.165	.198
Oklahoma City, Okla.	.110	.044	.144	.154	.254
Omaha, Nebraska	.179	.011	.050	.190	.229
Phoenix, Arizona	.048	.145	.390	.193	.438
Pierre, South Dakota	.203	-	-	-	-
Pittsburgh, Pa.	.150	.009	.036	.159	.186
Pocatello, Idaho	.198	-	-	-	-
Portland, Maine	.207	0	0	.207	.207
Portland, Oregon	.129	0	0	.129	.129
Rapid City. S. D.	.208	0	.007	.208	.215
Red Bluff, California	.086	.050	.153	.136	.239

TABLE 1 (CONCLUDED)

City & State	Heating, W_w	Cooling, W_s		Heating & Cooling, W	
	Any Wall, Roof or Window	Masonry Walls	Lightweight Roofs	Masonry Walls	Lightweight Roofs
Reno, Nevada	.177	-	-	-	-
Roseburg, Oregon	.131	-	-	-	-
St. Louis, Mo.	.138	.021	.083	.159	.221
Sacramento, California	.085	.009	.032	.094	.117
Salt Lake City, Utah	.165	.007	.036	.172	.201
San Francisco, Calif.	.093	0	0	.093	.093
Sault St. Marie, Mich.	.261	-	-	-	-
Seattle, Washington	.137	0	0	.137	.137
Spokane, Washington	.193	0	0	.193	.193
Syracuse, New York	.185	-	-	-	-
Tampa, Florida	.023	-	-	-	-
Tonopah, Nevada	.172	-	-	-	-
Topeka, Kansas	.148	0	0	.148	.148
Trenton, New Jersey	.147	.006	.022	.153	.169
Tucson, Arizona	.060	.075	.215	.135	.275
Washington, D. C.	.132	.019	.068	.151	.200
Wichita, Kansas	.141	.021	.068	.162	.209
Winnemucca, Nevada	.180	0	0	.180	.180
Winslow, Arizona	.144	.016	.072	.160	.216
Yellowstone Park, Wyo.	.255	-	-	-	-
Yuma, Arizona	.033	.154	.377	.187	.410

The derivation of the thermal economic coefficient is based on equations presented in the Guide and Transactions of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers. The study is meant to be applicable to smaller projects and the assumptions made for the variables involved in the coefficient are predicated on that basis. We, therefore, used fuel consumption levels based on a gas-fired, fan-driven, warm air system. Most other systems would tend to increase annual operating costs. Fuel costs were estimated at 10¢ per therm. Interior temperatures were assumed at 70° F in winter and 75° F in summer. Electrical power consumption was based on 500 kwh per month. The air conditioning plant was assumed to have a capacity of 25 tons or less, with a power input of 1 kw per ton. An average orientation of masonry walls was assumed, and their color was assumed to be medium. Variation in color may produce a variation in the thermal economic coefficient for air conditioning costs of plus or minus 15%. Lightweight roofs were assumed.

Thermal economic coefficients for heating were prepared for 75 cities of the United States, and were plotted on a map as shown in Figure 1. Isobars were drawn at appropriate increments. It should be emphasized that, where possible, the values should be taken from tabular data for the individual cities rather than from maps, because of microclimatological variation, especially in mountainous areas. To find the annual fuel cost per square foot of wall or roof area, simply multiply the U value of the assembly by the thermal economic coefficient for heating. Although Figure 1 is titled "Masonry Walls and Lightweight Roofs," these coefficients for heating are applicable to any wall, roof, or window.

For example, in Albany, New York, the annual cost of fuel attributable to 1 sq. ft. of wall having a U value of .30 would be determined as follows:

> The thermal economic coefficient for heating in Albany is found to be .18. The annual cost is, therefore, .18 x .30, or $.054 per sq. ft. per year. If the wall were insulated to provide a U value of .13, the annual fuel cost would be .18 x .13, or 2.3¢ per sq. ft. per year. The annual saving due to the insulation is, therefore, 3.1¢ per sq. ft. per year. If the insulation cost is 10¢ per sq. ft., the annual return on the investment is 31%.

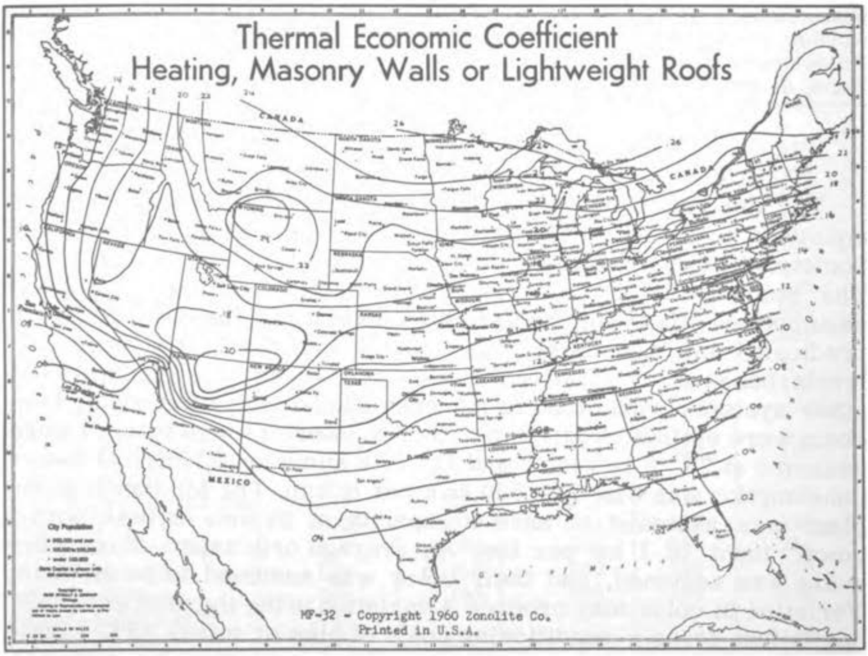

Figure 1

Similarly, the thermal economic coefficients for heat gain through masonry walls were computed and plotted on a map of the United States. Isobars were drawn at appropriate increments. The thermal economic coefficient for cooling for masonry walls is shown in Figure 2. For example, in New Orleans, Louisiana, the annual cost of electricity for air conditioning attributable to 1 sq. ft. of masonry wall having a U value of .30 would be determined as follows:

> The thermal economic coefficient for cooling buildings with masonry walls in New Orleans is found to be .078. The annual cost of electricity per square foot of wall area is, therefore, .078 x .30, or 2.3¢ per sq. ft. per year. If the wall were insulated to provide a U value of .13, the annual cost of electricity would be reduced to .078 x .13, or 1¢ per sq. ft. of wall area. The annual saving attributable to the insulation is 2.3 - 1.0, or 1.3¢ per sq. ft. per year.

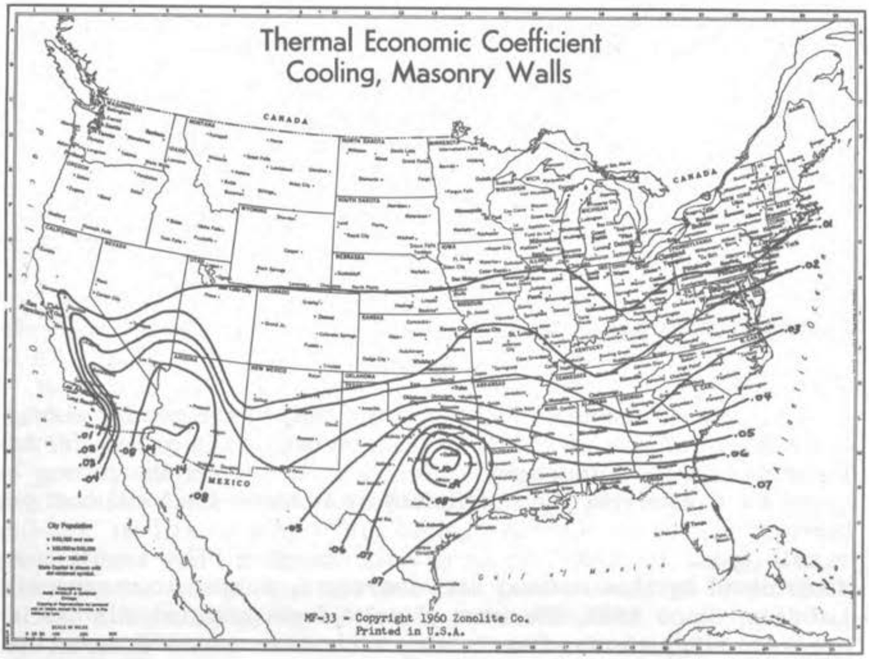

Figure 2

LIMITATIONS OF THE DATA

It is important to recognize the limitations of these data. The thermal costs determined in accordance with this method do not include all costs of operating the mechanical equipment, e.g., manpower, maintenance, and water consumption. The figures are, therefore, conservatively low for non-residential construction. Costs computed by this method ignore income and property taxes.

They do not consider fuel costs as tax deductible, nor do they provide for an annual depreciation tax credit on the plant. Property taxes and insurance have been neglected.

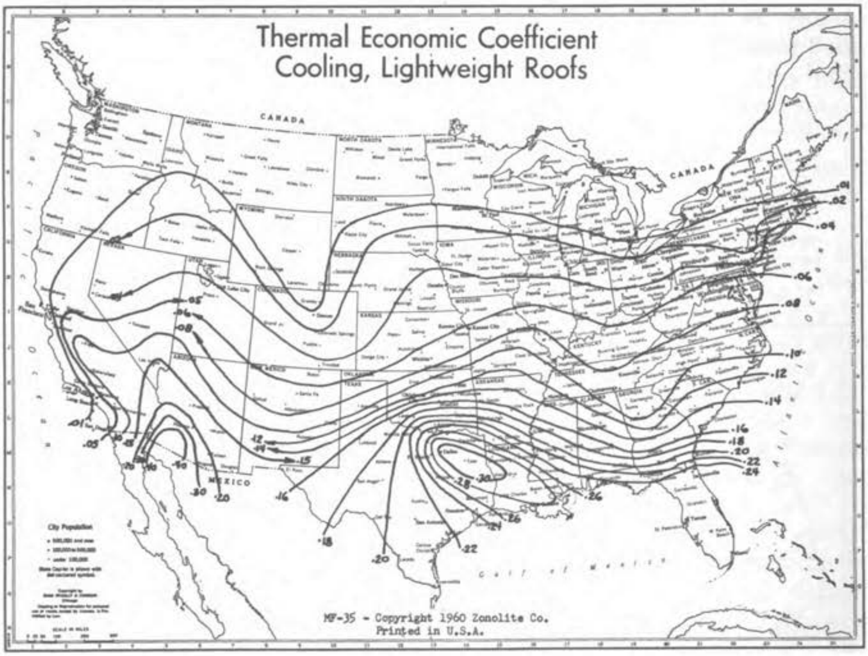

Figure 3

The method assumes that the initial cost of the heating plant is independent of the heat transmission through walls and roofs. Adjustment for local fuel costs differing from 10¢ per therm may be made by multiplying the coefficient by 10 times the local cost per therm.

All types of costs are constantly changing. The annual costs determined by this method are, therefore, subject to change with inflation. Since 1935, the cost of solid fuels and fuel oils has increased 2-1/2 times. Gas heating fuels now cost 45% more than the 1946-50 average. During the same period the rise in cost of electricity has been about 11%. The annual costs determined by this method are current. The annual savings achieved by insulation will, therefore, no doubt increase with time, again tending to make the savings computed for insulation by this method conservative.

The cost considerations mentioned above are variable with individual owners and the national economy. Their inclusion would, therefore, preclude a general solution to the problem. A method of thermal economic analysis which includes such variables is presented in a paper titled "The Ultimate Cost of Building Walls," published by the Structural Clay Products Institute in 1958.

It is not necessary to a determination of the relative economics of insulation that the variables which I have just mentioned be included in the economic study. If the analyst becomes very precise and includes all the variables, he will come to the same conclusion in any event--namely, that insulation of building enclosures is a good investment and that the thicknesses of insulation now generally employed do not approach the economic break-even point.

Generally, masonry walls are not now insulated, perhaps for these reasons:

> (a) Lack of general recognition of the magnitude of monetary savings achieved by insulation; (b) The high initial cost of insulation of walls (25¢ or more per sq. ft. for 2 in. in place); (c) The inability to place rigid or batt insulations in unfurred masonry walls; (d) The lack of adequate fill-type insulations; (e) The mistaken belief that since so much heat is transferred through glass, it makes little difference how much goes through opaque areas.

While there is a germ of truth in each of these objections, they are either no longer valid or they lead to false conclusions. It is hoped that the data presented here will lead to a greater understanding of the magnitude of savings which insulation can achieve.

The other objections may be met as follows: The initial cost of insulating masonry walls properly is less than half as much today as it was five years ago. Water repellent vermiculite masonry fill insulation for the cores and cavities of unfurred masonry walls is now available. Its use was described at the BRI Conference on Insulated Masonry Cavity Walls, the proceedings of which are available as BRI Publication 793.

It is true that heat loss through glass is typically 300 to 400% greater than through walls. However, heat, and therefore money, is lost through opaque areas in considerable quantities. That loss can be greatly reduced by insulation. To argue that large glass areas eliminate or reduce the need for insulating opaque areas in the same building is like saying, "I'm losing so much money now a much greater loss won't make me feel any worse." On the contrary, large glass areas make the use of wall insulation even more vital.

Aside from reducing operating costs, the addition of insulation can in some cases reduce the size of mechanical equipment by an amount sufficient to pay for the entire cost of the insulation before the building is occupied. This is true of a standard, two-company army barracks when air conditioned. The reduced size of the heating plant alone is sufficient to pay for half the cost of the insulation before the barracks is occupied, even in moderate climates.

The need for insulation of roofs is somehow more generally recognized, and such insulation is in common use. However, the thicknesses employed are usually minimum. The use of the thermal economic coefficient for roofs as presented herein would permit a designer to make a better evaluation of greater thicknesses, which may be ultimately more economical.

NEED FOR RESEARCH

For those interested in the ultimate economy of buildings, I would recommend that general studies be made more applicable to small structures. I tire a little of reading ads in national architectural magazines illustrating what a wonderful job the XYZ Company or some architect has done on a multistory structure in a major metropolitan area. On such huge projects, almost anybody could do a good job -- the money is there, the prestige is there. But what is the construction industry doing to assist the average small architectural firm to make economic decisions? Economic studies can and should be made simple, for quick and easy use.

Further consideration should also be given to building economics in collegiate schools of architecture. More persons should be encouraged to study in this field. The researcher in the Library of Congress, Washington, D. C., will find pathetically little on architectural economics. The construction industry should apply itself to this field. We owe it to our clients, our customers, ourselves and, indeed, our Nation.

Present Worth Method

An Economic Analysis of Integrated Lighting

By Otto F. Wenzler, Libbey-Owens-Ford Glass Company

Abstract: A method is described for making an engineering analysis of integrated lighting, using study of an office lighting problem as an illustration. The economics of three types of lighting are analyzed: fluorescent, incandescent, and daylight through windows. Consideration is also given to the heat generated by lighting and its effect on the over-all economy of the various alternate systems.

DAYLIGHT IS A NATURAL RESOURCE which has enormous value, and it is economically wasteful not to use it. The economic value of natural fuels and water power has been fully recognized, but the economic value of daylight has been disregarded in the last few decades due to the great progress in the development and use of artificial light.

Studies in recent years have proved that daylight is a very reliable source of abundant, high quality illumination, and competent engineers are beginning to recognize its economic value in determining the illumination requirements of buildings. The illuminating engineer should design the lighting environment to meet the tasks involved, using the most economical means for accomplishing the desired results. If this is not done, the engineer is obtaining engineering fees for doing a technician's work.

This paper will set forth a method for making an engineering analysis of integrated lighting which recognizes the economic value of daylight as well as the need for artificial light. A study of an office lighting problem will be used to illustrate the method. We will use cost values from the Federal Construction Council's Publication No. 18, Selection of Windows, and published manufacturers' prices. Cost values, of course, are unique to the particular locality and to the owner of the building, but the method outlined here will be the same for all cost values. The method is primarily intended to assist in determining which type or types of lighting will be most economical.

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Certain design criteria and physical conditions must be established before the study can be started. We will therefore assume that the office space will be 30 ft. long by 20 ft. wide with a ceiling height of 10 ft. The ceiling will be painted white, and the walls have 50% reflectance. The office tasks will be such that 70 to 100 foot-candles will be required. The office will be used five days a week or approximately 2500 hours per year. It will be located at 40° north latitude and will have approximately 120 overcast days per year.

THREE TYPES OF LIGHTING

The three types of lighting to be analyzed will be fluorescent, incandescent, and daylight through windows. They have been chosen to meet the brightness ratios and limitations recommended by the Illuminating Engineering Society (2). The incandescent unit is a 300-watt, silvered-bowl luminaire with a concentric ring louver. The fluorescent unit is a 4-40-watt, rapid-start commercial luminaire with 45° by 45° louvers. The office furniture and work areas will be oriented in such a manner that the problem of reflected glare will be negligible. The daylight source will be a window wall 30 ft. long and 7 ft. from the ceiling to the sill. It will have adjustable Venetian blinds over the entire window.

The cost per foot-candle will be used to compare the economics of the various sources. To establish this criterion for each alternate, it is necessary to compute the number of units required and the illumination they provide. This is accomplished by using the lumen method of artificial lighting prediction (2) for the electric alternates, and the lumen method of daylight prediction (4) for the daylight alternate.

Seventeen fluorescent fixtures will be required to provide a minimum of 70 foot-candles on the working areas, if all of the illumination is provided by this source. This level is provided if warm white lamps are used. If all the illumination is from fluorescent lighting, the more desirable, deluxe lamps should be used. This would require 24 luminaires to give color quality comparable to incandescent lighting.

Due to excessive heat, it is not practical to supply 70 foot-candles of illumination from incandescent lighting alone. Instead, the predicted level of illumination for the incandescent source is set at 30 foot-candles. Ten incandescent luminaires will be required to produce the 30 foot-candles considered necessary for supplementary lighting. After the cost per foot-candle has been established, the cost of providing 70 foot-candles from incandescent sources can be determined if desired.

The amount of daylight in an office varies with exterior conditions. It is, therefore, necessary to compute the distribution of daylight in the office for the low exterior conditions. The distribution of daylight in the office will be assumed to be 192 foot-candles near the window, 97 foot-candles in the center, and 56 foot-candles near the inner wall, if the exterior condition is a 1000 foot-lambert overcast sky, and the ground has an average reflectance of 20%. This condition represents one of the low values of daylighting in the room. Other exterior conditions may produce higher levels of daylighting, as desired by the occupant. The average illumination from daylighting can, if desired, be greater than 100 foot-candles, or it can be reduced by closing the blinds. However, for economic comparison the daylight will be assumed to be 70 foot-candles.

A step-by-step economic analysis of these three types of light sources is shown in Table 1 (page 32). Each is analyzed independently for 2500 hours of annual use. The first seven items of Table 1 are self-explanatory. Item 8 of Table 1 is the first cost of each alternate installed. The electric alternates include the cost of the luminaires and $10 installation cost per unit, which is a conservative figure. The differential cost of 50% operable windows, as opposed to a typical brick and block wall, is used as the first cost of daylight. The actual differential of $2.51 per sq. ft. was obtained from FCC Publication TR-18 (5), and may be high for some areas.

Item 9 of Table 1 is the uniform annual cost of recovering the first cost, with interest at 6% and a useful life of 40 years. This is probably too long a life for the luminaires. Replacement of the luminaires in 20 years would favor daylighting. Item 10 is the annual cost of insurance based on a 3% rate of first cost. Item 11 is the annual property tax based on a rate of 3% of first cost.

In Item 12 the annual cost of electric energy is based on 2500 hours of operation at 2-1/2¢ per kilowatt hour. Item 13, the uniform annual cost of replacing lamps or blinds, is based on a 7500 hour life for fluorescent lamps, a 1000 hour life for incandescent lamps, and a five year life for the Venetian blinds. Interest is 6%.

Item 14 represents the annual cost of maintenance, and includes the cost of cleaning each alternate once a year. The assumed cost is 50¢ per electric unit and 6¢ per sq. ft. of window area for daylighting.

Item 15 is the total annual cost, or the sum of Items 9-14. Item 16 is the annual cost per foot-candle for each alternate, or the total annual cost divided by the illumination.

It is quite obvious that the daylighting cost is considerably less than electric lighting and, for one source only, the fluorescent is more economical than the incandescent. Had the first cost of each system been used for the decision as to which alternate to use, it would have resulted in a costly mistake.

Obviously, no one would recommend building an office without electric lighting any more than a windowless office, without careful analysis of the over-all operating costs. If 30 foot-candles of electric lighting are needed for emergency use and night-time cleaning, the analysis in Table 2 (page 33) can be applied. In this analysis for integrated lighting, the first seven steps are the same as those in Table 1. The primary difference is in the reduction of electric lighting requirements due to the combination with daylight. The electric lighting is assumed to be used only 1000 hours per year as a supplement to daylight, and for night-time janitorial use. The costs in Items 8, 9, 10, and 11 remain the same as in Table 1, and the other costs vary with use. The annual costs per foot-candle of both the electric lighting systems are lower, owing to the savings in energy cost. However, the fluorescent system is still more economical than the incandescent.

TABLE 1 -- ECONOMIC ANALYSIS FOR ONE LIGHT SOURCE
(2500 hours use per year)

1. Type of lighting	Incandescent	Fluorescent	Daylight
2. Distribution	Indirect	Direct-indirect	Direct-indirect
3. Control	Concentric ring louver	45° x 45° louvers	Venetian blinds
4. Source	1-300 watt silver bowl	4-40 watt warm white rapid start	Overcast (minimum conditions)
5. Electric watts per unit	300	184	0
6. Number of Units	10	17	30' x 7' window wall
7. Ft-c Design illumination	30	70	70 (low average for minimum conditions)
8. First cost installed	$249.00	$1,215.00	$527 differential compared to typical masonry wall
9. Uniform annual cost of recovering first cost	$ 16.55	$ 80.75	$ 35.03
10. Annual cost of insurance	$ 7.47	$ 36.45	$ 15.81
11. Annual cost of property tax	$ 7.47	$ 36.45	$ 15.81
12. Annual cost of electric energy	$187.50	$ 195.50	0
13. Annual cost of lamps or blinds	$ 35.00	$ 38.16	$ 24.93
14. Annual cost of maintenance	$ 12.50	$ 8.50	$ 12.60
15. Total annual cost	$266.49	$ 395.81	$104.18
16. Annual cost per ft-c	$ 8.88	$ 5.65	$ 1.49

A summary of the annual costs and their present worth, covering 40 years of service, is shown in Table 3 (page 34). These are not net costs, since no figure has been shown for depreciation allowances, which should be proportionate for each system and are not needed for comparison of alternates. Since the annual cost per foot-candle decreased further for incandescent than fluorescent, when the electric use was cut to 1000 hours per year, it is obvious that at some number of hours it would pay to use incandescent and daylight,

TABLE 2 -- ECONOMIC ANALYSIS FOR INTEGRATED LIGHTING
(Electric Lights Used Only 1000 Hours)

1. Type of lighting	Incandescent	Fluorescent	Daylight
2. Distribution	Indirect	Direct-indirect	Direct-indirect
3. Control	Concentric ring louver	45° x 45° louvers	Venetian blinds
4. Source	1-300 watt silver bowl	4-40 watt warm white rapid start	Overcast (minimum conditions)
5. Electric watts per unit	300	184	0
6. Number of units	10	17	30' x 7' window wall
7. Ft-c design illumination	30	70	70 (low average for minimum conditions)
8. First cost installed	$249.00	$1,215.00	$527 differential compared to typical masonry wall
9. Uniform annual cost of recovering first cost	$ 16.55	$ 80.75	$ 35.03
10. Annual cost of insurance	$ 7.47	$ 36.45	$ 15.81
11. Annual cost of property tax	$ 7.47	$ 36.45	$ 15.81
12. Annual cost of electric energy	$ 75.00	$ 78.20	0
13. Annual cost of lamps or blinds	$ 14.00	$ 15.26	$ 24.93
14. Annual cost of maintenance	$ 5.00	$ 8.50	$ 12.60
15. Total annual cost	$125.49	$ 255.61	$104.18
16. Annual cost per ft-c	$ 4.18	$ 3.65	$ 1.49

making the annual cost models for each alternate equal to each other, and solving for the hours as follows:

$$(\$571.60)(.06646) + (.06)(\$571.60) + x(186)(8)(\$.000025) + \frac{(32)(\$1.50)}{7500}x\ (\$.50)(8) =$$

$$(\$249)(.06646) + (.06)(\$249) + x(300)(10)(\$.000025) + \frac{(10)(\$1.40)x}{1000} + (\$.50)(10)$$

TABLE 3 -- SUMMARY OF ECONOMIC ANALYSIS FOR LIGHTING AN OFFICE

Lighting Source	Illumination	Uniform Annual Cost	Present Worth of 40 Years of Service (at 6% Interest)
Incandescent	70 ft-c	$621.61	$9,353
Fluorescent	70 ft-c	$395.81	$5,955
Daylight	70 ft-c	$104.18	$1,568
Daylight and incandescent 1000 Hours Operation	70 ft-c daylight 30 ft-c incandescent 100 ft-c total	$104.18 125.49 $229.67	$3,456
Daylight and fluorescent 1000 Hours Operation	70 ft-c daylight 30 ft-c fluorescent 100 ft-c total	$104.18 109.50 $213.68	$3,215

Where $571.60 is the first cost for eight fluorescent units to provide 30 foot-candles, .06646 is the capital recovery factor for 6% interest and 40 years life; .06 is the tax and insurance rate applied to the first cost; x is the break-even hours of use per year; 186 is the total watts per fluorescent unit; eight is the number of units; .000025 is the cost of energy per watt; 32 is the total number of fluorescent lamps; $1.50 is the cost per lamp; 7500 is the lamp life in hours; $.50 is the cleaning cost per year for each of the eight luminaires; and the factors on the right side of the equation are the equivalent values for the annual cost of the incandescent alternate.

Solving the equation for x shows that 876 hours is the break-even number of hours. If the expected use of electric lighting is below this, it would be more economical to use incandescent lighting with daylight.

Thus far, the economic analysis has been based on lighting alone. Where there is light there is heat, and this may be a factor in the over-all economy of the various alternates. If the building is to be air conditioned for year-round comfort, the extra refrigeration as well as heating must be considered.

In developing this cost method to compare the heat gain and loss for the various lighting alternates, it was necessary to study offices with both east and west exposures. All things being equal, if an office building has only one glass exposure, it would probably be oriented to the north for economical design of the air conditioning system. However, most offices have two or more glass exposures, and a building which has large glass areas facing both east and west has a more severe heat gain problem than a north-south orientation.

Again, it is necessary to assume certain design criteria and physical conditions in order to make a study. The two offices, one facing east and the other facing west, will have the same characteristics used in the previous study. The summer design temperature will be 95° F outside and 80° F inside. The winter design temperature will be -5° F. The number of heating degree days will be 5000. The equivalent full-load operating hours for air conditioning will be 1000 in the daylighted designs, and 1250 hours for the artificial lighting with no daylight. Artificial lights are assumed to be used 300 hours during cooling periods and 700 hours during heating periods, with integrated lighting. The peak heat load is computed at 4 p.m. on July 23 (3) using regular plate glass and Venetian blinds adjusted at a 45° angle. The cost of an extra ton of air conditioning to overcome natural and artificial lighting loads is assumed to be $700. Heating costs are assumed to be $1.00 per 1000 pounds of steam at 1000 BTU per pound. Air conditioning operating costs are based on the use of 1.25 kilowatts per ton.

The heat loads and losses for the various combinations are computed using standard techniques (1). These are shown in Table 4 (page 36) with the economic analysis. The cost analysis of a 100 foot-candle fluorescent installation using deluxe lamps has been included in this table. If an all-artificial lighting design is used, deluxe lamps would have to be used to give a color quality similar to that obtained with integrated or incandescent designs.

Table 5 (page 37) is a summary of the total comparative annual costs and present worths of various lighting systems.

It is quite obvious that economic analysis of the over-all design of lighting is necessary for satisfactory results. Any air conditioning analysis based on heat load of daylighting without the economic comparisons of equivalent artificial lighting costs is worthless both to the building owner and architect for making decisions between alternates, and should not be tolerated.

In these studies no cost reduction has been included in the daylight analysis for the economic advantage of having a more desirable office. This advantage can be estimated on the basis of the higher rent charged for an office with window walls, as opposed to one without windows.

Each owner of a building has his own rate of return and tax position. Each locale has its particular tax and insurance rates, as well as its own electric rate and daylight conditions. These vary enough to require an economic cost analysis for each different building. Any attempt to generalize on an economic analysis may prove very costly.

TABLE 4 -- ECONOMIC THERMAL ANALYSIS OF TWO 30' x 20' OFFICES, ONE ORIENTED EAST AND ONE WEST

1. Type of lighting	70 Ft-c daylight 30 Ft-c fluor. Standard lamps	70 Ft-c daylight 30 Ft-c incandescent	100 Ft-c fluor. Standard lamps No daylight	100 Ft-c fluor. Deluxe lamps No daylight
2. Heat gain BTU/hr. Window or masonry wall	25,704	25,704	672	672
Artificial lighting	10,048	20,478	30,144	42,416
Maximum	25,704	25,704	30,816	43,088
3. Tons of A/C to remove maximum heat gain at design conditions	2.23	2.23	2.57	3.59
4. Total first cost for extra A/C	$1,561.00	$1,561.00	$1,799.00	$2,513.00
5. Uniform annual cost of capital recovery, 20 yrs. @ 6% Interest	$ 136.08	$ 136.08	$ 156.83	$ 219.08
6. Uniform annual cost of taxes & insurance, 6% of first cost	$ 93.66	$ 93.66	$ 107.94	$ 131.45
7. Annual energy cost for extra A/C	$ 74.76	$ 82.91	$ 100.40	$ 140.23
8. Uniform annual maintenance cost $5.00/ton of extra A/C	$ 11.15	$ 11.15	$ 12.85	$ 17.95
9. Total uniform annual cost of A/C due to lighting	$ 306.39	$ 306.39	$ 378.02	$ 508.71
10. Uniform annual cost of heat loss through windows or masonry wall	$ 56.95	$ 59.95	$ 10.08	$ 10.08
11. Uniform annual savings in heating due to artificial lighting load	-$ 7.03	-$ 14.33	-$ 10.08	-$ 10.08
12. Comparative uniform annual cost due to heating & cooling	$ 356.31	$ 352.01	$ 378.02	$ 508.71

TABLE 5 -- SUMMARY OF NET COSTS FOR THERMAL AND LUMINOUS COST FOR TWO TYPICAL OFFICE DESIGNS

Lighting Source	Illumination	Uniform Annual Cost of Illumination	Comparative Uniform Annual Cost of Heating & Cooling	Total Comparative Uniform Annual Cost of Illum., Heating & Cooling	Present Worth of 40 years of Service (at 6% Interest)
Daylight and incandescent	70 ft-c daylight 30 ft-c incandescent 100 ft-c total	$ 459.34	$352.01	$ 811.35	$12,208
Daylight and standard fluorescent	70 ft-c daylight 30 ft-c fluorescent 100 ft-c total	$ 427.36	$356.31	$ 783.67	$11,791
Fluorescent only, standard lamps	100 ft-c	$1,130.00	$378.02	$1,508.02	$22,690
Fluorescent only, deluxe lamps	100 ft-c	$1,590.00	$508.71	$2,098.71	$31,578

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Nomograph Computer Method

Optimization of Building Systems of More Than Three Variables

By Gershon and Milton Meckler, Meckler-Hoertz & Associates

Abstract: This paper presents a method of utilizing nomograph computers to develop alternate, integrated building designs for economic analysis. It illustrates the development of economic criteria and related factors for economic cost analysis. The nomograph computer, its construction, and its use are described in detail. This method makes it possible to avoid repeated calculations, while permitting the study of simultaneous changes in several design factors.

AGAINST A DYNAMIC BACKGROUND of changing requirements and a more complete utilization of new materials and techniques for mechanical, electrical, and structural system design, the architect must create volumes and shapes that successfully integrate the total environment with the building structure. In order to prepare an economic analysis of alternate, integrated building designs, all of the factors that go into determining total initial and annual building operating costs must be carefully considered and evaluated. All of the criteria relating to the properties of construction materials must be considered in terms of corresponding energy demands and characteristic operating cycles of the interrelated mechanical-electrical building systems. To do this practically, our firm has developed a technique which utilizes nomograph computers.

Where several variables are subject to change, and with the magnitude of such changes undetermined, nomograph computers provide a useful method of avoiding repeated calculations while permitting the study of simultaneous changes in several design factors (5) against specific criteria. These factors and criteria can be related by equations or other mathematical techniques (8). This relationship is then expressed by means of graphical or automatic nomograph computers. Actually, each criterion and its related factors constitute a specific program.

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One of the most significant benefits of utilizing techniques of integrated building design is that the characteristics of the energy-consuming systems can be changed, and designed to provide the most favorable operating cycle and utilization of energy for each specific building. The operating cycle relates the energy demands of the building to the initial cost of materials, systems and products used in the building.

Dynamic integration as a building design technique requires that all building system design variables be evaluated concurrently against criteria which relate to building material properties, energy and occupancy requirements. This significant feature affects the economic evaluation of building structures in a very profound way.

The object of this paper is to suggest a procedure and describe a method of utilizing nomograph computers to develop alternate, integrated building designs for economic analysis. It will illustrate the development of economic criteria and related factors for economic cost analysis. We shall describe nomograph computers and their construction, and demonstrate their use in solving a specific problem. The design decisions resulting from solution of the nomograph computer problem will then be evaluated in terms of the corresponding effects on initial and annual building operating costs.

EVALUATION TECHNIQUES

Decision-making is one of the most challenging problems for the modern building designer. The appropriate selection of specific materials and systems to be used in the preparation of an economic analysis for evaluating alternate building designs can only be made after the variables of one technology are established in terms of the design variables of all associated technologies through application of the proper criteria.

With regard to building design, appropriate criteria are established by defining the relationships that exist between the energy-consuming characteristics of the building system, the requirements for a specific occupancy, and the location, orientation and climate.

Economic analysis of alternate building designs requires a technique which permits all of the related design factors to be compared in terms of their net effect on total annual owning and operating costs. In order to bring this about, it is first necessary to develop a relationship which quantitatively represents the total cost involved in constructing, owning and operating various alternate building designs. Economic cost analysis of alternate building designs can be developed to relate the initial operating and maintenance cost to specific monetary values, provided the alternates used are based on valid design criteria.

Applying economic cost analysis to only one element of a building design as a basis for decisions among alternate building designs is often misleading. To illustrate, let us evaluate the use of various proportions of glass in the exterior walls of two or more buildings, otherwise identical.

A very definite relationship exists between the thermal and light-transmitting properties of a building exterior designed for a specific occupancy and climate, and the associated initial and annual operating costs. The following variables are but a few used by the architect to relate the heating and cooling energy demands (annual operating costs) to the amount of certain materials used in the building (initial cost):

1. Roof area/total floor area
2. Percentage and type of glass in exterior wall
3. Perimeter floor area/total floor area
4. Perimeter wall area/total floor area.

In evaluating an exterior building glass-wall combination, at least two important design criteria must be considered:

<u>Criterion No. 1:</u> Effect on building lighting system

(a) Initial cost

(b) Energy use cost

<u>Criterion No. 2:</u> Effect on heating and cooling demand

(a) Initial heating-cooling plant cost

(b) Energy use cost

The optimum use of a specific glass-wall combination that satisfies Criterion No. 1 may not also satisfy Criterion No. 2. Optimizing the glass-wall combination must satisfy some combination of Criteria Nos. 1 and 2 which represents the minimum cost. To determine this combination, the architect must be able to evaluate these two criteria simultaneously in relation to the type and extent of solid wall and glass used, as well as to the mechanical and electrical systems.

Before economic cost analysis can be properly applied, all of the interrelated architectural-mechanical-electrical-structural design factors must be compared simultaneously in terms of several important criteria. Alternates expressing the best solution for the total building are established for each criterion, and specific materials, products and systems are selected. Each alternate is then expressed in terms of appropriate cost models. Only then are economic decisions among alternates valid.

The need to establish and explore the most important criteria prior to application of the economic cost analysis must not be overlooked. The economic cost analysis can be applied effectively only in combination with a proper selection of alternates.

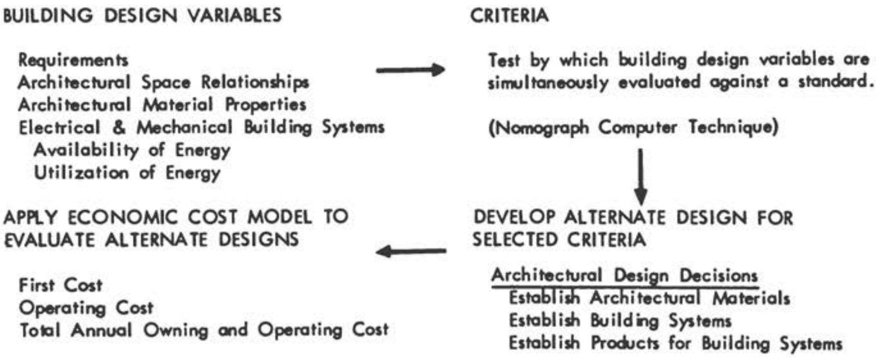

Figure 1 -- Procedure for economic evaluation of integrated building design.

Referring to Figure 1, the most rigorous economic evaluation technique is limited by the judgment used in establishing alternates. Simply stated, a proper procedure for economic analysis requires:

1. A thorough investigation of the most important criteria that affect building costs.
2. Development of alternates that express the best solution for the selected criteria.
3. Application of the economic cost model to these alternates.

CONSTRUCTING NOMOGRAPH COMPUTERS

Nomograph computers can be geometrically constructed. As such, they are preprogrammed relationships that represent mathematical equations relating quantities known or selected with design factors required for building systems evaluation. Nomograph computers can be used by the architect-engineer to relate criteria to building requirements, material properties, building systems, and products. The utilization of selected criteria and nomograph computer programs of many types can provide realistic design alternates for economic evaluation.

The accuracy achieved with graphical nomograph computers should be comparable to that obtainable on a slide rule, provided care is taken in the selection of scales. Automatic nomograph computers can achieve even greater accuracy if required.

Nomograph computers can be utilized to permit the simultaneous evaluation of the several design factors established by the architect, the climate and indoor comfort requirements, occupancy requirements, the mechanical and electrical systems designer, and the energy requirements of the associated building systems -- all against a single criterion.

The construction of nomographs of all types is well documented in the literature (2,3) and is beyond the scope of the material presented here. To construct the nomograph computer, it is first necessary to develop the underlying equation or equations that relate the design variables. These equations can usually be built up through simple arithmetic operations.

The development of nomograph computers of the type required for evaluating most of the variables associated with the economic analysis of integrated building systems can be explained in a few simple constructions. Namely:

1. Addition relationships of the type:

   $f(z) = f(x) + f(y)$

2. Subtraction relationships of the type:

   $f(z) = f(x) - f(y)$

3. Multiplication and/or division relationships of the type:

   $f(x) = \frac{f(y)}{f(z)}$

Typical examples of addition and subtraction types of nomographs using linear functions are illustrated in Figures 2 and 3 respectively. As shown, the first step is to lay out x and y scales of convenient length and distance apart. These scales are first calibrated temporarily, using values of the functions involved rather than the variables. This temporary marking will be linear, increasing in the same direction or opposite direction as required. To lay out these scales, it is necessary to know the range of the function, which depends on the probable range of values of the respective variables.

The multiplication and/or division operation involving three variables can be related by means of "N-Charts" constructed for equations of the type given in Figure 3. As before, three lines are required, one for each variable. For this type of nomograph, only two lines are parallel. These variables can represent y, and either x or z. Referring to Figure 3 for the function illustrated, two scales, x and z, are assigned to the two parallel lines as shown. The center line represented by y is slanted and intersects the parallel lines, accounting for the name, N-Chart.

By proper arrangement of the nomograph scales in relation to the reconstruction by steps of the underlying criteria equation, a nomograph computer can be rather easily constructed from combinations of Figures 2, 3, and 4. The effects of changes in all of the major design variables are represented in relatively compact nomograph computers.

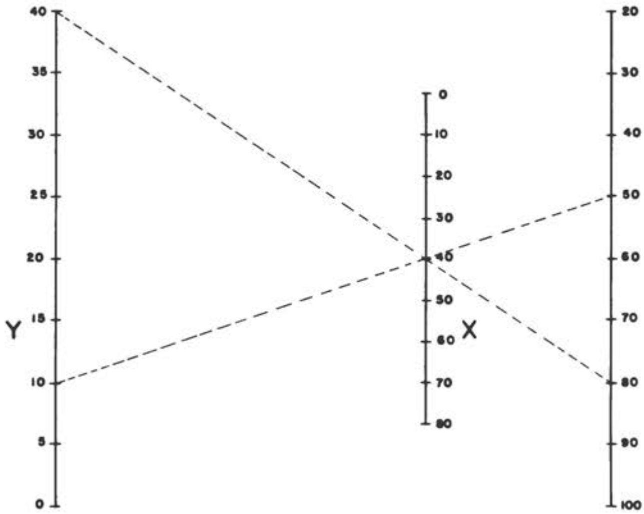

Figure 2 -- Equation of the form f(x) + f(y) = f(z)

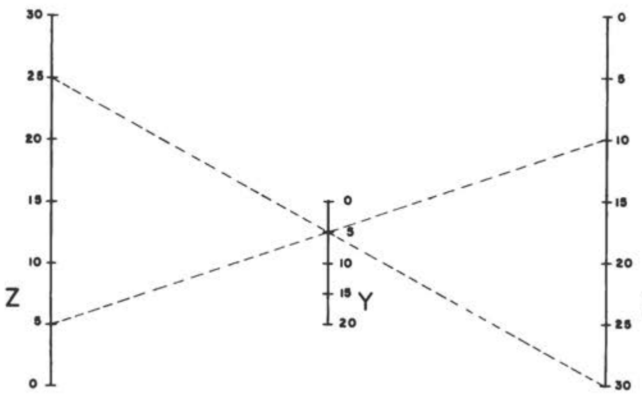

Figure 3 -- Equation of the form f(x) - f(y) = f(z)

AUTOMATIC NOMOGRAPH COMPUTER

A new automatic electronic computer (1) which utilizes the principles of nomograph construction[1] apears to have significant application for architectural-engineering design analysis. This computer requires no graphical construction prior to use and avoids

[1] Now under development for the United States Air Force, RADC, New York.

the accuracy limitations and slowness of human operation often accompanying the use of the graphical nomograph computers described above.

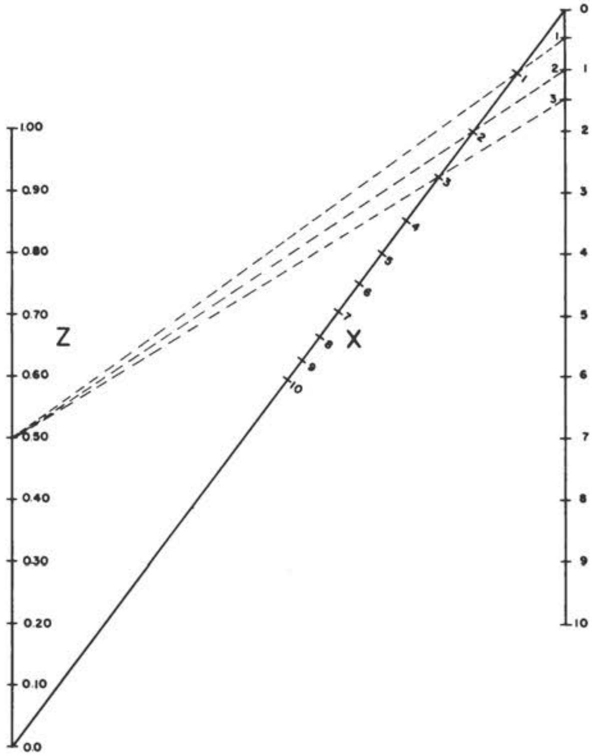

Figure 4 -- Equation of the form $f(x) = \frac{f(y)}{f(z)}$

As shown in Figure 5, the automatic nomograph computer permits a remapping of the nomograph equation F(U, V, W) = 0 from the standard graphical nomograph form to columns of countable bits which are detected and counted by a sensitive electronic circuit.

If a nomograph for a three-valued equation is placed in a Cartesian coordinate system, answer values (U, V, W) lie on a straight line, and so have x and y coordinates related in a simple linear manner. This permits solution of functions -- analytical or empirical -- by the techniques of automated nomography.

On running the film image past photoelectric reading heads, identification has been made of preset U and V values, hence of U and V addresses, etc. The original equation, which was difficult in the original variables and content values, is easy in terms of present addresses (locations) of these contents; namely, a linear function of them. Circuitry can identify an address on the W film strip of the stored, cumulative x and y values which satisfied this linear relation. It simultaneously identifies, or recognizes, the corresponding stored W content (value) that is the answer.

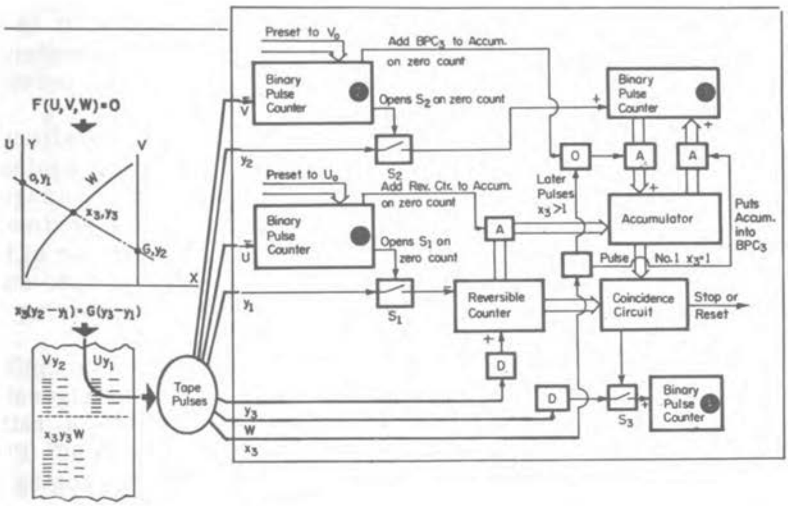

Figure 5 -- Automatic nomogram.

In this counting circuit, the pattern of bits (on film or plate) is conveyed to and read by a photoelectric cell. U and V pulses are counted as they are received up to the point where they equal input values, U_0 and V_0.

Corresponding Y's, on a parallel column, are counted at the same time and are shut off with the U, V counts so that, by the time the first stage of the film has been scanned down to the dotted line, a count of Y_2 has been built up in BPC3, of $-Y_1$ in Rev. Ctr., and of their sum in the Accumulator.

As the film below the dotted line is scanned, W counts are accumulated in BPC4. On the very first X_3 pulse, and only on that pulse, the Accumulator amount of $Y_2 - Y_1$ is dumped into BPC3. Thereafter, BPC3 goes into the Accumulator with every X_3 pulse so that at any time there are X_3 of the quantity $Y_2 - Y_1$ in the Accumulator.

The Rev. Ctr., however, holds $Y_3 - Y_1$, and the Coincidence Circuit opens the switch S_3 when these two counts are equal, identifying and holding W, the answer count, in BPC4.

DEFINING THE PROBLEM

An important problem in some of today's modern buildings is posed by simultaneous heating and cooling demands during winter operation. Heat must be supplied to perimeter spaces while cooling loads are simultaneously generated in building interior spaces. Utilization of the principle of heat redistribution (4) in the design of a building can be evaluated, provided criteria are available to compare the requirements of simultaneous heating and cooling in different parts of the same building. Where "free cooling" with outside air cannot provide sufficient cooling capacity, it is advantageous to use heat rejection from the refrigeration condenser to offset the building and ventilating air heating load, provided the level of the heat source is usable.

Criteria, as defined, are tests by which design factors affecting the economics of heat redistribution may be compared against a standard. We can now establish as our criterion the percentage of the design heating load capable of being supplied to the perimeter after the ventilation air has been preheated. The evaluation of this criterion, when related to the applicable design variables, could be used to justify operating refrigeration equipment during the winter cycle as a heat pump.

For every 12,000 BTU/hr removed by the refrigeration chiller, approximately 15,000 BTU/hr are available at the refrigeration condenser. The building lighting system can provide a rather stable heat source which can be easily removed with 60° F (or above) chilled water (7). This is accomplished by arranging the refrigeration equipment and piping as follows. In Figure 6, condenser water leaves the refrigeration machine (6) at 125° F and a portion of it is circulated first to the outside air coil. The condenser water leaves the outside air coil and mixes back with the remainder of the 125° F condenser water before entering the perimeter heating system loop. A quantity of water equal in amount to that entering the perimeter heating system loop is returned to the condenser water system, completing the circuit. A portion of the condenser water is continuously exchanged with an outdoor cooling tower or air cooler in relation to operating refrigeration demands.

The applicable system variables which affect the selection of architectural materials of construction and mechanical refrigeration equipment can be related in terms of criteria, climatic, occupancy, and system requirements, as follows:

BUILDING SYSTEM VARIABLES

1. Design Factors Established by Architectural Designer

   a. Percentage glass in exterior wall: The percentage of total exterior floor to ceiling wall area represented by single pane glass. This architectural design item has a significant effect on the building system heating and cooling loads.

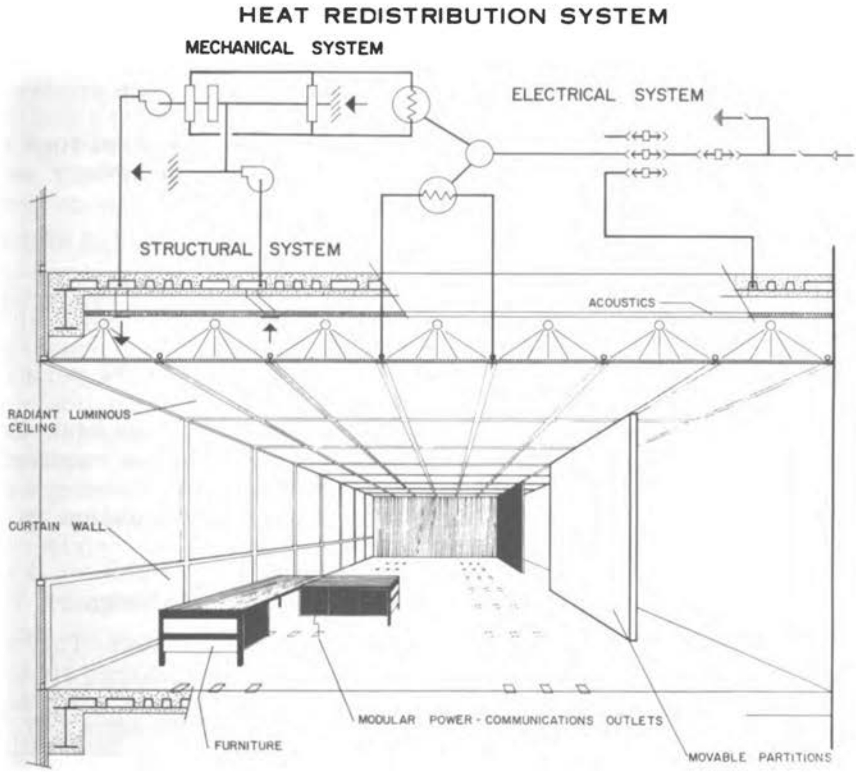

Figure 6 -- Total environment: Dynamically integrated system.

b. Wall U factor: The heat transmission coefficient for the component masonry or curtain wall section, expressed in units or BTU/hr-ft^2 -$^\circ$ F. This item is determined according to the procedure recommended in the 1961 ASHRAE guide and also effects building system heating and cooling loads.

c. Perimeter wall area/total floor area: The ratio of the total building exterior floor to ceiling wall area to the occupied building floor area. This item is determined by space requirements and established building to floor to ceiling height.

d. Roof U factor: The heat transmission coefficient for the composite roof section expressed in units of BTU/hr-ft^2 -$^\circ$ F.

e. Roof area/total area: The ratio of the total roof area to the total occupied building floor area. This item decreases as the number of floors increases.

f. Perimeter floor area/total floor area: The ratio of combined floor areas for all perimeter occupancy zones to the occupied building floor area. This item expresses the percentage of the total occupied building area that is considered perimeter occupancy.

2. Occupancy Requirements

   a. Interior sensible load to panels: The estimated load removed by chilled water in all interior occupancy zones during winter operation.

   b. Perimeter sensible load to panels: The estimated load removed by chilled water in all perimeter occupancy zones during winter operation. This item is usually evaluated at a "no sun" condition.

3. Requirements of System Equipment

   a. Refrigeration machine brake horsepower/ton as heat pump: The actual operating brake horsepower per ton required to run the refrigeration machine with elevated condenser water temperature of approximately 125° F and no change in the specified chiller leaving water temperature.

4. System Design Factors Selected by Mechanical Designer

   a. Preheat coil outlet air temp -- outside air temp: The temperature difference between the preheat discharge air temperature selected and the winter outside air design temperature.

   b. Outside air circulated: The total outside air quantity required expressed in per square foot of conditioned space for all occupancy zones combined.

   c. Space D. B. temperatures: The design space dry bulb temperature in winter that is required for comfort.

Once these primary system variables have been defined, they must be related by an equation or other mathematical technique which is then used as a basis for constructing the nomograph computer.

MATHEMATICAL CRITERIA

For the problem previously described, a mathematical equation can be derived to relate the materials of building construction and the extent to which they are used with economic criteria previously defined. Applying the principle of heat redistribution for winter building operation, the following variables and criteria provide a basis for deriving a mathematical equation relating economic criteria to specific design parameters. For the purpose of derivation we must define the following nomenclature:

T_e = absolute temperature at the refrigeration evaporator ($460^\circ + {}^\circ F$).

T_c = absolute temperature at the refrigeration condenser ($460^\circ + {}^\circ F$).

E_m = efficiency factor for conversion of electrical to mechanical energy at motor operated compressor.

E_c = refrigerant Carnot efficiency factor.

B_t = actual refrigeration machine brake horsepower/ton at a specified T_c and T_e.

Q_i = interior heat gain (BTU/hr-ft^2 interior floor area).

Q_p = perimeter space heat gains (BTU/hr-ft^2-perimeter floor area).

C_v = CFM ventilation air/ft^2-total floor area.

U_w = exterior wall construction U factor (BTU/hr-ft^2-$^\circ F$).

U_r = Roof U factor (BTU/hr-ft^2-$^\circ F$).

H = Criterion: percentage heating load supplied to perimeter system/100.

F_r = roof area/total floor area.

F_w = perimeter exterior wall area/total floor area.

G = percentage glass in exterior wall/100.

P = percentage perimeter floor area/100.

t_n = required discharge air temperature leaving ventilation air preheat coil ($^\circ F$).

t_a = winter space controlled dry bulb temperature ($^\circ F$).

t_{oa} = winter design outside air temperature ($^\circ F$).

The minimum thermal energy for heating by redistribution of available heat gains is evaluated at a "no sun" condition. For a "no sun" condition, the energy supplied by the refrigeration condenser circuit to the building ventilation air and to the perimeter heating system equals

$$F_r U_r H(t_a - t_{oa}) + F_w U_w H(1 - G)(t_a - t_{oa}) + 1.13\, GF_w H(t_a - t_{oa}) + C_v 1.08\,(t_n - t_{oa})$$

which, upon combining and factoring of terms, reduces to

$$H(t_a - t_{oa})\left[U_w F_w (1 - G) + 1.13\, GF_w + F_r U_r\right] + 1.08\, C_v(t_n - t_{oa})$$

The heat removed at the load source per square foot of total floor area is given by the expression

$$[(1 - P)\,Q_i + PQ_p]$$

The coefficient of performance of a refrigeration system is defined as the ratio of the desired effect to the energy required to produce that effect or

$$\text{C.O.P.} = \frac{\text{heat absorbed in evaporator}}{\text{energy supplied to compressor}} = \frac{E_c T_e}{T_c - T_e}$$

where (E_c) relates the actual thermodynamic efficiency of the refrigerant in terms of an ideal reversible Carnot cycle.

The reciprocal of the coefficient of performance of a refrigeration system can be expressed in terms of the performance of a specific refrigeration machine operating between heat source and heat sink temperatures of (T_e) and (T_c) respectively by means of the following dimensional equation:

$$\frac{T_c - T_e}{E_c\,T_e} = \frac{(2545\ \text{BTU/hr-BHP})\ E_m\ B_t}{12{,}000\ \text{BTU/hr-ton}}$$

Assuming a conservative value for (E_m) equal to 0.85, the above equation reduces to

$$\frac{T_c - T_e}{E_c\,T_e} = B_t/4$$

where ($B_t/4$) represents the ratio of BTU/hr heat of compression to BTU/hr heat removed at the evaporator.

The total heat rejected by the refrigeration condenser and thus available for heating, ventilation air, and offsetting building heat losses equals:

$$[(1 - P)Q_i + PQ_p]\,[1 + B_{t/4}]$$

Equating the total heat rejected by the condenser to the heat required for the building heating and ventilation load in terms of our defined criterion (H), and rearranging, we obtain the following equation:

$$[1 + B_t/4] = \frac{H(t_a - t_{oa})\left[F_w U_w (1 - G) + 1.13\ F_w G + F_r U_r\right] + 1.08\ C_v (t_n - t_{oa})}{[(1 - P)Q_i + PQ_p]}$$

This equation is the derived equation expressing the mathematical relationship among the architectural-mechanical-electrical-structural design factors, climatic, occupancy and system requirements and the basic criteria. Each such equation represents a program with only one criterion. In practice, many programs with separate criteria can be arranged together.

Figure 7 (page 52) represents a nomograph computer relating the variables in this equation. Appropriate nomographs can be constructed by combining several nomographs of the addition, subtraction, and multiplication type described in Figures 2, 3, and 4. To better illustrate the procedure used in the construction of Figure 7, let us first rearrange our Criterion Equation in the following form:

$$1.08C_v(t_n - t_{oa}) = [1 + B_t/4][(1-P)\,Q_i + PQ_p] -$$
$$H\,(t_a - t_{oa})\;[F_wU_w(1-G) + 1.13\;F_wG + F_rU_r]$$

The entire right side of above equation was transformed into 14 separate simple multiplication, addition, and subtraction functions as given in Table 1.

TABLE 1 -- CONSTRUCTION ANALYSIS OF NOMOGRAPH COMPUTER

Variables		Multiplication Nomograph	Addition Nomograph	Subtraction Nomograph
R_1	=	$1.13G$		
R_2	=	$(1-G)U_w$		
R_3	=		$R_1 + R_2$	
R_4	=	R_3F_w		
R_5	=	$R_4(t_a-t_{oa})$		
R_6	=	$U_r(t_a-toa)$		
R_7	=	R_6F_r		
R_8	=		$R_7 + R_5$	
R_9	=	R_8H		
R_{10}	=	PQ_p		
R_{11}	=	$(1-P)Q_i$		
R_{12}	=		$R_{10} + R_{11}$	
R_{13}	=	$R_{12}[1 + B_t/4]$		
R_{14}	=			$R_{13} - R_9$

Upon analysis of the simplified functions above and by proper choice of coincident scales, a continuous nomograph was constructed to solve for the value represented by the entire right side of the rearranged Criterion Equation. Referring to Figure 7, notice that line solution steps 1 through 9 enable us to determine the value of the right side of our equation which from Table 1 is represented by R_{13}-R_9.

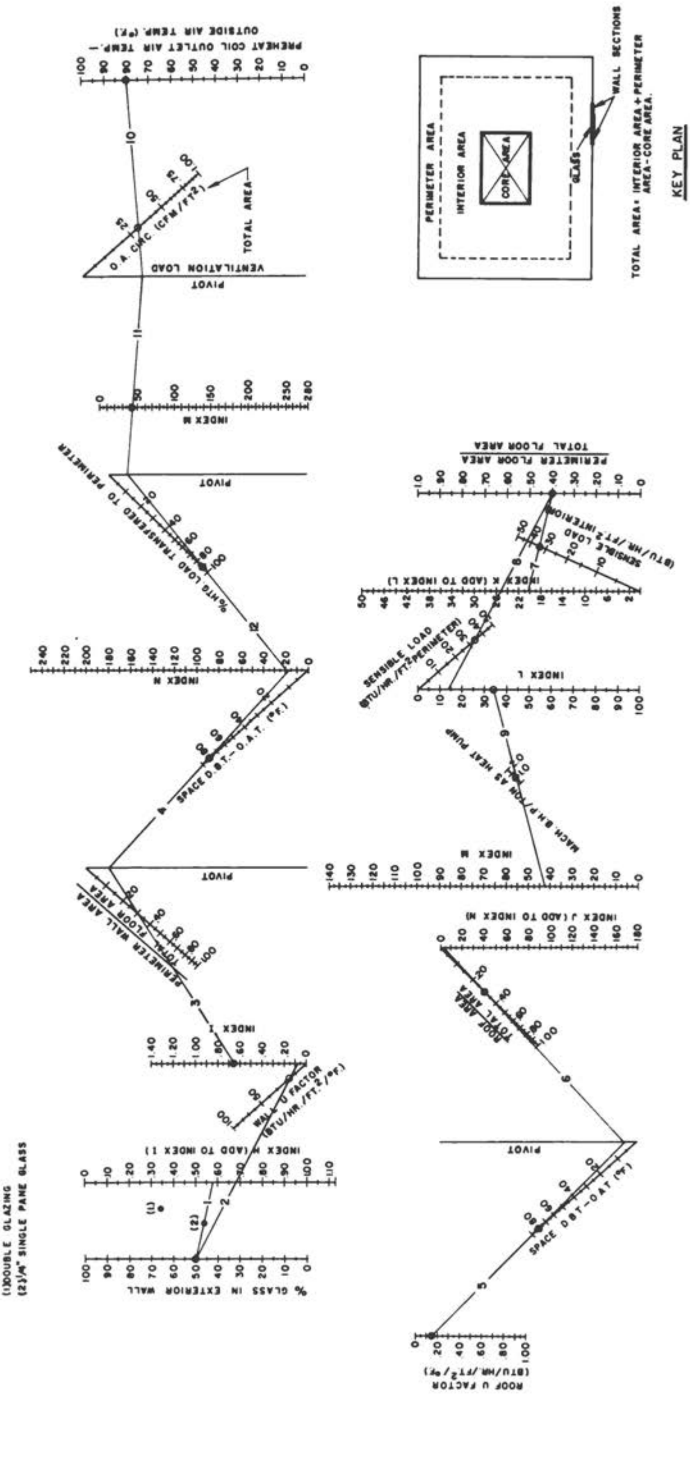

Figure 7 -- System heat redistribution nomograph: Typical solution.

Scales that do not directly relate material properties, energy sources, building requirements, equipment and space design factors may be left unscaled and treated as "pivots" or scaled and identified as "indexes." Notice that the R_n variables previously given as R_1 through R_{14} have been either treated as index scales or pivots. The pivots are left unscaled since only the intersection of the solution line with the pivot is required. Variables R_4, R_6, R_9, and R_{14} are represented by unidentified pivots. The remaining R_n variables have been treated as index scales and can be readily identified from Figure 7 by means of Table 2.

TABLE 2 -- IDENTIFICATION OF NOMOGRAPH SCALES

Index Heating	Corresponding Value of R_x
H	R_1
I	R_2 and R_3
J	R_7
K	R_{11}
L	R_{10} and R_{12}
M	R_{13}
N	R_5 and R_8

Note that the left side of our rearranged Criterion Equation can be rewritten as: $R_{14} = 1.08C_v(t_n - t_{oa})$. By construction of a nomograph section relating the variables of the left side (as given by Steps 10 and 11 of Figure 7) we are able to join the two separately arranged nomograph constructions by means of a coincident scale (R_{14}) between $R_{14} = R_{13} - R_9$ from the right side of the Criterion Equation and $R_{14} = 1.08\ C_v(t_n - t_{oa})$ from the left. Notice that the final step in the illustrated line solution (Step 12) is arranged to solve $R_9 = R_8H$ intersecting our criterion (H) along the diagonal. We have thus constructed a computer from separate nomographs capable of relating all input variables in terms of their net effect on the selected criterion (H).

A NOMOGRAPH COMPUTER PROBLEM

The problem is to establish the feasibility of utilizing 125° F condenser water to provide heat for a three-story building and proposed lighting levels of 50 and 150 foot-candles. The fixtures utilized are integrated,2-lamp,4-ft. recessed luminaires which are cooled by circulating chilled water at 60° F. Determine the quantity of heat capable of being supplied to the building ventilation air and perimeter heating systems if the heat release from the lighting system is used as the heat source for the refrigeration machine operated as a heat pump during the winter cycle. The proposed building architectural, mechanical, and electrical system design conditions are given below:

Factors Established by Architectural Designer

1. Percentage glass in exterior wall 50%
2. Wall section U factor . . . . 0.15 BTU/hr-ft^2-° F
3. $\frac{\text{Perimeter wall area}}{\text{Total floor area}}$ 0.3
4. Roof U factor . . . . 0.15 BTU/hr-ft^2-° F
5. $\frac{\text{Roof area}}{\text{Total area}}$ 0.3
6. $\frac{\text{Perimeter floor area}}{\text{Total floor area}}$ 0.4

Factors Established by Electrical Designer

1. Electrical input to lighting system per square foot:
   a. 50 foot-candles . . . . 3.3 watts
   b. 150 foot-candles . . . . 9.9 watts

Factors Established by Mechanical Designer

1. Space dry bulb temperature . . . . 75° F
2. Outside air temperature . . . . -5° F
3. Ventilation air requirements . . . . 0.3° CFM/ft^2

Occupancy Requirements

1. Heating equivalent of electrical input to lighting system:
   a. 50 foot-candles . . . . 11.2 BTU/hr-ft^2
   b. 150 foot-candles . . . . 33.6 BTU/hr-ft^2

Requirements of System Equipment

1. Machine brake horsepower per ton 1.1

Referring again to Figure 7, all of the known or selected system design variables (designated by circles) are located on the appropriate scales. Solution is accomplished by connecting with straight lines each scale of the nomograph computer as indicated. The solution of each section of the nomograph computer requires that any two of the three variables be known and be used in the solution of the scale adjacent to it, etc., until a complete path is made connecting all these scales, pivots, and indexes of the nomograph computer in the order illustrated by the line numbers.

For the case of a 150 foot-candle installation, operating the building refrigeration system as a heat pump during the winter would provide 100% of the ventilation air heating demand, and supply approximately 90% of the maximum building heating load. Although not illustrated, the 50 foot-candle installation could provide only approximately one-half of the ventilation air heating requirements. Note that reducing the amount of glass area and/or modifying the exterior wall and roof construction would decrease the heating demand required by the building heating system. Under such new conditions, a lighting level below 100 foot-candles might prove equally adequate.

ECONOMIC ANALYSIS OF FIRST COSTS

Having established the criteria for comparing the relative effects of interrelated system variables, an economic cost analysis can now be made of specific first costs and operating costs for each alternate design selected.

Carrying our illustrative problem one step further, let us next evaluate the first costs of alternate building designs using conventional and integrated condenser water cooled luminaires. This comparison will permit us to determine whether or not significant first cost savings are possible by dynamically integrating the building mechanical and electrical systems. This comparison is illustrated in Table 3.

TABLE 3 -- FIRST COST COMPARISON:

150 Foot-Candle Conventional and Integrated Air Conditioning and Lighting Building Systems

		Conventional Luminaires		Integrated Water Cooled Luminaires[1]					
Building Alternate	TBC	LTG Cost as % TBC	AC Cost as % TBC	LTG Cost as % TBC	AC Cost as % TBC	Increase in LTG Cost as % TBC	Decrease in AC Cost as % TBC	Decrease in Arch. Cost as % TBC	Total Decrease Bldg. Cost as % TBC
#1	$18	18.3	27.8	20.8	15.2	2.5	12.6	1.7	11.8
#2	$20	16.4	25.0	18.8	13.7	3.4	12.3	1.7	11.6
#3	$25	13.2	20.0	15.0	11.0	1.8	9.0	1.9	9.1

[1] Four (4) foot recessed luminaires were used in all comparisons.

KEY: TBC = Original total building cost in $/sq. ft. floor area at 150 foot-candles.
LTG = Lighting system.
AC = Air conditioning system.

It is interesting to note that, in the case of the building alternate costing $20.00 per sq. ft., an increase of 3.4% in the cost of lighting out of the total building cost required for integrated luminaires over and above that for conventional luminaires, permits a 12.3% savings in total building cost associated with the air conditioning system, and an architectural savings of 1.7% of the total building cost associated with less space between floors for mechanical rooms, shafts, etc.

DESIGNING THE OPERATING CYCLE

The character of the operating cycle for a specific building occupancy and climate can be evaluated by determining the month-by-month energy demand of the building heating and air conditioning system. The significance of designing the operating cycle to match specific building requirements is apparent from an analysis of comparable systems on a month-by-month basis, wherein differences in the energy demand for each type of system can be demonstrated during different seasons of the year. Figures 8, 9, and 10 are based on a comparison study (6) of a 15-story, free-standing, steel-framed structure, sheathed with 100% floor-to-ceiling insulating glass curtain wall. The building is of a contemporary type and the analysis is based on a comparison of conventionally separate mechanical and electrical building systems with an integrated mechanical-electrical building system.

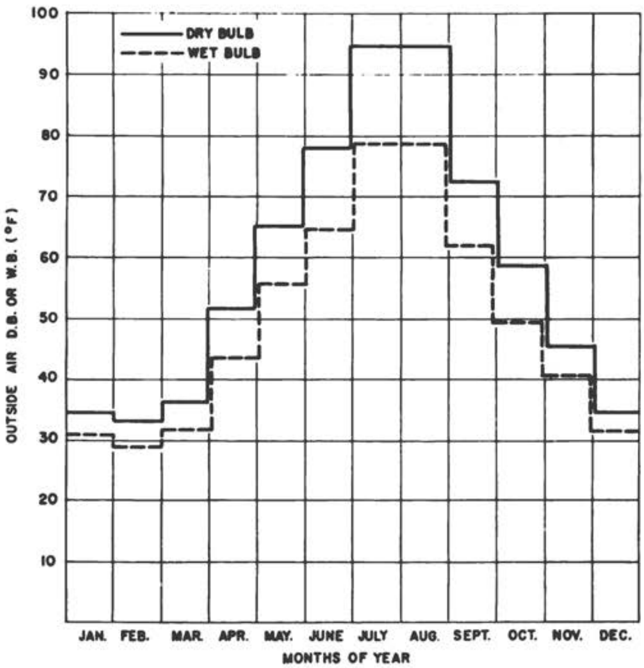

Figure 8 -- Monthly air temperatures for systems comparison.

A specific climate was selected, using monthly average outside air, wet and dry bulb temperatures, and a maximum sun-loading to establish the probable maximum steam and electrical demands for each month. Differences in ordinate values represent direct annual operating savings resulting from the interaction of the integrated mechanical-electrical system responding to the same cooling load as conventionally separate mechanical and electrical systems.

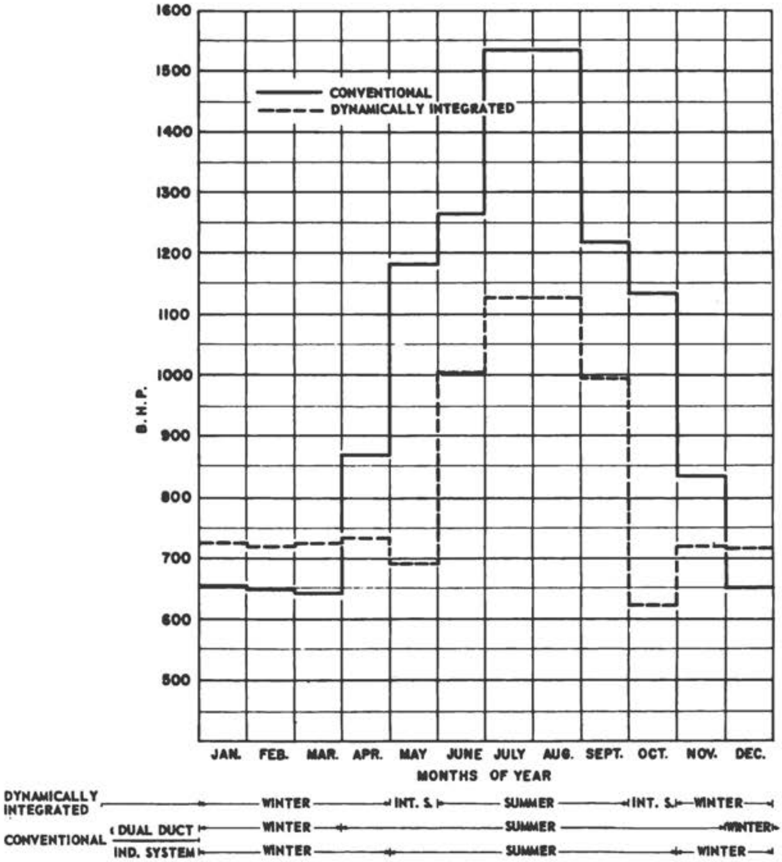

Figure 9 -- System brake horsepower demand.

SUMMARY

Facilities design requires intelligent development and utilization of design concepts and techniques which permit each system to become a functional part of all others.

The creation of total environment is possible only through the dynamic integration of the mechanical, electrical and structural systems. These systems must no longer be considered as independent of each other; the selection and design of each system must be developed concurrently. The dynamic integration of the building mechanical and electrical systems with the structure can only be achieved when all of the building system variables are analyzed simultaneously to utilize all available energy sources affecting the building. Therefore, it is obvious that economic analysis requires evaluation of total alternate building designs.

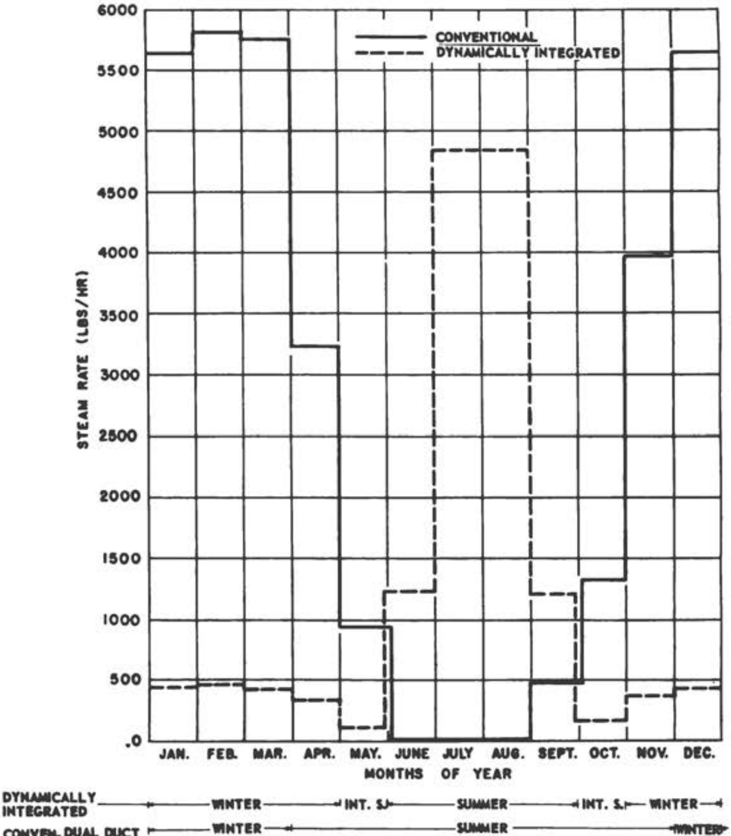

Figure 10 -- System steam demand.

We have described a method of constructing a nomograph computer for economic evaluation of alternate building designs. Nomograph computers permit material properties, architectural space relationships, building occupancy and climate requirements, etc., to be related directly to building energy demands through appropriate criteria. Starting from basic equations and/or system relationships, we have shown how to relate pertinent design variables with specific criteria graphically and automatically. We have also demonstrated the use of nomograph computers in a typical design example, as a practical tool for establishing dynamically integrated, alternate building designs. This technique enables the thorough evaluation of all pertinent design variables established by the mechanical-electrical-structural-architectural designers prior to the application of economic cost analysis procedures.

Utilizing this technique, the architect-engineer can design the optimum operating cycle for a building with a specific climate and occupancy, by applying selected criteria to the properties and amounts of architectural materials as related to the heating and cooling demands of the structure and the environment. The nomograph computer technique permits the architect-engineer to select and economically evaluate a wide range of architectural materials, once their properties and proportions have been related to corresponding energy demands.

As nomograph computers become more widely used by architects and engineers, building systems research programs can be established to develop mathematical relationships which include a wise variety of criteria for economic evaluation in areas where current techniques of analysis are not at present adequate.

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Methods of Measuring the Area and Volume of Buildings

By Allen E. Brass, National Research Council of Canada

Abstract: The importance of establishing a uniform method of measuring area and volume of buildings for the purpose of cost comparisons is recognized by building scientists and building owners throughout the world. This paper reviews the material on this subject available in the library of the Division of Building Research (Canada), and reports on an international survey involving 34 organizations in 24 countries. Similarities and differences among methods of measurement currently in use are summarized in tabular form.

CALCULATIONS OF THE SIZE of buildings may be made for a variety of purposes. Perhaps the most common of these is to establish the cost of construction in terms of cost-per-unit area, or volume. It is important that calculations of the size of different buildings be made in a similar manner, so that comparisons will be valid, and so that the resultant figures for different cases will be consistent. This suggests that there is a need for the establishment of a standard method for the calculation of building sizes.

Such a need has been recognized by different groups associated with the construction industry, and some work has already been done toward standardization. In the United States, England and Australia, for example, there are standards or recommendations prepared by organizations such as the American Standards Association, American Institute of Architects, the Royal Institute of British Architects, and the Royal Australian Institute of Architects. Similar standards have been prepared by comparable organizations in Finland, Norway and Sweden. Recently, the Division of Building Research of the National Research Council of Canada undertook a study of this matter at the request of the Research Committee of the Royal Architectural Institute of Canada.

Even a cursory examination of the literature on the subject indicates a wide variation in the procedures used for determining building size in countries around the world, as well as a resulting general lack of uniformity in terminology and methods of measurement. It was decided, therefore, to undertake a comprehensive

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study of existing methods as a first step toward the possible development of suitable standards of measurement.

This study has been completed, and it is being reviewed by a Committee of the Royal Architectural Institute of Canada. In the meantime, the importance of establishing a uniform method of measuring area and volume of buildings for the purpose of cost comparisons was recognized by the Building Research Institute Committee on Methods of Building Cost Analysis. This paper deals with that subject. It is based upon a review of material available in the library of the Division of Building Research, as well as on an international survey involving inquiries to 34 organizations in 24 countries. It is interesting to note that replies from Denmark, France, Japan, and New Zealand indicate that the cubic content of a building is a measurement rarely used in those countries.

The survey was concerned in very broad terms with methods of measuring the size of buildings, and was not confined to the methods used in calculating area and volume for cost analyses. This paper is, therefore, an extract from that more general work. The aim of this report is not to propose a specific standard for adoption, but to summarize the similarities and differences among various methods of measurement currently in use. It is hoped that this comparison will stimulate discussion and encourage a further exchange of ideas on the subject, and that in this way it will assist in the further development, and perhaps the eventual broad adoption, of suitable standards for determining the area and volume of buildings for the purpose of cost comparison.

METHODS OF MEASURING AREA

The various methods of measuring the area of buildings are applicable to buildings of all types. They refer to over 24 items for which 18 terms are used. An analysis of these items according to the detailed definition and method of taking dimensions reveals that they can be grouped into six general categories: gross area, net area, occupancy area, usable area, circulation area, and service area. The methods of measurement which fall into the first category, referred to as "gross area," are those intended primarily for use in cost comparisons.

In gross area measurement are included all those methods that encompass the area contained within the outer faces of exterior walls, or the center line of party walls between buildings. Fourteen methods of measurement fall into this category and some of the terms used include the following: total story area, gross area, architectural area, building area, and story area. Table 1 lists the items mentioned in the various methods of measuring gross area, other than in the major usable portions of a building. The items shown as "Included" are those that were specifically mentioned as being included in more than half of the methods of measurement, or which would presumably be included by the definition and method of taking dimensions. The same is true of items in the "Excluded" column. In the "In Doubt" column are those items that are included in some methods and excluded in others, but which are not mentioned as either being included or excluded in more than half of the cases.

TABLE 1 -- ITEMS MENTIONED IN METHODS OF MEASURING GROSS AREA OF A BUILDING OTHER THAN ITS USABLE PORTIONS

Items Included in Majority of Cases	Items Excluded in Majority of Cases	Items in Doubt
Interior partitions Stairways Elevator shafts Duct spaces Projecting stories Mezzanines Halls Vestibules Closets Fireplaces Bay Windows Dormers Garrets Chimneys Utility rooms Finished rooms in basements and attics and stairs and halls leading to them	Exterior paved areas Exterior steps Pipe trenches Crawl spaces Roof overhangs and canopies Carports Interior light shafts	Porches Balconies and balcony corridors Penthouses Attached and built-in garages Unfinished portions of basements and attics Unenclosed portions of a story under another story Unenclosed roofed-over paved area

METHODS OF MEASURING VOLUME

The majority of methods of measuring the volume of a building are applicable to all building types; the remainder apply primarily to housing. The various items fall into two categories which, for purposes of this study can be referred to as gross volume and net volume. The gross volume figure is the one that would be used as the basis for cost comparisons. Some of the terms used in referring to this item are: building cube, cubic contents, cubical extent, total volume, architectural volume, and building volume.

With respect to the calculation of gross volume, without exception the plan dimensions are taken to the outer faces of exterior walls or to the center line of walls separating buildings. There is considerable variation, however, in the methods outlined for the measurement of height to be used in calculating gross volume.

The various low points for taking the height are:

1. Bottom of concrete foundations
2. Average depth of footings
3. Plans of the foundation which may be:
   a. Level of bottom of the foundation trenches or under side of the slab, or
   b. Half the depth of piers or piles below the under side of beams carried on them, or
   c. For existing buildings, 2 ft. below lowest floor level for buildings up to three stories, and 5 ft. for buildings four or more stories, or
   d. Mean depth for irregular foundations
4. Top of the concrete foundation
5. A plane 6 inches below the lowest floor
6. A plane 20 cm below basement floor level where it is on ground
7. The under side of the lowest floor
8. One foot below the top surface of the lowest floor or one foot below the average ground level around the enclosing walls, whichever is lower
9. The upper surface of the lowest floor level
10. Grade level (for porches only).

The most common low point for taking height dimensions is 9 (the upper surface of the lowest floor level). It is indicated in seven of the 14 methods for measuring volume. The next most common is 7 (the under side of the lowest floor level) indicated in five of the 14.

The high point to which the height dimension is taken also varies considerably and is specified in various ways as follows:

1. Half the height of a pitched roof from the intersection of the walls and the roof to the ridge
2. Half the height of a pitched roof between the level of the eaves and the ridge.
3. The level of the eaves of a pitched roof
4. A plane 2 ft. above a flat roof
5. The exterior surface of the roof

6. The interior surface of the roof construction
7. The upper surface of the upper ceiling construction
8. The top of the ridge, or peak of an attic roof.

Of these, the most common is 5 (the exterior surface of the roof), which is indicated in nine of the 14 methods. The next most frequently used are 1 and 2, which are referred to three and four times respectively.

Table 2 lists the total number of different items mentioned in the 14 different methods of measuring volume in addition to the major usable portion of a building. It was compiled in a manner similar to that used for Table 1.

TABLE 2 -- ITEMS MENTIONED IN METHODS OF MEASURING GROSS VOLUME OF A BUILDING OTHER THAN ITS USABLE PORTIONS

Items Included in Majority of Cases	Items Excluded in Majority of Cases	Items in Doubt
Porches	Terraces	Verandas
Bay windows	Exterior steps	Balconies
Oriels	Exterior garden walls	Fleches
Turrents	Breezeways and paved roofed-over areas	Lanternlights and skylights
Domes	Light wells and areaways	Foundation and construction below lowest floor level
Dormers	Canopies, cornices, roof overhangs	Interior courts
Chimney stacks	Parapet walls	Attached buildings
Attics and roof spaces	Gateways	Penthouses
Interior staircases	Sheds and covered yard spaces	Crawl spaces
Cellars and mechanical rooms below basement floor level	Covered walks	Garages
Basements		Towers
Mezzanines		

CONCLUSION

In general, the various methods of measurement are concerned with four categories of space. These are:

1. The major usable portions of the building
2. Plan projections such as porches, carports, bay windows, and balconies
3. Roof spaces such as attics, penthouses, machinery rooms and other spaces above the roof

4. Foundation spaces such as basements, crawl space, pipe trenches, unexcavated spaces, and special foundations.

The greatest difficulty arises from the arbitrary way in which the last three categories of spaces are handled. With respect to these, some of the methods in use have extensive lists of the items to be included and excluded and are, therefore, very comprehensive in their scope. Others list only a few items and leave many open to question.

In several of the methods, these additional spaces are considered in part, and their size is multiplied by an appropriate factor. For example, some methods indicate that only half the area or volume of an enclosed porch is to be included in the calculations. In others, the spaces are included only where the height exceeds a certain minimum, and excludes where it is less. For example, some methods provide that all spaces 6 ft. 6 in. or higher are to be included in area and volume calculations regardless of use, while in others attic spaces higher than 1.5 m or 5 ft. are included and those lower are excluded from the calculations. In most methods, however, all of the spaces included in the calculations are measured in full.

The two standards for the measurement of area and volume of buildings prepared by the Finnish Architect Association Standardization Institute deserve special mention, because they are among the most comprehensive and detailed standards reviewed in the study. They are virtually glossaries of methods for making various measurements of the size of buildings. The one on area, for example, includes methods of measuring the area of a room, of a dwelling unit, of one story, of a building, and of the projected plan area. In each case, information is included on the method of taking dimensions as well as the items to be included and excluded, and there are illustrations to amplify the text. Each of these standards carries an explanation of the number of significant figures and the degree of accuracy to be used in the calculations, as well as an example worked out to show how to calculate and express the results. In the standard on the measurement of area, there is also a list of definitions of terms such as story, attic and mezzanine, to further clarify the description of the items listed.

It is apparent that an outline of the method of measuring building size should specify the method of taking dimensions and the items to be included as well as excluded, and should be presented in sufficient detail so as to be applicable to the wide variation in configuration of building plans and sections. The study has revealed considerable information from which standards for measuring the area and volume of buildings can be developed for use in cost analyses. It is hoped that this paper will be a contribution toward that objective. The study of the measurement of buildings is continuing within the Division of Building Research and, on an international scale, it is expected that the Conseil International du Batiment will be developing it still further in the near future.

Open Forum Discussion

Moderator: Charles A. Bogert, Western Electric Company

Panel Members: Messrs. Brass, Griffith, Grimm, Meckler, and Wenzler, and:
Homer J. Smith, Registered Architect*
William S. Kinne, Jr., Deputy Director, Planning and Construction; and Consultant, University Facilities Research Center, University of Wisconsin*
W. Allen Cleneay, Staff Architect, Monsanto Chemical Company
Dan E. Morgenroth, Manager, Technical Market Development, Owens-Corning Fiberglas Corporation.

Mr. Kinne: I am going to supplement what was said, rather than comment directly on the papers. Equal value is not particularly susceptible to tax manipulations of the sort that we have discussed. I would caution you, as you make an analysis, to consider such aspects as how much money your client has, where it comes from, and what it is worth in today's society. One other somewhat divergent point -- I was very curious about some of the measurement values that our Canadian colleague Mr. Brass, had to offer. Again, I am talking about the specialty that happens to be my current interest. We have some measurement values that need defining, and that are being defined. You may run into these sometimes as you have occasion to do business with or give service to universities. We talk in terms of assignable space (which requires definition), gross space and net space -- they are all different. We talk in terms of student stations. This, again, reiterates the great importance of making sure that we understand our definitions when we are dealing with cost analysis. One of the big weaknesses to date in the attempts on the part of universities and colleges to determine what their costs have been, both for construction and operation, has been in this matter of the basis of measurement.

Mr. Cleneay: My only comment is that every architect in the country will have to go back to college for four years of mathe-

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*BRI member

matics. The detail to which we are expected to design here has left me sort of flabbergasted. The pragmatic way in which we analyze buildings and arbitrarily select materials would be unacceptable in terms of this discussion.

Mr. Griffith: I would have to take issue with you there. If the architect can add, subtract, multiply, and divide, he can follow all of this.

Mr. Morgenroth: Each paper covered its individual subject very thoroughly, but it may be difficult to derive any single denominator for the evaluation of the over-all building as a unit, because they covered various systems that, together, make up a building. I think this also points up the need for more work by this Committee on methods of cost analysis to reduce much of this to a common denominator to be used for evaluating total building construction.

Mr. Smith: Could the effect of rising prices be incorporated in a cost model?

Mr. Griffith: You can take care of rising costs very easily. However, in most cases, the number of units that you have to manufacture and sell to produce $50,000 first cost today will be approximately the number of units you would have to produce to equal the future cost. In other words, the cost of materials inflates with inflation.

Gustave A. Keane, Eggers & Higgins, Architects: Your presentation shows the heat gain from artificial lighting is greater than that from daylighting. Is this always true?

Mr. Wenzler: This is always true. The BTU's from artificial light are more than the BTU's from natural light, assuming the same level of illumination. In other words, per foot-candle, artificial light will induce more load in the cooling system than natural light through ordinary window glass.

Mr. Meckler: Mr. Wenzler qualifies his statement by saying "for equal foot-candles." How does one keep natural light foot-candles from coming in? If they are above the specified level, it's not required.

Mr. Wenzler: You do this by using controls that are common to building. This means employing a physical operation, such as tilting of the slats for Venetian blinds, or some such arrangement to regulate the natural illumination to your requirements.

Mr. Meckler: Does this mean that we don't get any increased load on our cooling system? With controls we don't, then, impose any additional load associated with natural light?

Mr. Wenzler: No, not if you use the controls.

Mr. Grimm: I'd like to comment on something Prof. Griffith said which I think was clear if you read the paper in its entirety. However, I think he left the impression during his presentation that the interest rate to be employed in an economic analysis is the bare cost of borrowed money. This may be true for a government agency which is not in competition with private industry, but for another owner, the interest rate should be that required to justify the investment, rather than the rate that he might pay on borrowed money. I am sure that his paper will bring out the effect of this on an economic study with all parameters constant except the change of interest rate. You can make one alternative look better than the other simply by changing the interest rate, so it's important that you use the interest rate required to justify the investment.

Mr. Griffith: The interest rate used depends, of course, on the individual company. Each company has particular projects within its annual budget, and each project must be evaluated in terms of significance in importance and risk. They have to take into account all of the operating factors. For instance, you may be able to borrow money, but you may lose control of your industry if the particular situation proves unprofitable. In that case, you put a much higher risk factor on your interest rate than simply the cost of borrowed money.

Mr. Meckler: I think that before we can apply economics to building construction one of the big problems is to establish what the requirements are, and second, to see that the solutions that satisfy those requirements are indeed the most economical alternative. One big factor in this is the operating cycle. I think that the operating cycle, or the way the building consumes energy, both from the standpoint of the lighting system and of the mechanical system, affects the total operation of the building and establishes the character of the building. This has to be established before you can apply economics. Otherwise, I don't think we are talking about the same thing. For example, if you take a building and use certain standard, established heating or cooling systems, you find that the operating cycles have a particular character, generally independent of the building. The only difference is the order of magnitude in which these cycles change -- the character of the cycle remains the same. However, proper design and proper evaluation of the requirements, and bringing the current technologies to bear on the particular design problem, can result in designing a different operating cycle so that we can have energy-consuming systems that are lower in first cost and in operating cost than we would otherwise have. This may not be a simple concept but, basically by the proper design and the interrelation of static and dynamic components of buildings, we can reduce and modify the operating cycle to fit the current needs of the energy sources available to us. I think this is most important because the costs of operation of buildings are very significant. Today, the mechanical and electrical systems within a building represent, in many cases, 40 or 50% of the total first cost, and often the energy-consuming components of the building account for the major operating cost. We are assuming that by using standard systems for selecting materials that appear to be cheaper, and applying them to buildings, we can reduce costs. I think that the significant thing here is to evaluate all the requirements and then see what systems we can use to reduce the total energy input to the system.

Mr. Griffith: What Mr. Meckler suggests is a far more extensive program than that outlined for this conference on Methods of Building Cost Analysis. We all recognize that you must have the proper engineering systems in a cost analysis. We've had many discussions of this and I am sure we'll have many more, but within the framework of this program, I have eliminated this as a factor and stayed strictly with the cost analysis itself.

Mr. Smith: Since light is distributed throughout a building, why is it necessary to collect heat and redistribute it to the same areas?

Mr. Meckler: Basically, this is because light and heat are distributed uniformly and we really want to remove heat from the interior areas that don't require it and use it in other areas that may need it. For example, in the interior spaces of buildings we have heat gains. We want the light, but we don't want the associated heat. However, at the perimeter we actually want all the heat we can get, so in many cases we put in systems which require sources of energy. What we are talking about here is developing the design of the system based on the requirements of the building. We have interior heat gains. Therefore, we put in a cooling system and do not try to relate heating and cooling in such a manner as to use the energy available in the interior as a source of heat at the perimeter.

Mr. Smith: That is the answer I expected, but I know of many cases where the perimeters are highly overheated.

Mr. Meckler: In that case, if we have an area where there is a net heat gain at the perimeter, then this heat must be removed. Obviously, we can't use heat redistribution as a technique in that building, and that is one criterion that wouldn't apply to that particular design. I think the concept here is to apply criteria to the requirements of the specific building, and not attempt to use one technique for all buildings. We have established building systems for the perimeter and for the interior, and we tend to use those techniques and systems for every building, independent of the requirements. I think what we have to do is evaluate requirements and then design the systems as a function of those requirements. Then we can arrive at a minimum first cost for materials to put our facility together, and a minimum operating cost.

Unsigned question: It is realized that further study and research into building materials and methods are needed. Do you feel that industry, the government or universities should pay for it?

Mr. Kinne: Industrial clients and university clients are paying for it, but reluctantly. They would prefer to have the producers, the manufacturers and the design profession do it for them. But, in the absence of this, I think you will find your enlightened client is forced to do it for himself, and possibly by this means he is being disciplined healthily to the better use of his construction dollar.

Mr. Bogert: Owens-Corning Fiberglas has produced a study entitled "Dividend Engineering." I believe it is in line with what we have discussed this afternoon. Can you tell us something about this?

Mr. Morgenroth: The Dividend Engineering Program is a study of the relationship between the thermal performance of the walls and roofs of buildings and the mechanical equipment. Most architects and engineers know that the calculation of a detailed, economic balance of design between the various systems of a building will require several man-hours. To speed up these calculations, Owens-Corning developed this Dividend Engineering system to expedite evaluation of the thermal performance of building constructions and their systems, and to encourage such analysis in the early design of the building. To simplify the analysis and comparison, we have developed two sets of ready reference charts and evaluation forms -- one for roofs and one for walls. These charts are used for determining the initial cost of mechanical equipment and the cost of its operation: that is, both the heating and cooling equipment, as related to the thermal performance of the wall and roof construction.

The data are entered in an evaluation form similar to an income tax form. You just fill out Line A from Chart 1, and Line B from Chart 2, etc., except that it requires professional judgment used on the input data. These charts are all based on standard ASHRAE techniques. There are no prejudged or preworked formulae, or any other mathematical gymnastics. It's a straight-forward analysis that can be done in about one hour. This method of balancing the cost and performance of the shell of the building versus the mechanical equipment is a scientific system. No specific material selection is involved in this so-called Dividend Engineering Program. It's only a cost and performance comparison. It can be used with other materials as well as our own.

Unsigned question: Do you think that the management of most firms erecting buildings for their own use will make decisions based on economic studies, or are arbitrary decisions inevitable, i.e., a decision such as, -- "Find some way to bring the cost down $25,000," which may result in a higher over-all cost when you consider future costs?

Mr. Cleneay: I think management is more prone to make arbitrary decisions to cut building costs by a given percentage than to really analyze the economics of the situation in terms of the materials used. However, we have a more enlightened management at Monsanto, I must say, because we've had very few directives issued on that basis in the past few years. They usually consider what we've done, and the estimates we give them as the base cost of the building.

Mr. Grimm: I think this indicates the necessity to educate vice presidents as well as architects.

Unsigned question: Several speakers mentioned economic studies made by Owens-Corning, Structural Clay Products Institute and the Zonolite Co. which can take the hard work out of such studies for smaller architectural offices. How widely do such offices make use of these studies? Must they be trained and encouraged to use these studies?

Mr. Grimm: I am not sure that I know how broad a use is made of these types of studies by architects. It probably is rather broad. The Zonolite study has only been available to the design profession about three or four months. The SCPI study has been out about two or three years. Architects have to be encouraged to use the studies, but it requires very little training. As Mr. Morgenroth said, you can decipher Dividend Engineering in an hour. In much less time, you can discover what the thermal economic coefficient is, and how to use it.

Mr. Griffith: If you are going to spend the time training architects, I think it would be worth while to train them on the general technique. Then they can apply it to all situations, and not to just one particular item.

Unsigned question: Mr. Brass' talk dealt with the results of a survey made by the National Research Council of Canada. Will there be a set of recommended standard methods forthcoming? Do you think that recommended standard methods would be widely adopted by all groups interested in buildings?

Mr. Brass: Let me clarify what the position of the Research Council was in carrying out this study. We have regular meetings with the Research Committee of the Royal Architectural Institute of Canada. At a recent meeting we discovered that the Division of Building Research and the RAIC were very interested in this question of a standard method of determining the area and volume of buildings for realistic cost comparisons. The Division agreed to undertake the study in view of our international association with the building research organizations around the world. We have prepared this paper. Our policy is that it is now up to representatives of the various facets of the building industry to get together, review this information, and reach some agreement on a standard for its use. An interesting development of this is that if you examine these recommendations, you find that although they differ, the differences are really quite minor and all the standards are, in effect, quite arbitrary. Therefore, with very little compromise on an international basis, it should be possible to develop one standard method of measuring the area and one of measuring volume for cost purposes. Mr. Legget, the Director of the Division of Building Research, is a member of the Executive Committee of the International Council for Building Research Studies and Documentations. That organization is going to investigate the possibility of promoting the development of an international standard. With regard to the anticipated adoption of a standard, I can't really see why there should be any strong resistance to it. The important thing is that everybody recognizes that this is a tool for our use and, until we have this tool, we are just complicating the problem of making cost comparisons between one building and the next.

Mr. Smith: Were automatic shade adjusters and light controls used to maintain even, total lighting intensity?

Mr. Wenzler: It was all done by manual control. Automatic controls are possible but their use has not been extensive. I don't know why. Maybe it's the economics. That may be one of the better developments that will come along as the sound economics of using this enormous value of natural lighting is realized.

Harry D. Lovering, A. G. C. of Minnesota: Are electronic computers useful to the building contractor's estimating quantity survey or to the accounting department? If so, please explain.

Mr. Meckler: They may very well be, but I don't see how, at least in the application I presented this afternoon. The electronic computer that I was talking about had to do primarily with evaluating design requirements and applying criteria to design situations, and it was not involved in estimating buildings from plans and specifications.

Mr. Lovering: In comparing the two 60-year over-all design costs, wouldn't it be more realistic also to take into account the fact that building construction cost indices have increased some 2 to 3% annually for over 15 years and probably will continue so to do?

Mr. Grimm: I would like to comment. To assume that the same number of units of production would be required to provide for renewal each 20 years is an oversimplification which might, in some cases, lead to erroneous conclusions. This negates increases in productivity which may, in fact, require fewer man-hours or fewer units of production to produce the increased cost, or to equal the increased cost. I think that, in some cases at least, it's important to consider the effect of inflation, particularly when the cost rate increases are different for different items. You may have one item which has a price history of increasing at 3% per year, another one at 1%, another one at 5%. If you average them all out at 3%, you may be inducing errors that would lead to false conclusions.

Mr. Griffith: My first comment would be: Are you trying to complicate this rather than simplify it? Actually, there is no problem at all in including cost variations. If you can predict them they can be added in with one multiplication. It's the prediction of this sort of thing that really creates the problem. After all, remember, you are building this model for decision-making. This model is not intended to be what actually happens after you buy the building. Then, it makes no difference what your calculations were; the money has been spent. From there on you have a new economic study to make for decision-making. This is the concept that people have a great deal of difficulty grasping. We are not interested in accounting problems. The accountant records history. We are interested in today's cost and an estimate of future costs. The only place the accountant's figures come into an economic study is in regard to what's left in the book value to be written off. This, of course, is tied in with the government's decision on your write-off. However, each of these variables can be included in the cost model with one simple multiplication if it can be forecast.

Mr. Bogert: In your experience, do you feel that it is common practice for designers to select a material or method arbitrarily just to save time and effort, when an unbiased economic study might result in a sizeable and worthwhile saving?

Mr. Smith: I am sure that many decisions are made quickly in order to get the job done. In Mr. Griffith's remarks a moment ago, he discounted the changes in prices. I would like to point out that every operation, from the first, is dealing in the future. I would like to see some plan for setting aside each little item in this puzzle so it could be added up at the end to come out with a number defined as present dollars necessary to buy, operate, maintain and use this building for its expected life. Every decision is dependent on some future prediction of use. You don't build buildings for history, you build them for the future.

Mr. Griffith: Again, you are suggesting something that is far beyond the scope of this meeting, because forecasting is much more difficult than actual calculation. I agree with you, a lot more work needs to be done on forecasting.

Mr. Meckler: How do you arrive at your alternate schemes before you apply your economic cost model? Do you consider arriving at the alternate schemes to apply the economic cost model as part of the economic evaluation?

Mr. Griffith: Of course, in the case of an engineering design, you have to employ a competent engineer who considers the correct engineering alternates. I am simply covering the cost models that you use after your proper engineering has been analyzed. If you will remember, I said that if you don't have the best alternates in your study, you are going to come up with a lesser alternate. I am basing this on the fact that you can employ competent engineering help, and then apply your cost models.

Mr. Meckler: Do you consider the engineering evaluation of the alternates as part of an economic analysis?

Mr. Griffith: You have to have them before you can run the economic analyses, so if you consider them as part of the manipulations for economic analysis, yes. I think you are quibbling over the term "analysis." If you are talking about pure economic analyses, this can be worked out on bad engineering results as well as on good engineering results.

Mr. Meckler: It's a matter of definitions, primarily. Are you divorcing the engineering decisions from economics; or do you consider that the evaluation, in other words, the establishment of the proper criteria to come up with a total design, is independent of economic evaluation?

Mr. Kinne: Some years ago at the University of Illinois, in some of our graduate studies in architecture and architectural engineering we talked about this same frame of reference. It was suggested then that it might be possible to compare various design alternatives by breaking down a big problem into seven, eight, or ten small ones, evaluating each by measurable devices. These could be insurance rate per thousand, cost per sq. ft. of surface, maintenance, first cost, and the rest -- even to such considerations as aesthetics, design appeal, saleability or rentability. It was suggested that each one of these factors, be they ideally large or ideally small, could be weighted from unity down to, say, one-tenth, depending upon their importance. You take desirably high factors as the numerator and desirably low factors as the denominator of a mathematical expression for each one of these, multiply out and get an index, an abstract number. It's a very neat, methodical procedure, but the point is that judgment enters in the factors, and this is where prejudice comes in. Designers have to have prejudice, although they may base their judgment on engineering facts.

Mr. Meckler: I agree with you completely. The important thing is that they have the opportunity to make the judgments, and the only way you can make judgments is to have established criteria. Once you know what you're doing, then you can make your decision. This is part of the question that I directed to Prof. Griffith. Does he consider the establishment of the proper criteria and then make these decisions part of the total economics, or does he consider this independent of economics?

Mr. Griffith: I think I can simplify this. By acting as a consultant in this field, I can run an economic analysis based on factors given me, say, by an aeronautical engineer. I do not have any idea whether the airplane will fly or not, but I can run an economic analysis on the facts he gives me. An economic analysis can be developed with any facts.

Mr. Bogert: Can you recommend a textbook covering the subject of techniques for economic analysis of building design? Such a book would be helpful as a reference when we must make such studies.

Mr. Griffith: I hesitate to do this because I may leave out some of them. There is a bibliography of many textbooks included in my paper. All of the book publishers in the technical field have excellent books on this subject. Unfortunately, I know of none written for the building industry. They have all been written for the engineering profession, but the techniques are applicable to the building industry.

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