

THE DESIGN AND APPLICATION OF AN OPTIMIZATION MODEL FOR THERMAL PERFORMANCE OF ATRIUM BUILDINGS

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ABSTRACT

Atrium building is a simple design technique commonly used by architects to enhance the interior architecture of hotels and commercial and public buildings. It is often assumed that an atrium would substantially increase building costs. This misconception stems from the fact that many designs involving atria were carried out without careful cost-effectiveness analyses.

This study is based on the assumption that it is possible to design atrium buildings without added cost and that savings in annual operating costs can be achieved through the atrium technique.

The paper is centered on the analysis and development of an optimization model, to be used by the architect at the preliminary stage of the design process with comparative analysis of optimal combinations of building groups such as apartment, office, and linear commercial buildings. The model also takes into consideration the relative savings due to construction and energy conservation. A computer is employed to obtain needed data in the decision-making process.

INTRODUCTION

An atrium is a relatively simple design technique used to enhance the interior architecture of buildings. It is popularly used in the design of luxury hotels, convention centers, commercial malls, etc. Usually considered by architects as an added cost in their budgets, cost-effectiveness analysis of atrium design has not received proper consideration. This study is the second phase of an earlier investigation (Ref. 1) in which the infill techniques were employed in an energy-conscious campus design. The premise of the paper is that, if designed properly, atrium building shall not only be architecturally attractive and energy conserving but could also be economical in its initial cost. The objective of this paper is, therefore, to construct a working model for assessing the feasibility, at the outset of the design process, of using the atrium as an economically viable alternative to the conventional open-air grouping of building clusters such as apartments, offices and hotels.

FUNDAMENTALS OF ATRIUM TECHNIQUES

The analysis of atrium building design may be discussed in three parts: the basic geometry of building cluster, the comparative analysis of atrium techniques and mathematical modeling, and design analysis and computer application.

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The Basic Geometry of Building Cluster

For easy conversion into atrium buildings, conventional buildings can be classified into three basic geometrical types, as shown in Figure 1. Type A is formed by two parallel building units with an atrium space in between, which is enclosed by two end walls and a roof. There are two options in this type: one has southern exposure for possible solar application; the other faces the other directions. Type B is formed by two or three building units and is oriented toward the south for possible solar application. Type C is formed by four building units with a roof for possible skylight application.

Comparative Analysis and Model Development

The analysis, which leads to model building, is based on two assumptions: (1) the atrium design will involve no additional heating cost and (2) no additional construction cost will accrue, other than that of a conventional building cluster of comparable size, materials, and construction method.

Equal Heating Load Relationship. The heating load calculation is based on heat transfer and air infiltration heat losses. Due to the fact that there is far less exposed enclosure area in atrium building than in conventional cluster building units, the heat loss for air infiltration will be omitted in this study.

For a type A atrium building (see Figure 1, A1):

$$HTLC = 2 UO (AFW + ARW + AEW) + UOR (AR) + 2 UOF (AF) (FCT) DT \quad (1)$$

where

HTLC = heat loss for cluster building units
UO = overall U-factor for walls, windows, doors, etc.
UOR = overall U-factor for roofs, skylights, etc.
UOF = overall U-factor for floors
AFW = area of front wall, W X H
ARW = area of rear wall, W X H
AEW = area of end walls, D X H
AF = area of floor, W X D
AR = area of roof, W X D
FCT = correction factor for indoor/ground temperature
DT = indoor/outdoor design temperature different

$$HTLA = 2 [UO (AFW + 2 AEW) + UOR (AR) + UOF (AF) (FCT)]DT \\ + [UO (2 AAW) + UOR (AAR) + UOF (AAF) (FCT)]DT \quad (2)$$

where

HTLA = heat loss for atrium building
AAW = area of atrium wall, DA X H
AAR = area of atrium roof, DA X W
AAF = area of atrium floor, DA X W
DA = depth of atrium space

If there is no added heating cost allowed, Equation 1 equals Equation 2:

$$HTLC = HTLA,$$

or

$$2 UO (AEW) = 2 UO (AAW) + UOR (AAR) + UOF (AAF) (FCT)$$

$$2 UO (W X H) = 2 UO (H) + UOR (W) + UOF (W) (FCT) DA$$

where

H = building height
W = building width
DA = $2 UO (W X H) / [2 UO (H) + (UOR + UOF X FCT) (W)]$

(3)

By using the same process for a type A option as shown above, similar equations may be derived for types B and C options. (Equation 4 is for type B1, Equation 5 for type B2, and Equation 6 for type C Atrium building.)

$$DA = \{6 UO (H \times W) - UR + UF (FCT) (FCR) W ** 2\} / \{2 UG (H) + UR + UF (FCT) (FCR) W\} \quad (4)$$

where

FCR = Correction factor

= 1 or less (see "Analysis section")

$$DA = 4 Uo (H \times W) / [2 UG (H/W) + FCS (UR) + UF (FCF)] \quad (5)$$

$$HA = \{4 UO (H) - FCS (UR) + UF (FCT)\} / 2 UG \quad (6)$$

where

FCS = Correction factor

= 1 or more (see "Analysis" section)

Equal Construction Cost Relationship. Referring to Figure 1 A1, the only potential savings in construction cost is where the rear wall becomes an interior wall of the atrium building. Additional costs of the building are for atrium walls, floor, and roof.

The rear wall construction cost is $C_w (2 ARW)$ where C_w is the unit cost of wall construction. The atrium space construction cost is $C_w (2 AAW) + C_r (AAR) + C_f (AAF) + C_{wi} (2 ARW)$ where C_r is the unit cost of roof construction, C_f is the floor, and C_{wi} is the interior wall construction cost.

If no added construction cost is allowed, then

$$C_w (2 ARW) = C_w (2 AAW) + C_r (AAR) + C_f (AAF) + C_{wi} (2 ARW),$$

or

$$C_w (2 W \times H) = C_w (2 DA \times H) + C_r (DA \times W) + C_f (DA \times W) + C_{wi} (2 W \times H)$$

and

$$DA = [(C_w - C_{wi}) (2 W \times H)] / [2 C_w (H) + (C_r + C_f) (W)] \quad (7)$$

By using the same process for a type A option, similar equations may be derived for types B and C options (Equation 8 is for type B1, Equation 9 for type B2, and Equation 10 for type C atrium buildings).

$$DA = [6 (C_w - C_{wi}) (H \times W) - FCR (C_r + C_f) (W ** 2)] / [2 C_g (H) + FCR (C_r + C_f) W] \quad (8)$$

$$DA = [(4 C_w - 2 C_g - 4 C_{wi}) H] / [FCR (C_r + C_f)] \quad (9)$$

$$HA = [4 C_w (H) - (C_r + C_f) W] / 2 C_g \quad (10)$$

Diagrams for Preliminary Design. To further simplify the model, Equations 3 and 7 may be rearranged to involve building height and width in expressions such as W/H for H is less than W , or H/W for H is larger than W .

$$DA = 2 UO (H) / [2 UO (H/W) + UOR + UOF (FCT)] \quad (3a)$$

$$DA = 2 UO (W) / \{2 UO + [UOR + FCT (UOF)] (W/H)\} \quad (3b)$$

$$DA = [2 (C_w - C_{wi}) (H)] / [2 C_w (H/W) + (C_r + C_f)] \quad (7a)$$

$$DA = [2 (C_w - C_{wi}) (W)] / [2 C_w + (C_r + C_f) (W/H)] \quad (7b)$$

These four equations may be plotted in two sets of graphs (see Figure 2) to illustrate the two sets of special relationships for a type A atrium building for heating and construction cost limitations. For any given building height and width, with a ratio of H/W or W/H, the atrium depth is limited to $DA = R(W)$ or $R(H)$, where the R value must be on or below the curve in order to produce an atrium building with no more heating demand or construction cost than a set of free-standing individual buildings. The x-axis indicates the building characters of H/W or W/H, and the y-axis indicates the R value for $DA = R(W)$ or $R(H)$, respectively, where DA is therefore easily computed. These diagrams are designed for use by architects to determine the atrium size at a preliminary design stage.

ANALYSIS OF APPLICATION OF ATRIUM TECHNIQUES

Practical Geometry Options

The basic geometrical options for a building cluster to form atrium buildings are illustrated above. But the geometry of atrium buildings, in a practical sense, will most likely be refined toward configurations as shown in Figure 3. Type A1 could become A2; type B1 will be B5, B3, or B4; type B2 will be B6; and type C most likely will become C2 or C3. The equations as developed in the preceding section will be somewhat similar, with some dimensional changes due to roof and floor shape changes. The simple diagram developed for preliminary design, as shown in Figure 2, as the maximum allowable atrium size will be difficult to compute without the use of a computer.

The Effects of Air Infiltration

In most cases, as shown above, the exposed enclosure area of the atrium building should be less than that of a conventional building cluster. Therefore, the air infiltration of an atrium building should be equal to or less than that of the individual units combined. The only possible increase in air infiltration is where there is too much glazing area, in option type B, or where the building is too tall so that the chimney effect may be increased to produce more air infiltration.

The Effect of Increasing Glazing Area

One of the two key factors in the model development is heat transfer through exposed enclosure areas. When the southern glazing increases, so will the heat losses. These may be offset by the solar heat gain into the atrium if so designed. Such an addition may produce two elements to be considered in the model development: one is to add a shading device to reduce potential summer heat gain that will increase the cooling load of the building; the other is that night insulation must be added to reduce heat loss during winter nights. These two factors must be taken into consideration for construction cost analysis.

The Effects of Construction Cost

In the construction industry, the first cost is most often used for the purpose of project control. Therefore, the atrium technique will most likely be discouraged initially by construction cost limitation. The major cost savings will result from the use of interior partitions facing the atrium instead of from exterior walls as in the case of free-standing building units. If there are extensive glazing areas, or if the interior partition cost is too high, the atrium technique may either be too expensive or the atrium space should be reduced in size. In order to produce a realistic cost plan, it may be necessary that the energy savings from the reduction of heat loss be included in the cost analysis and that the cost analysis be based on a life-cycle costing method.

The Effects of Atrium Roof/Floor and Skylight Sizing

In the development of the basic model, for option types B and C, correction factors, FCR and FCS, are used for computing the roof, floor, and skylight sizes, so that simple diagrams may be produced for preliminary design studies. These correction factors may be expressed as follows (see Figure 4).

For option type B1:

$$FCR = [W^{**2} - 0.25 (DA - W)^{**2}]^{**0.5} / W \quad (11)$$

When $DA = W$, $FCR = 1$, the maximum possible value. If $DA = 3W$, then $FCR = 0$, the minimum value. As a choice of more acceptable geometry to most designers, $DA = 2W$, and the correction factor may be used in the preliminary design computation to be $FCR = 0.866$.

For option type B2:

$$FCR = [W^{**2} - 0.25 DA^{**2}]^{**0.5} / W \quad (12)$$

If $DA = 0$, $FCR = 1$, but there is no atrium area allowed; if $DA = 2W$, $FCR = 0$, but again there is no atrium area allowed. The most preferred size would most likely be $DA = W$, and $FCR = 0.866$, the same value as in Equation 11.

For option type C:

$$FCS = [(HA^{**2} + W^{**2}) / W^{**2}]^{**0.5} \quad (13)$$

The smallest value for correction factor FCS is 1 when $HA = 0$, but there is no skylight possible. The most likely value for HA is when it is equal to the roof depth or W, and $FCS = 1.4142$, which should be used in preliminary design studies.

The Effects of User Behavior

For a conventional free-standing building cluster, in isolation or in a group, all exterior windows have an open view to the "outside" of the building. The quality of these views may not be as important in this incident, but the users "feel" they are facing the outdoors, regardless of the quality of the outdoor view. In the atrium environment, almost one-half of the "outside" windows are now facing the atrium space. Psychologically these may not be considered "outdoor" views by the user, and the acceptance of such environment is subject to question. In an enclosed space like an atrium, loud sound would become noise, which can be undesirable for all the "windows" facing the atrium space. Therefore, soundproofing the interior partitions and landscaping of the atrium space are necessary to overcome the psychological problems of user acceptance. This issue is of particular concern for the design of shopping malls and hotels, where atrium spaces are the centers of activities.

COMPUTER UTILIZATION

Many architects dislike the technical information needed in the process of building design and tend to overlook such information when it becomes too involved. To counter the trend, this paper sets out to develop a model to assist and encourage the average designer to use atrium techniques in the design task when appropriate. The working model developed above for preliminary design requires only the input of local data from the designer for its operation. A simple act on the part of its user would result in computer production of a set of diagrams of the types of geometry and construction for the feasibility analysis of atrium building design.

Computer Friendly Techniques

To accommodate computer-shy designers, the computer model shall be simple, easy to use, nontechnical, and computer friendly. Six characteristics are required of the model:

1. Self-Paced Process: The program shall have built-in pause action on each screen display, and will require the user to press any key in order to continue work at his own pace.
2. Conversational Mode: The program shall be in conversational mode by "talking" to the user in a direct and friendly manner.
3. Multiple Choice: When there are decisions to be made by the user, the computer will provide all the options on the screen. All the user needs to do is type in one single letter or number from a list of choices presented for selection.
4. True or False: When the decision is limited to "true" or "false", the computer will ask the user to type in "y" for yes (or true) or "n" for no (or false) for the statement or description on the screen.
5. Numerical Input: When input data are needed, the computer will require the user to type in a set of numbers, such as building cost, areas, dimensions, etc.

6. **Word Input:** When information is needed, the computer will require the user to type in one or two words for information directly related to the design decisions.

The Computer Packages

The computer program is composed of eight related and interconnected packages: program title; project identification; atrium building type identification and selection; default data; data input and default value review; computation and evaluation; output selection; and recycle option selection. All packages, except program title, default data, and computation and evaluation are designed to be interactive with the user.

Program Title Package. The program provides all basic information needed to operate the computer. The components of the package includes the title of the computer program (with all its statements and declarations) and a program description with short user instructions for users already familiar with the PC operating procedure. There is optional user instruction for first-time users.

Project Identification. The package is designed to initiate the program and to set up a data bank for input and output data storage as well as a record keeping file for items such as project name, project number, user name, date, etc.

Atrium Building Type Identification and Selection. The program provides a complete description and graphic illustrations of all the atrium building types. The user may select one or more of the atrium building types for preliminary analysis and study development. The computer will process one atrium building type each time and present its results in two ways: a set of diagrams to be used for comparative analysis, and the limits of the maximum atrium size allowed for the specific data provided by the designer.

Default Data. This is an internal package prepared to provide a set of default values for a typical data base, as examples may be required by the user in case s/he is unsure of such values. There is an optional subroutine to be used to change the default value if necessary.

Data Input and Default Value Review: The package asks the user to review all the default values provided for the selected atrium type. The computer will ask the user to make any necessary changes or enter new data input, such as building areas, construction costs, etc., where no default value is provided.

Computation and Evaluation. The program is another internal package designed to provide all the necessary computations needed for the generation and evaluation of solutions. There are optional programs for users computing building properties such as the U-factors, unit costs, etc.

Output Selection. The program provides different types of output for the user to make choices or to store the data for later use.

Recycle option selection. The package provides an on screen list of recycle options for the user to select from changing some of the default values or dimension revisions to selecting a new atrium building type or ending the study as desired.

The Flow Diagram of the Computer Program

See Figure 5 for the flow diagram of the computer program described above.

CONCLUDING STATEMENTS

The primary purpose of this study is to develop simple techniques to assist architects in determining the option of basic geometry and the range of allowable sizes of the atria at the preliminary stage of the design process. The study has indicated, however, that there would also be considerable savings from the reduction of heat transmission losses in atria buildings. Consequently, it becomes possible to increase the size of the atrium as a trade-off for such a saving in building operating costs or to integrate the savings by using life-cycle costing analysis in the comparative study.

With the aid of the computer, the working model developed in this paper will help the architect in two ways in his preliminary design: one is to provide the range of allowable sizes of the atrium, and the other is to provide the maximum allowable atrium size for the design solution. Additional study is needed for the development of techniques for final design evaluations.

Solar energy utilization in atrium techniques is feasible and could result in greater savings. A detailed analysis is needed for each specific geographic location for justification of such an application.

The critical and an unresolved question in this study is the extent of air infiltration savings, if any. Theoretically and from all indications, there should be energy savings in the atrium buildings. There is, however, no reliable method for its estimation at present.

REFERENCES

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Saxon, R.. 1983. Atrium Building, Development and Design. Van Nostrand Reinhold Co.

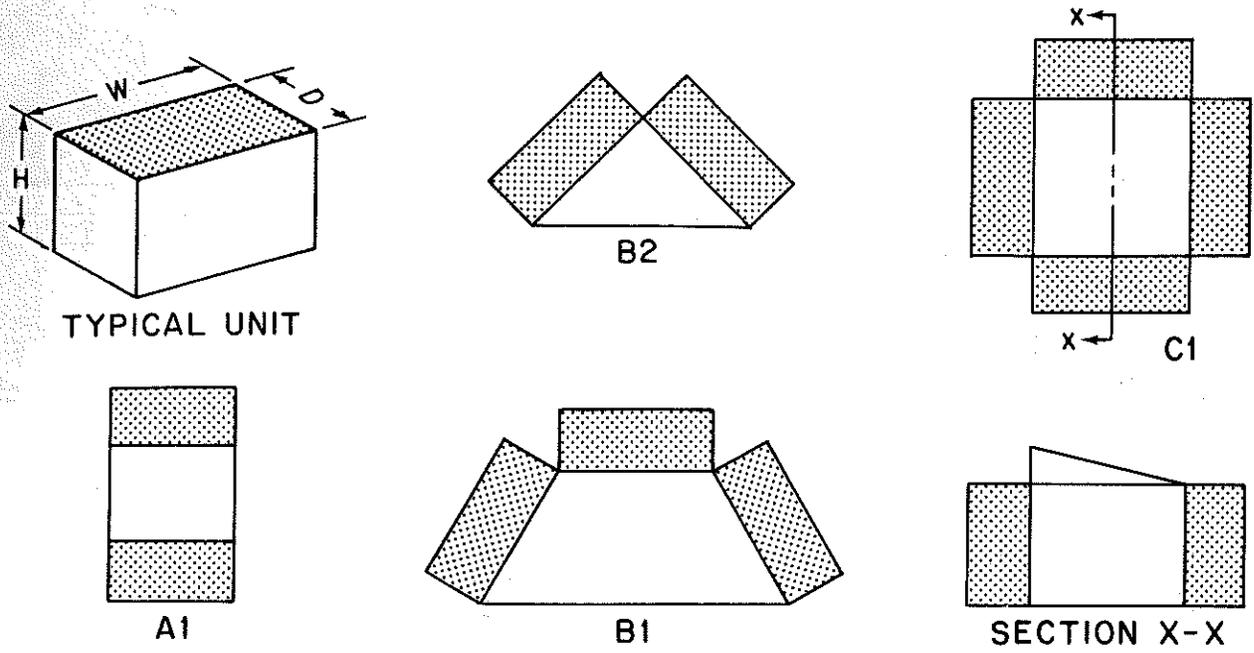


Figure 1. Basic geometrical types of building cluster

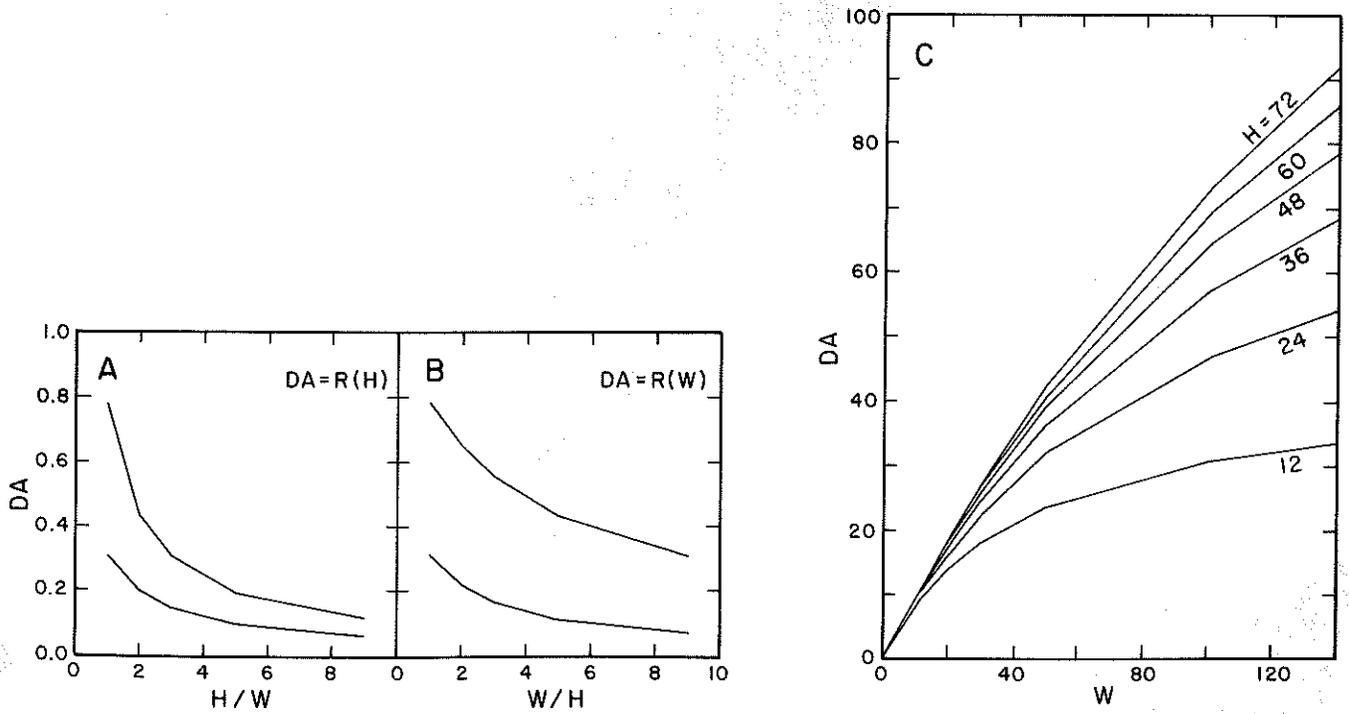


Figure 2. Typical diagrams of Equations 3 and 7. Data based on Virginia Tech campus buildings

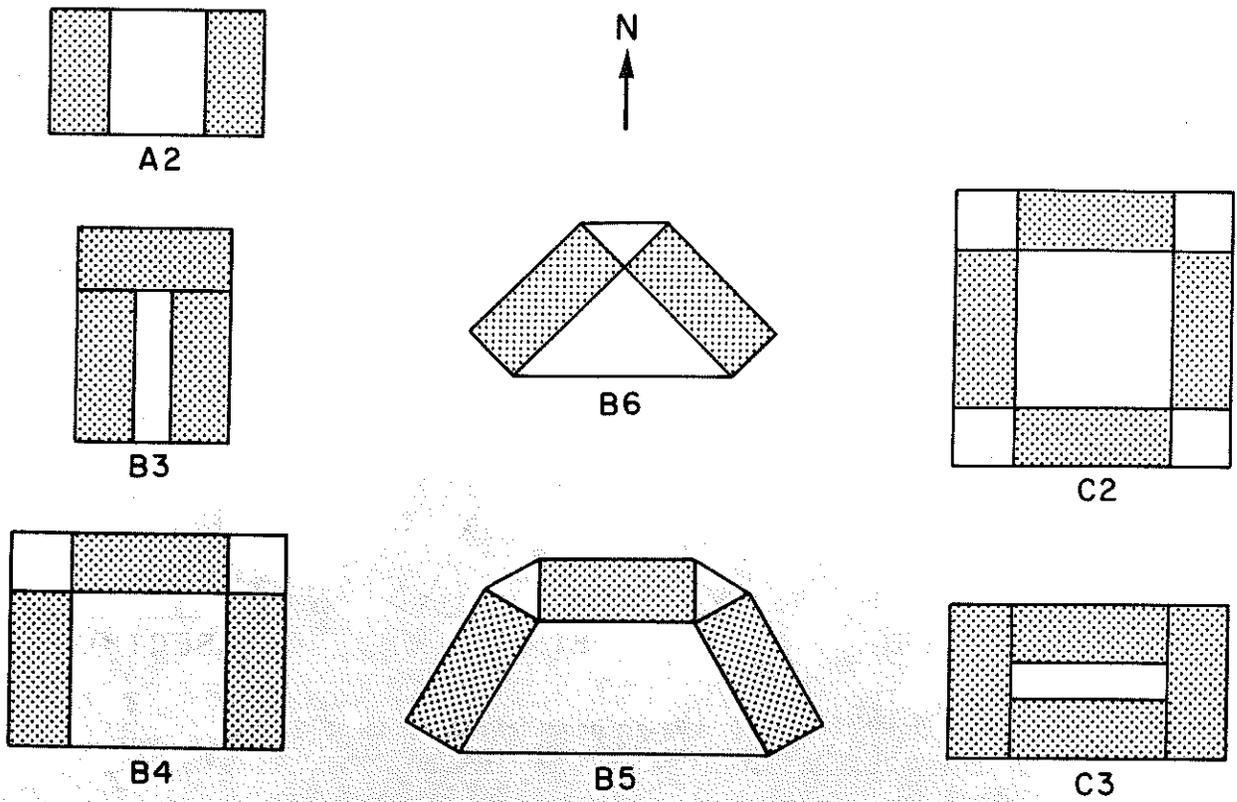


Figure 3. Practical geometry options

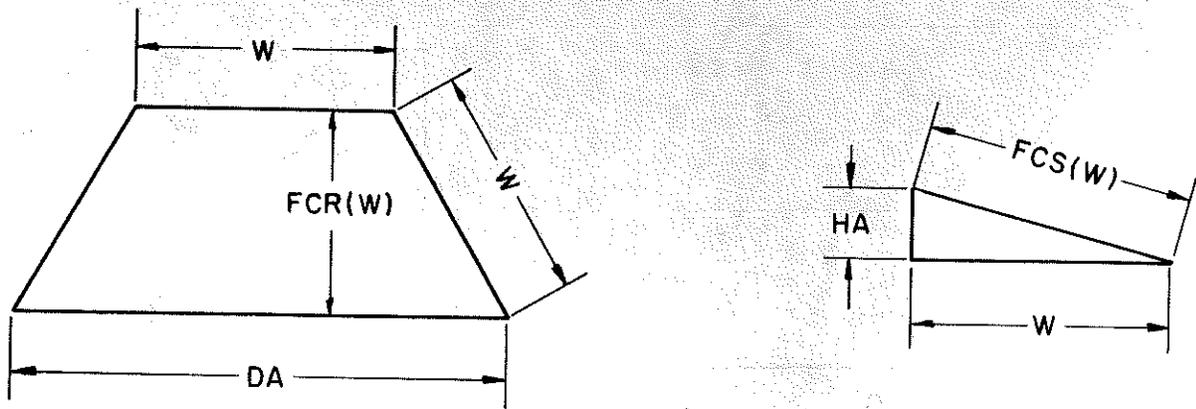
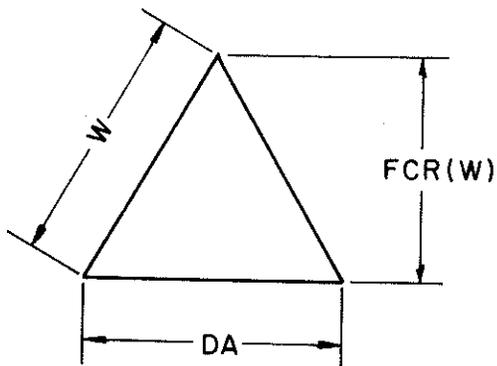


Figure 4. Geometric relationship of correction factors



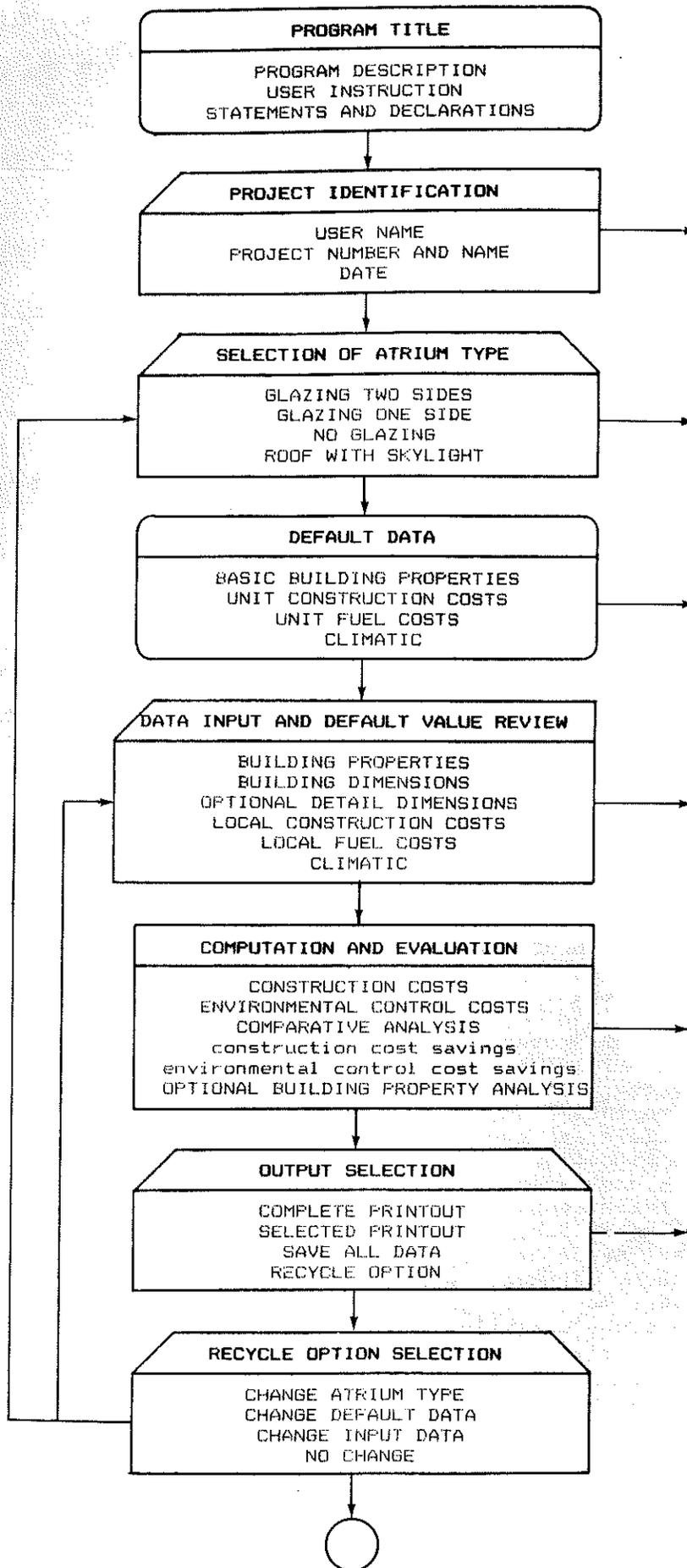


Figure 5. Flow diagram of computer programs