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GENWIN: A Generative Computer Tool For Window Design in Energy-Conscious Architecture*

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The use of computers as aids in energy-conscious building design has hitherto been confined primarily to evaluative tasks. These are no doubt important, but they do not fully exploit the tremendous potential of computer technology. Generative tools are a move towards using the computer as an 'active' complement to the design process rather than merely a 'passive' tool. Such a generative tool for window design, named GENWIN, was developed. This paper explains the theory and principles underlying this model, and concludes by illustrating the output derived by running GENWIN for a test case.

1. GENERATIVE COMPUTER TOOLS

1.1. *Definition*

THESE are tools which are able to generate alternative solutions for various limited aspects§ of the design that satisfy some given well-definable specification. A generative process is essentially one of searching through all possible solutions to a given problem to find those that meet specific goals. The idea of a generative tool is *not* to produce *the* solution to a problem; this is because there will always be other criteria—especially in architecture, and even in the aspect of energy efficiency—that cannot be quantified or specified and are therefore best left to the discretion of the designer. Instead, a generative tool aims to produce alternative solutions meeting *some* objective criteria, possibly in the form of 'tests'. Using more subjective, non-computable criteria, the architect can then make a selection from among the solutions offered by the computer, with modifications and refinements if necessary.

1.2. *Why 'Generate and Test'?*

The need to follow the methodology of 'Generate and Test' essentially arises because designs are composed with one set of variables and evaluated with another [1]. The relationship between design and performance variables is complex, involving a many-to-many correspondence. One design variable (e.g. a change in window size) might affect several performance variables (light levels, thermal performance, view, ventilation, etc.). Similarly, the value of one performance variable might depend upon many design variables (the heat load for instance depends upon building geometry, window area and orientation, materials of construction, occupancy, and so on). This is why the generation of a design has to be separated from its subsequent evaluation; there *must* be a design before it can be assessed.

1.3. *The testing of solutions*

The testing process used by a generative tool would involve the use of computation to evaluate the solution and ensure that it meets the specified design goals. In this process, it helps to use heuristically powerful algorithms such as analytical procedures and mathematical programming techniques. Exhaustive search is heuristically very weak as it produces an exponential number of design alternatives; it is therefore generally ineffective in practice. It can, however, be used to solve small, well-defined problems, as will be demonstrated in GENWIN.

2. THE PURPOSE OF GENWIN

The objective underlying the development of GENWIN was essentially to demonstrate the use of the computer as a generative tool for a specific aspect of energy-conscious design.

Most currently available tools for this purpose are evaluative; they are used to progressively test solutions which are manually generated by the designer until one that is considered to perform satisfactorily is found. This approach has a major drawback discussed below, which a generative tool like GENWIN can overcome.

2.1. *The drawback of the evaluative tool*

The evaluation process is essentially one of testing whether the performance of a design is acceptable or not; if not, certain parameters of the design have to be

*The model that this paper describes was developed as an important part of the author's M.Phil. dissertation entitled 'Computers in Energy-Conscious Building Design', completed at the University of Cambridge in August 1993.

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§The use of the term 'limited' is important here. Generative tools do not claim to provide solutions to the complete design brief.

modified and the evaluation process repeated. Thus, a trial and error sequence is inevitably involved, although each successive iteration may provide a clue as to which parameters should be modified and how [2]. This process of repeated analysis and evaluation will be concluded when an 'acceptable' design is obtained.

This very trial and error sequence is the inherent weakness of the evaluative tool; the final solution arrived at will be 'acceptable', but it can never be guaranteed to be the 'best' for that particular problem. Also, the 'degree' of acceptability of the solution will depend solely upon how well the designer is able to apply the results of the evaluation procedure for one solution in the formulation of appropriate design decisions for the next.

A generative tool on the other hand, by virtue of generating and testing *all* possible alternatives (within certain constraints), will offer solutions that will assuredly be the best that meet *at least* the specified criteria; in this way it overcomes the disadvantage of the trial and error process used by the evaluative tool.

2.2. *Other advantages of generative tools*

Even generative tools which deal with only a single design aspect have an important contribution to make—they can help avoid design decisions being made randomly, which is what usually happens when the requisite information or tools are unavailable. Examples in energy conscious design include decisions such as those about the surface to volume ratio of the building, room proportions, location of fenestration, and so on.

Using the computer to generate a large number of design solutions can also open up for the designer, possibilities which may never have even been conceived of earlier. Thus a generative tool can act as a catalyst rather than a sop to creativity. Also, seeing novel, even if unconventional (and unfeasible), solutions to a particular problem can be deemed as an education in itself!

Although a generative tool is not without its share of limitations (discussed in the next section), it is undeniably a move towards a more 'intelligent' use of the computer than the traditional evaluative tool, which functions primarily as a sophisticated calculator.

2.3. *The limitations of generative tools*

Generative tools need to be governed by as many constraints as can be defined so as to reduce the number of feasible solutions generated. Even so, they can rarely produce a 'unique' solution to a given design problem, even if all the performance characteristics are defined in detail; this is because there will, most often, be many configurations of design variables offering the same performance characteristics.

The largest drawback of generative tools is, however, the limit to the number of performance variables that they can consider simultaneously because of processor and memory limits. Generation of solutions gets increasingly difficult when there are more than 2 or 3 criteria to be taken into consideration at the same time. At present therefore, generative tools, even in those fields in which the use of computers is far more advanced as compared to architecture, can handle relatively simple design problems only.

3. THE APPLICATION OF GENWIN

The sizing and placement of windows is crucial in energy conscious buildings from the perspective of both lighting and thermal performance. The former parameter can greatly affect the heating energy consumption, while that of lighting depends upon *both* factors. Because lighting energy consumption can account for as much as 35% of the total primary energy consumption of a non-domestic building, it is essential in the move towards energy-efficiency, to rely on natural lighting as much as possible to meet the building's lighting requirements.

Available daylighting tools such as DAYLIGHT, ESP, GENELUX, SUPERLITE, etc. can calculate daylight factors at various locations in a room given a particular window configuration. GENWIN does the reverse; for a desired daylighting performance in a room, it can generate all window configurations that satisfy it. It is anticipated that such a model could be useful to assist in the window design of a prototypical room with very specific lighting criteria to be satisfied. Examples include rooms in drawing offices, where a good light level (6% DF) is required at the locations of the drawing boards; in schools and offices where a good uniform distribution of daylight is essential; or in any room where, for some reason, excessively dark corners have to be avoided.

Given a room facing a certain direction, and with certain minimum daylight factors to be obtained at specified locations, GENWIN first calculates the optimum glazing area (in proportion to the surface area of the external wall*) which minimizes both the lighting *and* heating energy consumption. For this calculated area of glazing and the number of windows specified, GENWIN then generates all possible window configurations, based on a modular grid. As soon as a configuration is generated, the daylight factor at each point on the user-defined reference plane grid is calculated. For a solution to be regarded as successful, this has to be higher than the minimum specified at that point, and has also to meet other criteria for good light distribution and uniformity on the work plane. All such solutions are finally displayed to the user in order of performance (measured by the daylight factor at the back of the room), who can then select one which meets other criteria such as view, aesthetics, or privacy.

4. LIMITATIONS

For simplicity, GENWIN, at this stage of its development, is limited to handling the case of a single right-angled room, with one external wall only. Windows are considered to be rectangular and vertical; rooflights cannot be modelled. Shading devices to the windows or

*Since a glazed area below the reference plane adds to only the internally reflected component and therefore does not significantly affect the total daylight factor *on* the reference plane, GENWIN only generates windows whose sill height is equal to or greater than the height of the reference plane. Thus the glazing ratio is actually calculated as a percentage of only that area of the external surface that is above the reference plane (and below a downstanding beam if any). It is however expressed to the user as a percentage of the entire external wall area for comprehensibility.

Table 1. The maximum limits on room parameters in the current version of GENWIN

Parameter	Maximum value
Room width	10.0 m
Room depth	10.0 m
Room height	5.0 m
Number of windows	6

internal obstructions within the room are not considered. Also, a modular system for sizing and placing the windows has been adopted. Due to these limitations, GENWIN may not be able to realistically simulate actual design situations. At present, it serves to demonstrate for what purpose and how a generative design tool can be developed.

Steady-state calculations are used for calculating the heating energy consumption that is required to derive the optimal glazing area. Summer-time overheating cannot be accounted for by this method. The glazing ratio suggested by the model, therefore, can only be approximate rather than completely accurate; especially for south-facing rooms, it is likely to be erroneous, as it suggests full wall glazing, which would in reality lead to a considerable cooling load. But as the suggested glazing ratio can be over-ridden by the user, this is not a serious limitation.

The climatic data required for calculating the optimum glazing ratio exist for four locations in the UK, all at different latitudes. From south to north, these are—Plymouth, Cambridge, Belfast and Aberdeen. Climatic data for other locations have to be manually input.

To be able to run the program on a microcomputer within a reasonable processing time, certain maximum limits have been placed on the values of certain parameters. These are listed in Table 1.

The modular grid adopted for window placement is 0.5 m. This is not user-defined but built into the program.

These limits have been placed merely to enable speedy processing. In itself, the coding of GENWIN can handle the largest conceivable room dimensions and window number, and the smallest modular grid for window placement.

5. INPUTS

5.1. *Preliminary inputs*

These are devoted to the description of the room that is to be modelled. They are as follows:

1. Room dimensions—width, depth and height
2. Beam depth and wall thickness
3. Height of reference plane for daylight factor calculation
4. Room orientation
5. Type of glazing
6. Details of external obstruction (if any)—distance from the building and height above reference plane
7. Internal surface reflectances
8. Factors for window maintenance and frame thickness

*The assumption here is that the room being modelled is not an independent building or block, which is why it cannot have all its walls external.

5.2. *Inputs for calculation of heating energy consumption*

1. Building Type (heavyweight or lightweight)
2. Number of External Walls (1–3)*
3. U-Value of External Wall
4. U-Value of Roof (if external)
5. Ventilation Rate
6. Rate of Casual Gains
7. Climatic data for each month (if different from that of the given four cities). This comprises of:

—Average degree days
—Average daily global solar radiation on a vertical plane for the given orientation

5.3. *Input for calculation of lighting energy consumption*

1. Datum Illumination Level in lux (100/150/300/500/750/1000)

5.4. *Inputs for daylight factor calculation and testing*

1. Number of Reference Points along room width
2. Number of Reference Points along room depth
3. Minimum daylight factor required at all points
4. Different values for minimum DF at specific points (if required)

Appropriate default values exist for each of these input variables.

6. METHODOLOGY

The methodology followed by the model is shown in Figure 1.

In order to make GENWIN a more comprehensive model for energy-conscious design, it also incorporates, in addition to window generation, options performing evaluative tasks such as determining the thermal and light energy consumption, and calculation of daylight factors for a specified window configuration. These can be used to refine the solutions proposed by the model. These options, being based on standard algorithms, are not described in this paper.

A detailed description of the methodology used by GENWIN follows.

6.1. *Checking for limiting depth*

The room configuration for good light distribution in a room with one window wall only, can be expressed in terms of its dimensions as follows [3]:

$$(L \div W) + (L \div H) \leqslant 2 \div (1 - R_b)$$

where

L = room depth
W = room width
H = height of window head from the floor
R_b = area weighted average reflectance of the rear half of the room.

If the room depth exceeds the value given by this equation, the daylight will be unsatisfactory whatever the glazing ratio. Therefore, as soon as the room dimensions are input, a check is made to see if its depth exceeds the limiting depth; if so, a message to this effect is displayed to the user, who can then be aware that for the specified room, a good daylight distribution cannot be achieved.

S/he then has the option to modify the room depth, or continue with the processing but specify at the daylight testing stage that the 'good distribution criterion' need not be met. This check can be regarded as a 'rule of thumb' that provides guidance towards an acceptable design solution.

6.2. *Determining the optimum glazing ratio*

The glazing ratio of a room has important energy implications. As the glazing area increases, depending on the room orientation, heat loss can also increase; but this may be offset by useful solar gain and daylighting. What is needed therefore is to determine the optimum glazing area which will minimize the sum of *both* the heating and lighting energy consumption.

Most computer tools for environmental analysis do not guide the designer in this aspect. The glazing area is usually determined on the basis of thermal performance alone; if this is found to be not in accordance with the light levels required, it is changed and the thermal performance is re-evaluated; the process continues until the right balance is found. A program that considers both lighting and thermal performance at the outset to determine the glazing ratio can avoid this tedious procedure to a large extent.

GENWIN gives the user the exact glazing ratio at which total annual primary energy consumption is minimum. The user is given the choice to over-ride this and specify a different value for window generation.

6.3. *Generation of window configurations*

Once the glazing ratio has been finalized, the total glazing area is calculated. This has to be mapped onto a surface extending throughout the length of the external wall, from the height of the reference plane to the bottom of the beam. For the number of windows input by the user, all possible configurations for this glazing area based on a modular grid of 0.5 m are then generated for testing.

GENWIN thus resorts to an exhaustive search which is the simplest search strategy, but also the least efficient and therefore the 'weakest', as it generates all possible window configurations for testing—even those which would, from considerations of aesthetics, view, or privacy, be completely unacceptable, and therefore useless. Such a generative procedure, not guided by any heuristics, can be computationally expensive, especially if the variables involved are large, as this will produce a larger number of possible solutions.

To be commercially viable, therefore, such a generative model needs to incorporate some rules as to where the windows can be placed, as well as on the relationships between the sizes and shapes of the windows, if more than one is being considered. (This would be similar to the process of defining rules in areas such as 'shape grammars'.) A limited number of solutions will then be produced which will satisfy other criteria and can then be tested by algorithmic procedures to find those, if any, that satisfy the specific requirement. Because of time constraints, this feature is not currently implemented.

GENWIN however does incorporate *one* constraint that helps to avoid a 'combinatorial explosion' of window

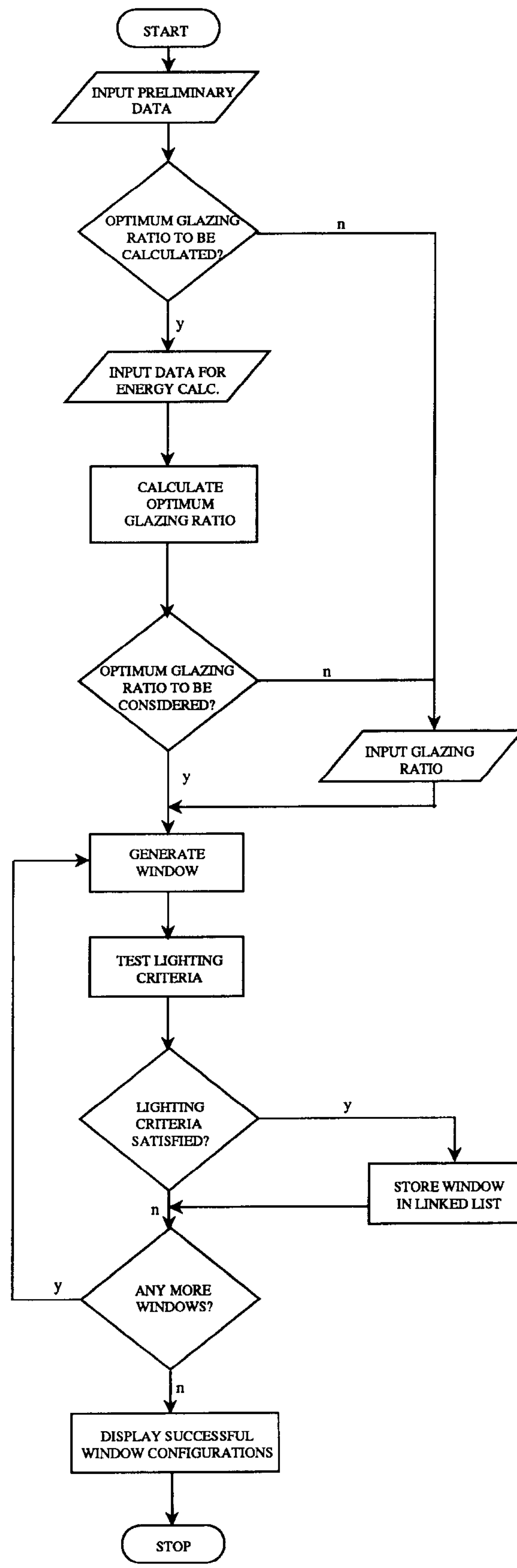


Fig. 1. Schematic flowchart diagram of GENWIN.

configurations and enable processing to take place within a reasonable time: for a window number exceeding 1, the ratio of the area of the largest to the smallest window should not exceed 4. A constraint on the minimum aspect ratio could also have been incorporated, but this would have excluded viable options like narrow full-width clerestorey lighting, hence it was not included.

The reduction in the number of configurations generated and tested is also facilitated by letting the user guide the generative procedure, and process only those combinations of window areas that seem promising to him.

6.4. *Daylight factor calculation and testing*

As soon as a window configuration is generated, the daylight factor at each point of the user-defined reference plane grid for that configuration is calculated, using the methodology given by Hopkinson *et al.* [4]. This is the sum of the sky component, the externally reflected component (if an external obstruction exists), and the internally reflected component at that point. A CIE overcast sky has been assumed.

After the daylight factors at all reference points have been obtained, the configuration is tested to see if it meets the specified lighting criteria. A configuration is judged as 'successful' if it satisfies the following requirements:

1. The daylight factor at each reference point must not be lower than the minimum specified by the user for that point.
2. The daylight factor at any reference point must not differ from the daylight factor at a reference point adjacent to it by a factor greater than 3. This is the inbuilt 'uniformity criterion' which helps to reduce glare on the work plane [5]. The user, however, is given the choice to over-ride this criterion.
3. The average daylight factors in the front and rear halves of the room should not differ by a factor greater than 3 [6]. This is the other inbuilt criterion to ensure a good light distribution within the room—which again the user can choose to over-ride.

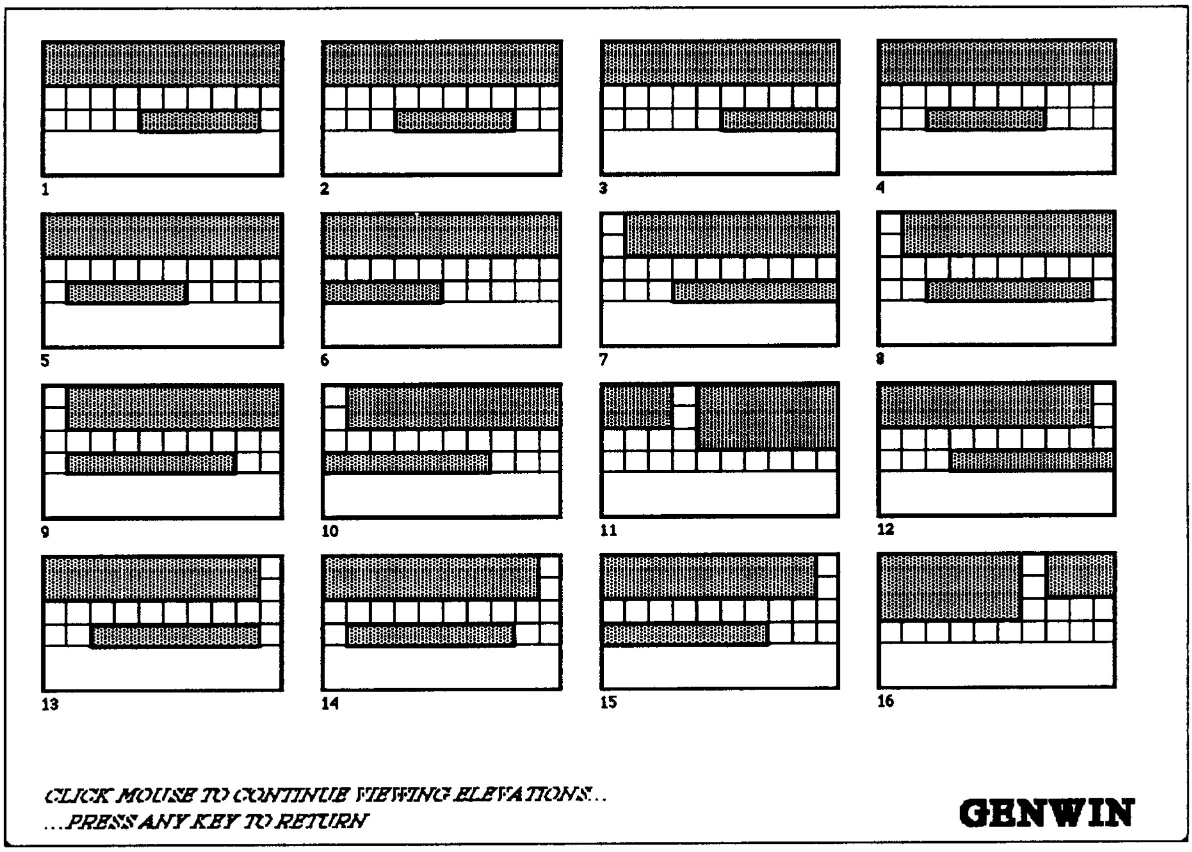
7. OUTPUT

All 'successful' window configurations are displayed to the user graphically in order of performance. The modular grid used is also depicted. One window configuration is rated better than another, if the daylight factor at the back of the room is higher. The user thereafter has the opportunity to take a detailed look at the configurations which seem promising; these are identified by their 'ranking' number.

Variations of desired configurations, if required, can

Table 2. The input details for the test room

Parameter	Value Input
Room width	5.00 m
Room depth	6.00 m
Room height	3.00 m
Beam depth	0.00 m
Reference plane height	1.00 m
Wall thickness	0.30 m
Room orientation	north-west
External obstructions?	no
Glazing type	single
Reflectance of internal walls	0.5
Reflectance of window wall	0.5
Reflectance of floor	0.3
Reflectance of ceiling	0.7
Maintenance factor for glazing	0.8
Frame thickness factor	0.85
Building type	heavyweight
Number of external walls	1
U-value of external walls	0.4
Ceiling an external surface?	no
Glazing insulated at night?	no
Ventilation rate	1.0 ac/h
Casual gain rate	10.0 W/m^2
Site location	Cambridge
Optimum glazing ratio as calculated	34
A different glazing ratio to be input?	yes
Glazing ratio (as percent. of external wall area)	40
Number of windows to be placed (1–3)	2
No. of reference points along room length (default = 5)	5
No. of reference points along room width (default = 6)	6
Overall minimum daylight factor (default = 0.5%)	1.25
Higher minimum DFs at certain points to be specified?	no
Uniformity criterion (1 : 3) to be met?	yes
Light distribution criterion (1 : 3) to be met?	yes



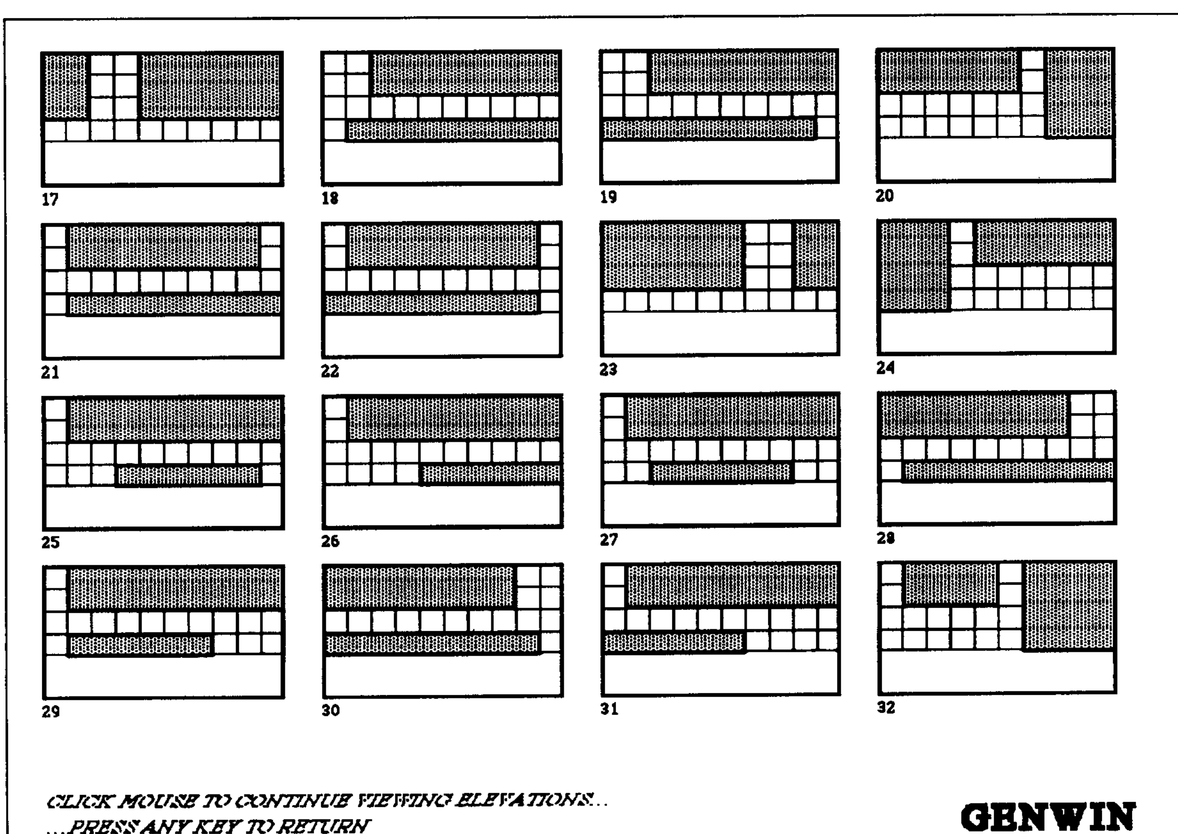
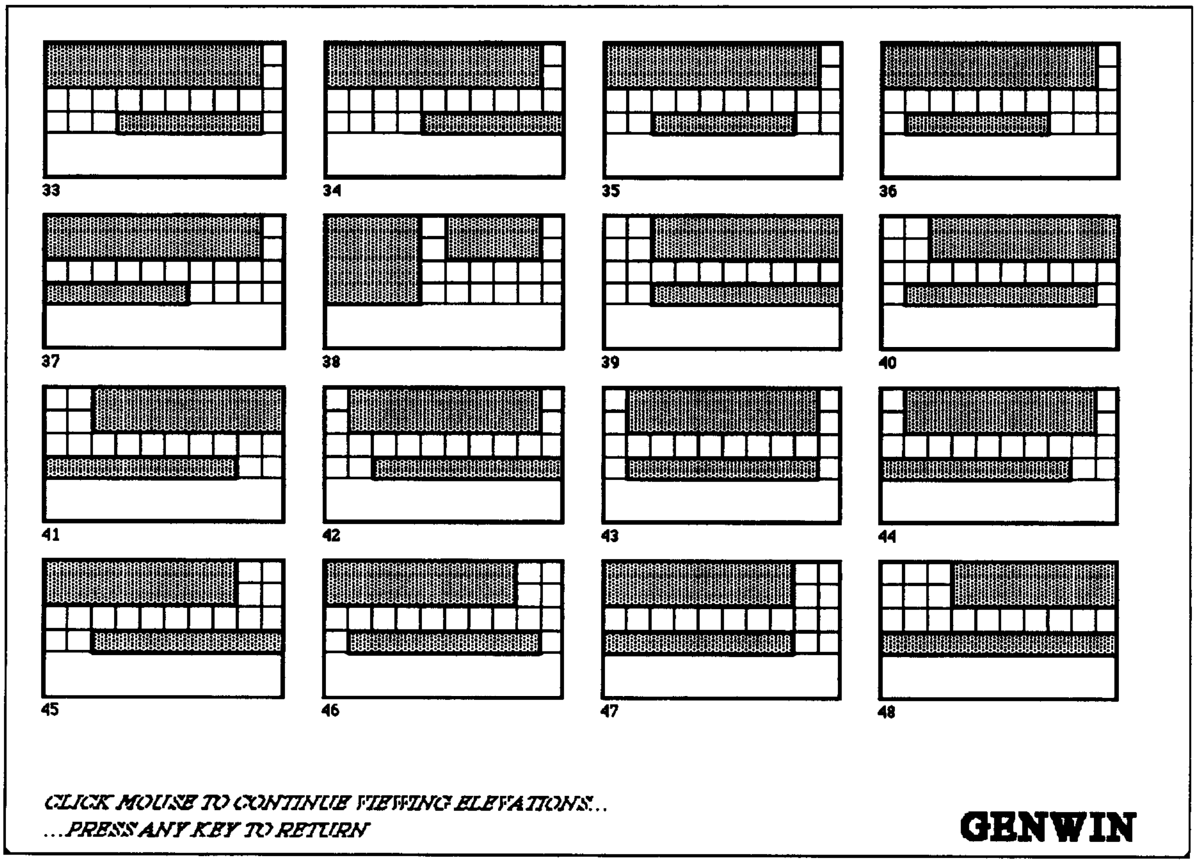


Fig. 2. The 51 configurations satisfying the lighting criteria for the test room, in order of performance.



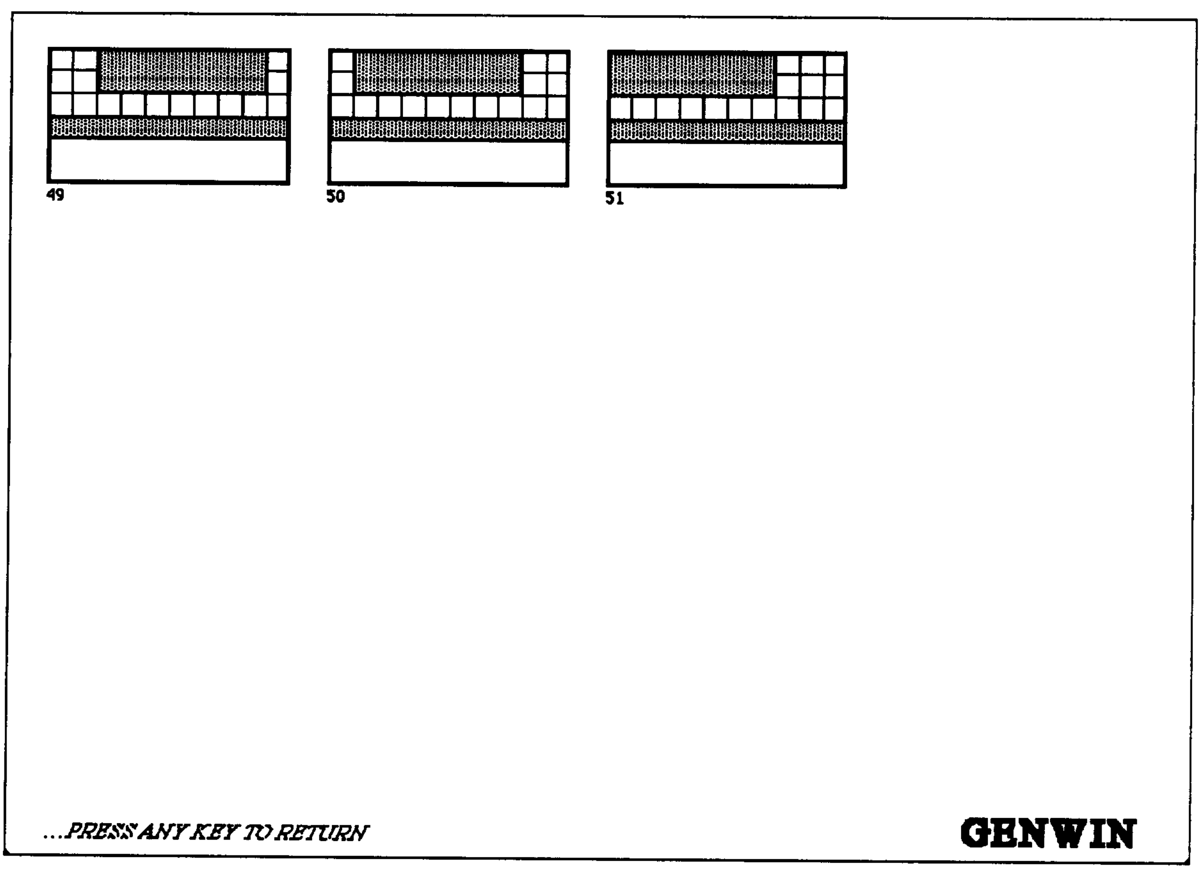
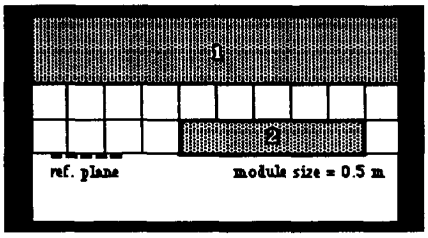


Fig. 2 (*continued*).



Internal Elevation of Window Wall

2.84 (1.25)	**3.62** (1.25)	**6.02** (1.25)	**6.25** (1.25)	**4.39** (1.25)
4.00 (1.25)	**4.95** (1.25)	**5.39** (1.25)	**5.20** (1.25)	**4.23** (1.25)
2.74 (1.25)	**3.17** (1.25)	**3.35** (1.25)	**3.22** (1.25)	**2.80** (1.25)
2.03 (1.25)	**2.22** (1.25)	**2.29** (1.25)	**2.23** (1.25)	**2.05** (1.25)
1.67 (1.25)	**1.75** (1.25)	**1.79** (1.25)	**1.76** (1.25)	**1.68** (1.25)
1.48 (1.25)	**1.52** (1.25)	**1.54** (1.25)	**1.52** (1.25)	**1.48** (1.25)

Plan with Daylight Factors
[top, bold : measured] [below, in brackets : minimum specified]

Room Configuration
Width : 5.0
Depth : 6.0
Height : 3.0
Ht of Ref. Plane : 1.0
(All dimensions are in metres)

Window Configuration
Glazing Ratio : 40

Window No.	1	2
Width	5.0	2.5
Height	1.0	0.5
Distance from left	0.0	2.0
Sill height	2.0	1.0

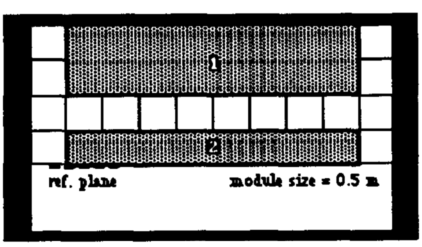
Daylight Factors
Minimum : 1.48
Maximum : 6.25
Average (front) : 4.14
Average (back) : 1.80

Annual Primary Energy Consumption (kWh)
Heating : 4241.81 (73 %)
Lighting : 1512.45 (27 %)

CLICK MOUSE TO CONTINUE...

GENWIN

Fig. 3a. A closer look at the 'best' configuration.



Internal Elevation of Window Wall

3.91 (1.25)	**6.02** (1.25)	**6.37** (1.25)	**6.02** (1.25)	**3.91** (1.25)
3.54 (1.25)	**4.76** (1.25)	**5.18** (1.25)	**4.76** (1.25)	**3.54** (1.25)
2.44 (1.25)	**2.92** (1.25)	**3.11** (1.25)	**2.92** (1.25)	**2.44** (1.25)
1.84 (1.25)	**2.03** (1.25)	**2.10** (1.25)	**2.03** (1.25)	**1.84** (1.25)
1.53 (1.25)	**1.62** (1.25)	**1.65** (1.25)	**1.62** (1.25)	**1.53** (1.25)
1.37 (1.25)	**1.41** (1.25)	**1.42** (1.25)	**1.41** (1.25)	**1.37** (1.25)

Plan with Daylight Factors
[top, bold : measured] [below, in brackets : minimum specified]

Room Configuration
Width : 5.0
Depth : 6.0
Height : 3.0
Ht of Ref. Plane : 1.0
(All dimensions are in metres)

Window Configuration
Glazing Ratio : 40

Window No.	1	2
Width	4.0	4.0
Height	1.0	0.5
Distance from left	0.5	0.5
Sill height	2.0	1.0

Daylight Factors
Minimum : 1.37
Maximum : 6.37
Average (front) : 4.12
Average (back) : 1.65

Annual Primary Energy Consumption (kWh)
Heating : 4241.81 (73 %)
Lighting : 1512.45 (27 %)

CLICK MOUSE TO CONTINUE...

GENWIN

Fig. 3b. A detailed view of configuration number 43.

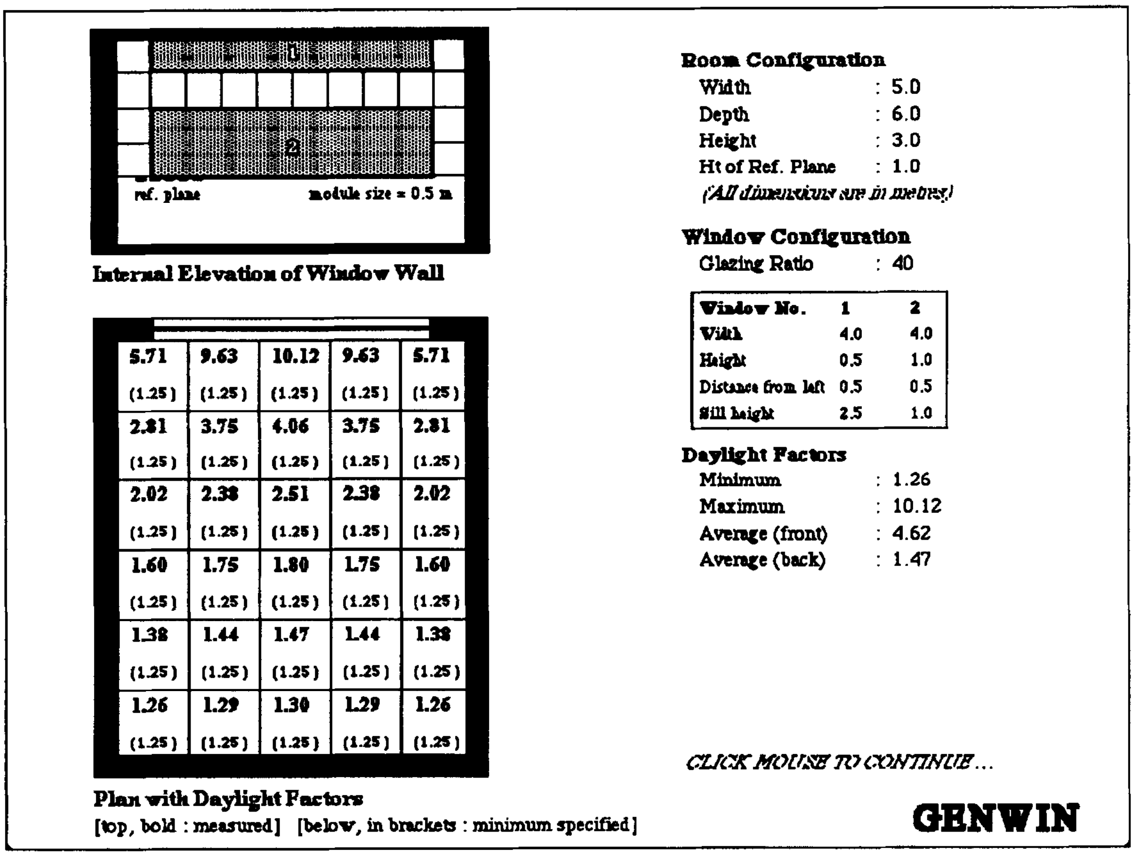


Fig. 4. Configuration 43 seemed promising, but not perfect! A variation of it, tested with the evaluative option included in GENWIN. As can be seen, the light distribution criterion just falls short of 3; this might be therefore an acceptable solution.

finally be tried and tested using the evaluative option mentioned earlier.

In conclusion, the results obtained by running GENWIN for a test room are illustrated. The input details of the room are as shown in Table 2.

Figures 2–4 illustrate the graphical output from the program. There are 260 possible window configurations for a glazing ratio of 40% on the external surface area of this room; of these 51 configurations satisfy the lighting requirements. The total processing time was 11.5 minutes.

8. FUTURE DEVELOPMENT

The future development of GENWIN is planned along the following lines:

- Incorporation of 'shape rules' to generate only aesthetically pleasing configurations.
- Modelling shading devices, light shelves, and internal obstructions.
- Using dynamic rather than steady state calculations to determine the optimum glazing ratio, and thereby taking summertime overheating into consideration.
- Improving the user interface.

9. CODING DETAILS

GENWIN is written in 'C' using the 'Think C' compiler on a Macintosh, and contains about 3500 lines of code.

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