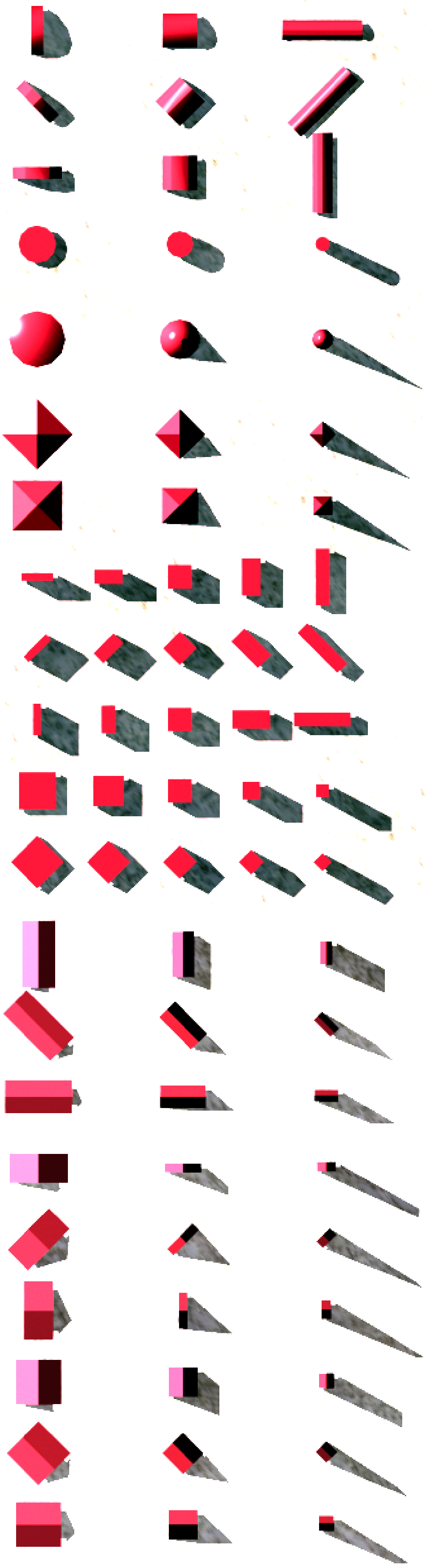


Thanos N. Stasinopoulos

Geometric Forms & Insolation

An Analytical Study Of The Influence Of Shape On Solar Irradiation

English Summary

Doctoral Dissertation
National Technical University Of Athens
Department Of Architecture

Athens
March 1999

Summary

Research topic

The solar energy **R** (global, direct, diffuse, ground reflected) incident upon a solid surface of area **F** exposed to the solar rays is the sum of the irradiation on the surface segments. It depends on various factors like the size, orientation and slope of each segment, as well as time, latitude, atmospheric conditions and ground albedo *(Chapters 2 & 3).*

The ratio $\varepsilon = \mathbf{R/F}$ is the *mean solar irradiance* on the surface and is independent of the surface size. It indicates the potential of a form to receive more or less solar radiation than others at the same time and place.

The present analysis of the relationship between geometric shape and solar irradiation is based on the mean solar irradiance ε on several shapes that relate to simple building types *(Chapters 7 & 10)*. Conclusions can equally apply to other artificial and natural forms, like tanks, typical vegetation shapes, topography formations, etc.

The mean solar irradiance ε varies over time & place, therefore is not a steady base for assessing forms in terms of insolation. For that purpose it is more appropriate to correlate the mean irradiance ε on a form with the solar energy ε_0 that is *available* at the given period and location, a measure usually indicated by the horizontal irradiance *(Chapter 8)*.

The present study introduces the notion of *relative irradiance* or **'insolation index'** μ, defined as the ratio $\varepsilon/\varepsilon_0$ of the mean solar irradiance on a surface ε to that on the horizontal plane ε_0: $\mu = \varepsilon / \varepsilon_0$.

Considering a solid surface as a solar *receiver*, the **μ-**index indicates its *'efficiency coefficient'* in that function, i.e. the ratio of *received* to *available* energy. The **μ-**index also denotes the incident energy change if a horizontal flat surface is converted into a 3-D form of the same area. Obviously as a form is transformed into flat & horizontal, its **μ-**index tends to 1 (100%).

Research process

The relationship between geometric properties and insolation levels is investigated here by comparing the μ-index of various geometric forms. The μ-index is computed in four steps:

1 Partitioning of the exposed surface **F** in **n** facets of area $\mathbf{f_n}$ and calculation of the solar irradiance $\mathbf{i_n}$ on each one.

2 Calculation of the total energy **R** on the entire surface as the sum of the irradiance on each facet multiplied by its area: $\mathbf{R} = \Sigma\,(\mathbf{i_n} \cdot \mathbf{f_n})$.

3 Calculation of the mean solar irradiance ε on the surface by dividing the total energy **R** to the total area **F**: $\varepsilon = \mathbf{R/F}$.

4 **μ-**index calculation by dividing the mean solar irradiance ε to the applicable horizontal one ε_0: $\mu = \varepsilon / \varepsilon_0$.

The irradiance calculation and all the subsequent computations were performed on computer spreadsheets based on the algorithm developed by Professor J. K. Page and other European scientists *(Chapter 4 & Appendix A)*. The algorithm is applied for the calculation of *direct*, *diffuse* & *ground reflected hourly* irradiance on a plane at any orientation & slope, according to the following parameters:

- *latitude* and *elevation* of the location
- monthly average *sunshine duration*
- monthly Linke *atmospheric turbidity* factors
- annual **a+b** *Angstrom coefficients*.

Climatic data from various sources were employed to compute the hourly horizontal irradiance (direct, diffuse & global) for the typical day of each month. The resultant hourly values **h** were normalised to the final **h'**, to match the ratio between global irradiance daily sums from measured data **H'** versus the initial calculation **H**:

$$h' = h \cdot (H' / H).$$

Hourly irradiance and daily irradiation (including ground reflected) on the facets of each form was calculated next, according to the normalised horizontal data. This was repeated for 7 generic types of convex solids in 71 variations of proportions & orientation. Since this study refers to *incident* energy only, not *absorbed* or *transmitted*, all forms were considered as opaque and of zero reflectivity.

The procedure was applied for 3 albedo values (0, 0.2 & 1) in 3 locations (London, Athens & Riyadh, located at steps of 15° latitude), giving a total of 71x3x3 = 639 cases. The irradiation output in each case was subsequently used to compute the monthly & annual **μ-**index for all types of radiation (global, direct, diffuse & ground reflected).

For each location, ground albedo and radiation type, the monthly output includes:

- Hourly & daily solar irradiance on a *horizontal* plane *(Chapter 11 & Appendix B).*
- Daily solar irradiance on the facets of a *polyhedral dome* ('*hemispherical irradiation distribution'*) *(Chapter 12 & Appendix C).*
- Total daily solar irradiation on *71 forms (Appendix E).*
- Insolation **μ**-indices of each form *(Chapter 13 & Appendix D).*

Research output

Further processing of the above data has led to various conclusions, like:

- **insolation indices μ**: The **μ**-indices vary from shape to shape, especially during summer. Monthly fluctuations of the global radiation indices are generally narrow for low forms and wider for tall ones. This is due to the higher seasonal variations of the direct component on tall forms, while the diffuse one remains rather constant in all cases *(Chapter 13)*.
- **Irradiation distribution**: The distribution of the total solar irradiation on the facets of a form depends not only on their size and orientation, but also on the time of the year, thus transposing the main solar collection surface and the need for solar control *(Chapter 14)*.
- **Orientation effects**: Changes of orientation affect *monthly* **μ**-indices of a form, but the *annual* values remain practically constant *(Chapter 14)*.
- **μ-indices & B/F ratio**: **μ-**indices and the '*Base-To-Exposed-Surface'* ratio **B/F** of a form have a direct *linear* relation. That applies generally to all forms, locations, months and radiation types, notably in the diffuse component. Some deviations from linearity occur mainly during winter, particularly in London, due to wider variations of the direct component in tall forms, i.e. those with lower **B/F** ratio *(Chapter 15)*.
- **u coefficients**: The linear relationship between **μ-**index and **B/F** ratio is expressed by a function like

  $$\mu = u \cdot (B/F) + v$$

  For **B/F**=**1** (flat shape) it is **μ**=**100**%, so **u**+**v**=**1**; hence

  $$\mu = u \cdot (B/F-1) + 1 \text{ , and}$$

  $$u = (\mu-1)/(B/F-1)$$

  The monthly **u** coefficients deriving from **μ** & **B/F** values as above, vary slightly from shape to shape. Their values have been averaged over all 71 forms for each location, radiation type and albedo. The average **u** coefficient can be used to estimate the typical **μ**-index of any form of given **B/F** ratio *(Chapter 16)*.

- **Irradiation calculation applying u coefficients**: According to the above equations, the mean solar irradiance ε on a convex form of ratio **B/F** is $\varepsilon = \mu \cdot \varepsilon_0$, or

  $$\varepsilon = [\mathbf{u} \cdot (\mathbf{B/F} - \mathbf{1}) + \mathbf{1}] \cdot \varepsilon_0.$$

  By definition $\varepsilon = \mathbf{R/F}$, therefore

  $$\mathbf{R} = [\mathbf{u} \cdot (\mathbf{B/F} - \mathbf{1}) + \mathbf{1}] \cdot \varepsilon_0 \cdot \mathbf{F}.$$

  This formula can be applied to estimate the total irradiation **R** on any convex form of exposed surface **F** and base **B**, using just horizontal irradiance ε_0 data and the **u** coefficients. The **u** coefficients found in this study refer to only three albedo values, but it is easy to convert irradiation **R** data from one albedo to another *(Chapter 16).*

- **Climatic insolation index** μ': The insolation level of a building form is beneficial or detrimental depending on the ambient temperature T_o, in connection with the comfort temperature T_i. The monthly difference $\Delta t = T_i - T_o$ is considered as a positive or negative factor that converts μ-indices into *'climatic insolation indices'* μ' according to the relation:

  $$\mu' = \mu \cdot \Delta t$$

  where T_i is the comfort zone limit closest to T_o (if T_o is within the comfort zone then $T_i = T_o$). Based on the mean monthly ambient temperature T_o in each location and assuming comfort zone between 18-25°C, the forms were sorted according to their annual average climatic index μ' for global radiation and albedo 0.2 *(Chapter 17).*

- **Relative climatic insolation indices** μ_c: The actual μ-index of a form may differ from the typical value μ_0 that corresponds to its **B/F** ratio. Based on the discrepancy between the actual & typical values $\Delta\mu = (\mu - \mu_0) / \mu_0$, a form is considered 'warmer' or 'colder' than others of the same **B/F** ratio, i.e. it receives more or less radiation than the norm. That feature can be of positive or negative significance, according to temperature T_o.

  Under that prism, the forms were sorted by their '*relative climatic insolation index'* μ_c, which integrates $\Delta\mu$ & Δt:

  $$\mu_c = \Delta\mu \cdot \Delta t$$

  Due to the complexity of heat transfer and thermal comfort issues, μ' & μ_c indices provide only general *clues* for the climatic compatibility of a form with respect to insolation *(Chapter 17)*.

- **Differences between locations**: The comparison of μ-indices in each location against those in the other two has shown that all forms, especially the tall ones, perform better as solar receivers in higher than lower latitudes, in contrast to the opposite tendency of the available radiation *(Chapter 18)*.

Major elements of the study

As major contributions of this study to the issue of insolation analysis, one can highlight the following:

- Introduction and application of the *'insolation performance'* notion, including computation of the associated *'insolation index* μ*'* of various typical forms.
- Disclosure of a *linear relation* between insolation level and **B/F** ratio.
- Formulation of a *simple method* for calculating solar irradiation on any convex geometric form based on horizontal irradiance data.
- *Appraisal and classification* of geometric forms in relation to local climatic conditions.

The study includes not only the *analysis* of quantitative data but also their *creation*, utilising methods proposed by other researchers and climatic statistics. In addition to their use in the present work, several of those data (e.g. solar angles or irradiance values) can be useful for other applications, therefore they are included in the Appendices.

Text structure

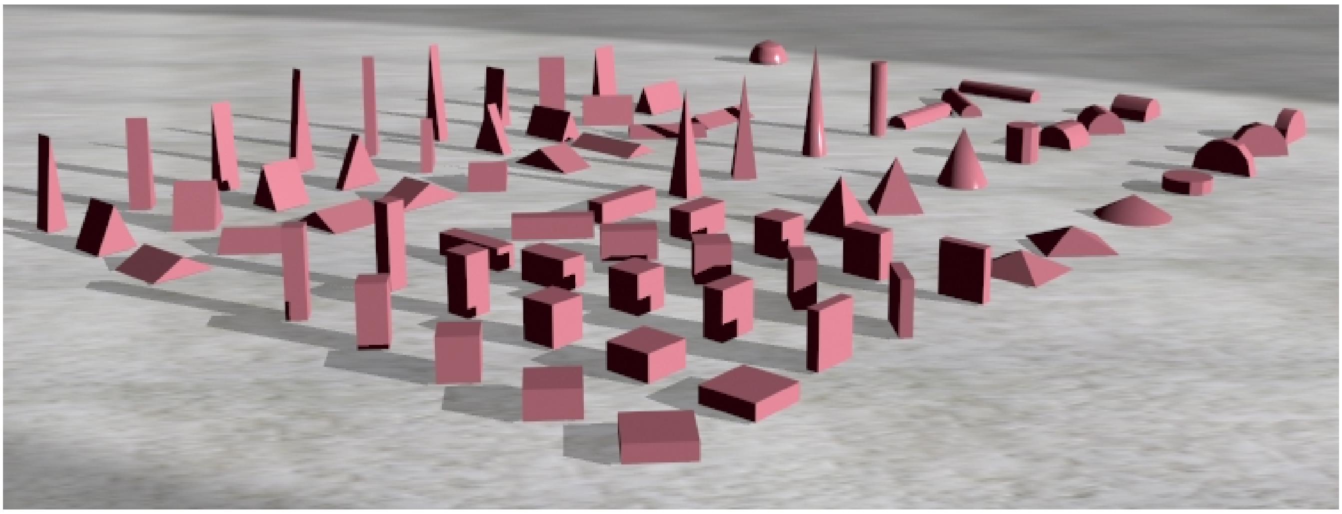
The study is divided in 4 parts:

A - INTRODUCTION: Review of solar radiation factors and related thermal properties of the building envelope, based mainly on selected references (*Chapters 1-6*).

B - THEORETICAL CONTEXT: Introduction to the conceptual framework of the study and research method (*Chapters 7-10*).

C - OUTPUT PRESENTATION: Presentation, assessment and interpretation of the findings, along with conclusions (*Chapters 11-19*).

D - APPENDICES: Additional details and assorted data of the research.



Thanos N. Stasinopoulos
Laskou 30, GR-156 69 Papagou, Athens, Greece
Tel. +30 210 6519403, mob. +30 697 7828414, fax +30 210 6532179
delaxo@central.ntua.gr
www.ntua.gr/arch/geometry/tns/