SUN AND CLIMATE MODELING FOR THERMAL SIMULATION
Parametric models relevant at early design stages

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ABSTRACT

The traditionally engineering-oriented approach to thermal building simulations tends to leave such analysis tools out of the reach of general design practitioners, especially during the early stages of building design when many of the most influential decisions regarding the thermal envelope are made. An alternative approach is proposed for making a situation-specific component of the overall thermal simulation model – the ambient climate conditions – accessible and informative at the level of schematic design considerations.

A means for profiling primarily the directional distribution of solar radiation is argued to be the most meaningful in this context, and a particularly useful parametric radiation model is briefly summarized, together with a description of how it is currently being implemented in the development of an architecture-oriented application method.

INTRODUCTION

With the increasing availability and power of computer-based methods for simulating the thermal behavior of buildings, simulation analysis appears to be gaining feasibility as a design guidance tool. The building design process in its earliest stages, however, does not generally include enough thermally relevant detail information to make such full-scale simulation results meaningful.

It is generally acknowledged that thermal performance assessments of environmentally responsive design are highly sensitive to preliminary assumptions made about solar/climate factors. Reliable assumptions are not only necessary for reliable simulation, but can also be used effectively for pre-simulation analysis of solar design potential.

To this end, solar radiation information should ideally be modeled with the same level of detail and validity as the geometric information that architects are accustomed to working with. This stipulates a tight coupling of solar radiation data and design geometry from the start of the design process in order to enhance intuitive understanding of solar influences, as well as to establish comparable design profiles for competing concepts.

Since it is in the early stages that the most significant decisions are made regarding sizing, placement, and orientation of the building volume, design tools are recommended which inform such key decisions in a schematic manner that is both flexibly specific and immediately interpretable. Moreover, the energy information gained should remain consistently applicable through subsequent design stages and, ultimately, serve as part of an overall thermal model.

Flexibility is best obtained by basing the solar design guidance methods on cohesive parametric models – as opposed to the standard method of relying on climate databases for relatively coarse, i.e. situationally unspecific, radiation data. In particular, an adequate model for calculating the solar dimensions of *geometry* and *radiation* on a daily basis is treated here for the express purpose of characterizing a building's solar potential from its inception, based on physical dimensions of energy rather than abstractly dimensionless "factors."

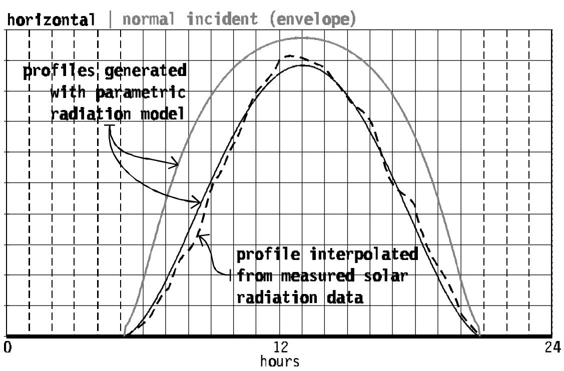
The subsequently suggested method of solar profiling is intended to facilitate the meaningful interpretation of solar dimensions in a schematic fashion and, therefore, focuses on extracting qualitative renderings and visualizations in lieu of precise numeric results.

Generally stated, the intensity of solar irradiation on a specified surface at any given point of time depends on solar position, meteorological conditions, as well as incident surface and obstructing geometry at the moment under scrutiny. Traditional methods for generating time-dependent descriptions of this "solar dimension" typically model the strictly geometrical aspects (in particular, solar position relative to incident surface orientation) in a fairly exact and situation-specific manner [1, 2].

The meteorological basis, on the other hand, is usually provided in the form of daily total solar irradiation on a horizontal surface [e.g., 3] as measured at some (it is hoped nearby and well-funded) meteorological station. The specific geometric model is then applied to the most plausible climate data available for the site at hand in order to derive a synthetically enhanced description to be used as an ambient driving function for solar gain [4, 5]. Aside from the obvious uncertainties that arise whenever adequately detailed and typified climate data is not readily available, this type of reference data may only be used "as is": the implied meteorological conditions can be neither adapted nor characteristically simplified for design-analytical purposes.

One possible way to compensate for these deficiencies is to implement a solar radiation model that incorporates parameters that clearly distinguish meteorological and terrain conditions from the geometric aspects, both solar and incident. A diurnal radiation profile generated synthetically by means of an appropriately selected parametric model has the particular advantage to architects of being inherently free of the "atmospheric noise" that gives historically based diurnal profiles their arbitrary character (even when "radiation-smoothed" with an interpolation algorithm [5], ill.1).

Thus a synthetic profile can be made to characterize primarily the directional distribution of solar radiation – clearly the most significant characteristic for assessing the impact of predominantly geometric design decisions. (More on the method of utilizing diurnal profiles to guide solar building design is related in the next section, "Solar Profiling".)



ILL. 1: DIURNAL PLOT OF SOLAR FLUXES [W/M^2]
– CHARACTERISTIC/REFERENCE DATA ON HORIZ. SURFACE
– CALCULATED NORMAL ON TRACKING SURFACE
(VIENNA, JULY 15, CLEAR SKIES)

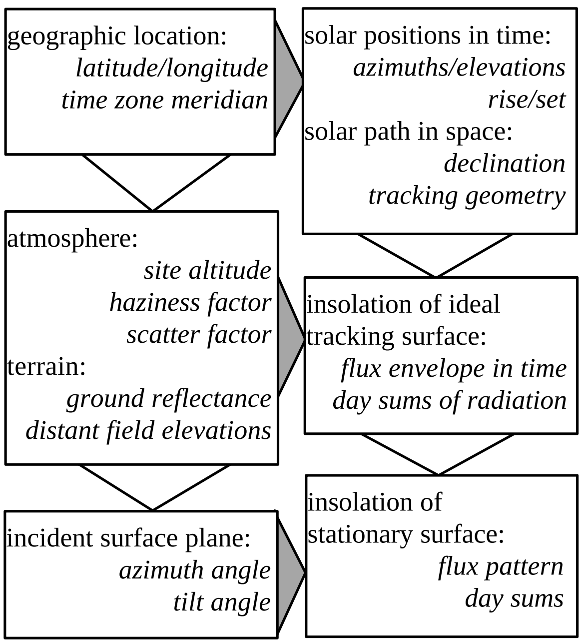
Ultimately, if preliminary design evaluations are consistently modeled as described in the following, they yield customized input data for solar driving functions when a fully developed building design is ready for thermal simulation analysis.

RADIATION MODEL

A method for computing the three main components of solar radiation incident on a given surface (direct beam, diffuse sky and ground reflected) has been made standard in the *ASHRAE Handbook of Fundamentals* [2 – chapter on *Fenestration*]. This involves a basic determination of solar angle in conjunction with tabulated monthly values for the extraterrestrial solar radiation intensity (*A*), the atmospheric extinction coefficient (*B*, together with regional "clearness numbers"), and the diffuse radiation factor (*C*). An alternative and, in certain respects, more flexibly analytical model has been presented in detail by *Heindl* and *Koch* [6] and shall be briefly summarized (and translated into English) here.

The algorithms for generating synthetic radiation data based on this model were originally developed for use in a variety of stand-alone solar calculation programs [e.g., 7] and also thoroughly tested within the framework of a diurnal building simulation program [8]. Work is currently in progress to re-design these tools based on an application method aimed specifically at satisfying the solar information needs of architects at early design stages [9]. Qualitative differences between the ASHRAE "*ABC*" method and the formulae implemented here shall only be highlighted in the following, as a thorough comparison of the two methods is not a core concern in the presented concept of building design guidance.

The diagram below (ill.2) summarizes the parameters involved in basic categories of solar input variables and the types of output information extractable from each categorical level.



ILL. 2: OVERVIEW OF BASIC RADIATION MODEL INPUT PARAMETERS (WITHOUT SHADING)

The mathematical equations for calculating solar position relative to the earth as related by *Heindl* and *Koch* [6] are derived from a thoroughly "astronomical point of view," a complete recapitulation of which would be beyond the scope of this paper. Suffice it to say that the resultant equations for solar azimuth a and elevation *ß* at a given terrestrial location and time *t* fully account for time-dependent deviations in distance, declination, and relative velocity which are attributable to the eccentricity and obliquity of the solar ecliptic.

The diurnal difference between apparent and mean solar time, which varies continuously with the earth's position on the ecliptic, is rectified by a special corrective term *z* to represent the *Equation of Time*. In this model, *z* is expressed analytically as a function of the day of year *d* (rather than taken from a table of monthly values [2]), and the equations are fully formulated to yield results for mean solar time directly. The effective shift between mean solar and conventional local time at a particular longitude is then easily derived given an appropriate reference meridian for the applicable time zone (e.g., 15° relative to longitudes of sites with Central European Time) in a distinct computational step.

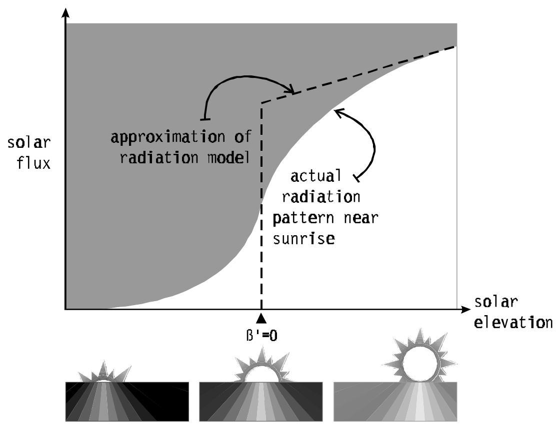
The only significant simplifications made here lie in defining the unit of a day *d* as 1/365 part of a solar year and, furthermore, in assuming that the ecliptic position of the earth j (and thus the solar declination d) remains constant throughout the course of one day. The maximum range of error that can result from these simplifications is proven quite negligible in comparison to other influences, especially when considered in the context of thermal simulations.

Unlike in the ASHRAE method, a means for correcting the apparent solar elevation to account for direct beam refraction through the atmosphere is also incorporated by *Heindl* and *Koch* [6]. Though this effect is only significant at low solar elevations, it must be taken into account to accurately predict the time of sunrise and sunset, i.e. when the refraction-corrected solar elevation *ß′* = 0 (as viewed from the earth's surface). Accurate solar angle prediction is especially critical in the case of sites located beyond the arctic circle, where a calculated solar elevation that has not been refraction-corrected yields to thoroughly misleading results as to whether the sun rises or sets at all on dates near the solstices.

The exact definition of sunrise and sunset varies from astronomical convention somewhat: it is here defined as the moment when the visible sun's *center* (rather than the top edge) passes the horizon. This allows a minor simplification in the radiation pattern that is convenient and sufficiently precise for the purpose at hand.

Solar radiation intensity is assumed to be null until the defined moment of sunrise and immediately after the moment of sunset. The points of dawn and dusk according to this description show a discontinuous jump from 0 to a basic start quantity of radiation associated with a fictitious full appearance of the sun. The actually visible "disk" of the sun, of course, does not pass the horizon in a single moment with a sudden jump. In other words, the actual radiation pattern at sunrise and sunset reflects a gradual, albeit steep, transition from "sun still completely hidden" to "sun in full view" (ill. 3).

As shown in the diagram below, associating the calculated moment of transition with the sun's center yields a close approximation of the actual curve in this detail, with negligible effect on the calculable insolation sum over the course of the day (the area under the curve).



ILL. 3: SCHEMATIC DIAGRAM OF RADIATION PATTERN – ACTUAL VS. CALCULATED – AT SUNRISE

The trigonometric equations for translating quantities of normal direct beam flux to the radiation intensity that is incident on a surface plane with azimuth a_i and tilt b_i (to describe the specific angle of incidence q_i and apply the *Lambert* cosine formula) are well known and so will not be reiterated. However, as meteorological stations cannot implement ideal tracking and measuring devices for determining direct beam normal flux throughout the course of a day, this theoretical base quantity is not directly available by empirical means.

Heindl and *Koch* [6] delineated a fundamental method for describing the insolation components on a normal surface in parametric terms, which – due to key differences to the ASHRAE "*ABC*" parameters – merits a more detailed re-introduction in this context.

The first step is to determine with reasonable accuracy the amount of unmitigated solar radiation that reaches the earth, before passing through the earth's atmosphere, I. This equation involves the time-varying distance between sun and orbiting earth to account for significant irradiation fluctuations (± 3.34 %) due to the eccentricity of the solar ecliptic. It defines extraterrestrial radiation as a diurnal function of the ecliptic longitude (instead of a tabular value for a given month, as is A [2]):

$$I = I_0 \cdot [1 - \varepsilon \cdot \cos(\varphi + 77.94°)]^2 \qquad (1)$$

whereby:

- I_0 = solar constant (e.g., 1370 W/m2)
- ε = eccentricity of earth's orbit (0.0167)
- φ = ecliptic longitude of earth (calculated angular distance from spring equinox)

As thoroughly related by *Nehring* [10], the mitigation of direct beam radiation intensity through the earth's atmosphere can be adequately approximated with a combination of two parameters, Γ and Q, reflecting meteorological "haziness" and the inverse effect of "relative air mass" at a particular altitude:

$$I_N^D = I \cdot e^{-\Gamma / Q} \qquad (2)$$

The parameter Q is a function of relative air mass f_A, which is in turn a function of site altitude H and the calculated (refraction-corrected) solar elevation *ß'*:

$$Q = \frac{c_1}{f_A} + c_2 \qquad (3)$$

with

c_1 = 9.38076
c_2 = 0.912018

and

$$f_A = \frac{2.0015 \cdot (1 - H \cdot 10^{-4})}{\sin ß' + \sqrt{0.003 + \sin^2 ß'}} \qquad (4)$$

Given appropriate values for the total haziness factor Γ – assumed constant over the course of the day – according to *Linke* and *Boda* [11], the equations above are shown by *Heindl* and *Koch* [6] to be sufficiently accurate for meteorological conditions from clear to partly cloudy skies. Typical clear sky values are, for example, Γ = 4.3 for urban sites, Γ = 3.5 for rural areas, and Γ = 2.7 for mountain locations. By means of a time-dependent series of momentary values for the haziness factor, variably cloudy conditions can also be described with this equation.

As compared with the ASHRAE formula [2], this still constitutes a simplification from the point of view of the user: instead of having to rely on regionally mapped data for "clearness numbers" to correct the average conditions assumed in the atmospheric extinction coefficient B (as well as to account for high altitudes), only two relatively clear-cut parameters need be specified (Γ and H).

Part of the direct radiation filtered by the atmosphere still reaches the earth's surface in the form of diffuse sky radiation. The relative portion of this component, referred to here as the "scatter factor" Π according to *Reitz* [12], has been proven to be nearly constant at around 1/3 for fair sky conditions and, above all, generally independent of the haziness factor as well as solar elevation. The diffuse radiation factor C according to ASHRAE, which varies strongly from month to month, does not possess such convenient characteristics for two reasons:

- the expression for diffuse sky radiation leaves the inherent dependency on solar elevation embedded in the value C, and
- C is applied to the quantity of direct normal flux, rather than to the remainder of extraterrestrial radiation that is scattered out of the direct beam.

Using the *Reitz* scatter factor Π, the diffuse sky component of solar flux incident on a horizontal surface is expressed as:

$$I_H^S = \Pi \cdot (I - I_N^D) \cdot \sin ß' \qquad (5)$$

The direct beam flux component incident on a horizontal surface, with the *Lambert* cosine formula, is given by:

$$I_H^D = I \cdot e^{-\Gamma / Q} \cdot \sin ß' \qquad (6)$$

Consequently, two further equations can be derived for correlating the two main meteorological parameters to actual radiation data ("custom" Γ and Π), in the event that applicable data is or becomes available. However, such fine-tuning of the radiation model would only be relevant for final and highly detailed thermal simulation. For the purpose of making initial assessments of the impact of primary design options, a model description that consistently works with standard values of Γ and Π is quite adequate, clear and, in most instances, preferable during early stages of analysis.

The diffuse sky component of solar flux that hits a planar surface of arbitrary inclination is, of course, less than that incident upon a horizontal surface, since the inclined plane does not "see" the full extent of the sky hemisphere. For the sake of completeness, the generally accepted formula for calculating this component on a plane i tilted at an angle of $ß_i$ from vertical is included here:

$$I_i^S = \omega \cdot I_H^S \qquad (7)$$

whereby the view coefficient w (equivalent to the angle factor F_{ss}) is defined as:

$$w = \frac{1}{2} \cdot (1 + \sin ß_i) \qquad (8)$$

Part of the total incoming radiation, direct beam and diffuse, is reflected by the surrounding ground and, to the extent that the plane is tilted into partial view of the ground plane, is also incident upon the inclined surface. The expression for this solar flux component assumes a simplified surrounding terrain that is horizontal and homogeneously diffuse reflecting (with ground reflectance r_G), isotropic sky radiation, and that the surface is exposed only to sky and ground:

$$I_i^G = (1 - w) \cdot r_G \cdot (I_N^D \cdot \sin ß' + I_H^S) \qquad (9)$$

For most purposes, only the resultant total solar flux on an incident surface, i.e. $I^D + I^S + I^G$, will be of immediate interest to the building designer. When developing solar apertures and shading configurations, a basic differentiation between direct beam and diffuse (sky + ground) flux components may also be useful.

For manipulating the calculation model, however, the more detailed breakdown is necessary for accurate calculation of total flux. This makes it possible to account for, among other things, the effect that terrain elevations (e.g., a mountainous horizon) have on the "flux mix" incident on an assumed plane. An approximation method that works with data of terrain elevation angles O_G (surveyed at azimuth intervals along the horizon) is also formulated by *Heindl* and *Koch*, but shall not be related in further detail here.

SOLAR PROFILING

Though at first glance, it may seem a more complicated proposition to work with custom calculated radiation data than to simply "plug in" a standardized sub-set from a reference climate database or use tabulated monthly values for simplified parameters, this potential objection loses its validity upon closer scrutiny.

The first and most obvious advantage to an analytical model is the relative independence it affords the building designer, who typically has other concerns than that of drumming up, evaluating the consistency and analyzing the applicability of available climate data. In this respect, a computer-based implementation of the parametric radiation model can immediately be used – without much further ado and with minimal computation time – to generate plausible solar geometry and radiation data for building sites situated anywhere on the globe.

The second, less conspicuous, but equally important advantage lies in the manageability and, therefore, interpretability of preliminary results. Instead of handling unwieldy tables of numeric values, which are generally impenetrable for anyone but an expert, the parametric approach allows the user to develop the thermal simulation model in parallel with progressively detailed design stages, whereby each stage can be consistently characterized with relatively small, manageable sets of parameters. This approach facilitates coherent model documentation by means of succinct parameter profiles. Furthermore, it allows the designer to extract valuable information to guide running decisions in a customized manner, that is, derive sketch assessments of parameter impact which are considerably more specific and secure than general "rules of thumb".

Since the data required of the solar/climate model roughly coincides with information typically available at the earliest stages of the building design process (i.e. programming, site assessment and conceptual phases), the intent here is to utilize this information to reveal as much as possible about where the design stands in solar terms – without making any premature assumptions as to the thermal properties of the building envelope. If computed primarily in terms of physical dimensions (e.g., W/m^2), such information can also be re-combined to compare results with other simplified methods, that typically work with some form of dimensionless ratios [13].

As mentioned before, any prospective simulation results are particularly sensitive to the description of solar and climate boundary conditions. With solar considerations, assessing the impact of decisions on diurnal patterns is just as important as grasping the effect over an annual cycle. In order to meaningfully profile these conditions, it is important to differentiate between "reference" and "characteristic" profiles (see also ill. 1).

Reference type input (such as a standardized Test Reference Year of climate data) yields sample results which may be highly detailed and intended to render a typical scenario as realistically as possible. However, scenarios based on high resolution data can be deceiving if used to ascertain the impact of a particular design parameter (e.g., tilting a facade, enlarging an aperture, selecting a different glazing, etc.), since the sample selection may inadvertently mask criteria that are most critical to the diurnal behavior. In other words, extensive reference data sets that encompass a full year of diurnal solar/climate conditions in highly realistic form are appropriate for final evaluations or when concrete predictions are sought, but they lack the necessary abstraction to reveal information as needed for design guidance.

An effective characteristic profile in solar terms is marked by a radical reduction of temporal radiation data to manageable quantities. The method of abstraction suggested for this purpose is to generate and query the solar/climate model according to *seasonal profiles* of characteristic days, depending on basic porperties of the climate zone and solar strategies:

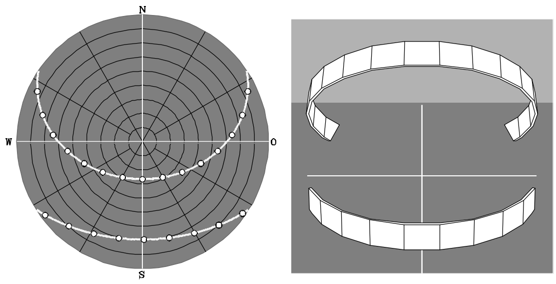
- ***Solar extremes*** *(solstices and equinox)* for mild to tropical climates — The annual and diurnal temperature swings are minor and the handling of solar geometry for shading as well as energy collection plays a dominant role.
- ***Climate extremes*** *(mid-months of January and July, with April as a transition month)* for temperate to cold climates — The ambient temperature swings require a fair degree of interior tempering that involves mixed passive strategies for optimally harvesting solar energy during the winter and avoiding/exhausting unwanted solar gain during the summer.

In the following theoretical breakdown, the concept of solar profiling shall be briefly illustrated by correlating hypothetical design stages with some schematic examples of solar sketch assessments.

The task of programming a building project (i.e. defining the project objectives in terms of required functions, spaces, budget, etc.) can be extended to encompass target values for thermal performance, thermal comfort, daylighting, and other energy-related objectives. These objectives also dictate the type of seasonal profile, or date query, to be established at the start and maintained throughout early analysis for consistent comparison.

Programming is typically accompanied by a thorough site analysis for determining the range of basic design options given by the urban context, available space for building, pedestrian and vehicular access, building regulations, and so on. Analogously, a solar site analysis would profile climate conditions and solar access potential in such a manner that a preliminary assessment of promising design strategies could be make (e.g., potential for the utilization of solar gain vs. conservation of auxiliary heating and cooling energy).

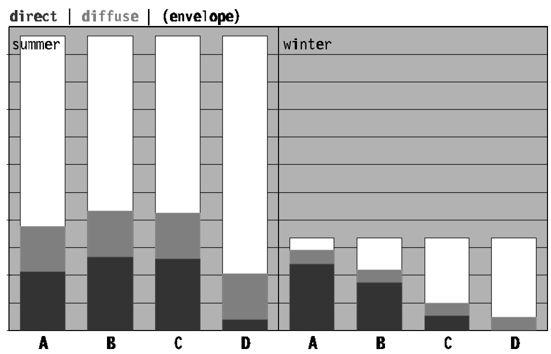
Given just the basic information of site location (geographic latitude/longitude and applicable time zone), the solar paths associated with the query dates can already be rendered. Alternately, a three-dimensional "terrestrial" rendering of this characteristic solar geometry may be generated to show the hourly positions (from sunrise to sunset on the selected days) of a theoretical tracking surface, that is, a plane assumed to ideally follow the daily path of the sun (ill. 4).



ILL. 4: SOLAR PATH DIAGRAM AND ASSOCIATED TRACKING SURFACE RENDERING FOR VIENNA, JULY 15 + JANUARY 15

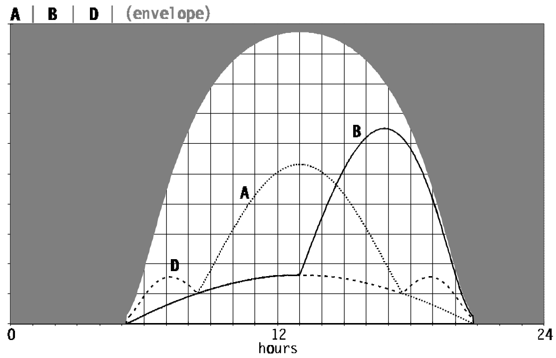
Adding a standard profile of meteorological and terrain parameters (haziness and scatter, altitude, ground reflectance and elevations of the horizon) to the site information allows the diurnal incident radiation on a tracking surface to be calculated. Since at any point in time, the incident radiation intensity on planes of any fixed orientation is less than or equal to the momentary value on the ideal tracking surface (= total normal flux I_N), this theoretical value constitutes the maximum available *solar flux envelope* over the course of a day. As a measure of the solar energy potential, it establishes the outer bounds for insolation profiles of the building site (ill. 5, 6).

Sizing and situating the building volume implies a preliminary definition of the orientations and tilts of its main exterior surfaces (facades, roof surfaces). With information about the positioning of the main incident planes, the actually accessible potential for utilizable solar energy is pared down to a profile specific to the situational geometry of the schematic design (ill. 5, 6).



ILL. 5: DAY SUMS OF SOLAR FLUX [WH/M^2] – FACADES FACING SOUTH (A) SOUTHWEST (B), WEST (C), NORTH (D) – SET AGAINST FLUX ENVELOPES (VIENNA, JULY 15 + JANUARY 15, CLEAR SKIES)

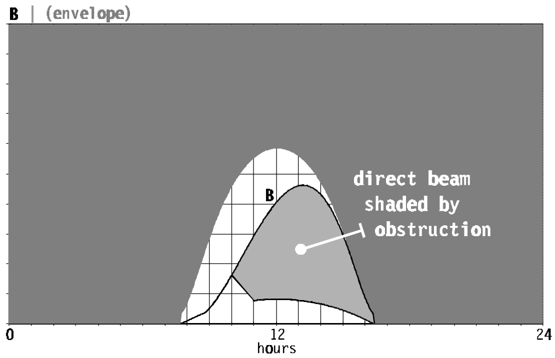
The extractable information at this level also includes information about the relative solar geometry of the incident direct beam for spotting significant obstructions, the angle of incidence on planned glazing, potential for overheating, as well as the effect of ground reflectance in conjunction with decisions about tilting facade surfaces.



ILL. 6: DIURNAL PLOT OF SOLAR FLUXES [W/M^2] – FACADES FACING SOUTH (A), SOUTHWEST (B), NORTH (D) – WITHIN SUMMER FLUX ENVELOPE (VIENNA, JULY 15, CLEAR SKIES)

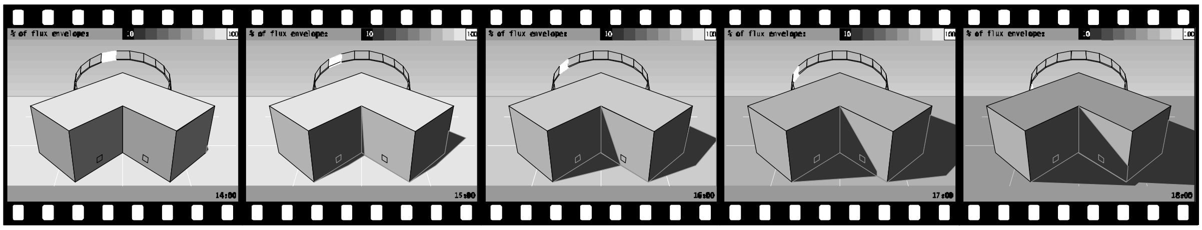
Beyond helping to avoid egregious misassumptions, gauging the relative reductions in overall insolation (ill. 7) caused by existing or designed obstructions provides a valuable measure for working with solar geometry consciously and effectively.

Visualizations which support this objective could, for example, couple the qualitative simulation of direct beam insolation and shading in the form of daylighting patterns on surfaces (similar to ray-tracing renderings) with quantitative solar data as yielded by the radiation model (ill. 8).



ILL. 7: DIURNAL PLOT OF SOLAR FLUXES [W/M^2] – SOUTHWEST-FACING APERTURE WITH OBSTRUCTING BUILDING VIS-À-VIS – WITHIN WINTER FLUX ENVELOPE (VIENNA, JANUARY 15, CLEAR SKIES)

ILL. 8, BELOW: FRAMES OF AN ANIMATED 3D RENDERING OF SOLAR FLUX ON BUILDING SURFACES – COLOR-CODED IN % OF FLUX ENVELOPE (MAX. FLUX ON NORMAL SURFACE = WHITE) – SUMMER TRACKING SURFACE SHOWS SOLAR POSITION ON THE HOUR (VIENNA, JULY 15, CLEAR SKIES)



TRANSITION TO SIMULATION

As other constraints weigh in to the developing design, committed information about the projected building gains depth and detail. Considerations about aperture sizing, placement, and type of glazing typically go hand-in-hand with the more detailed design of the entire building envelope. In combination with a parametric model for glazing properties, such givens allow a first look at quantities of direct solar gain in terms of radiation that can be expected to pass through transparent components to the building's interior spaces.

Absorbed radiation as well as the exchange of long-wave radiation with the sky have a strong influence on the momentarily effective temperatures at building surfaces and, therefore, on the indirect solar gain through the thermal envelope by means of conduction and convection. Though a complete picture of indirect gain crosses over into the realm of thermal simulation, an initial sense of the dimension of such heat transfer effects can still be obtained as soon as design decisions about building materials and surface finishes become an issue and sufficient parameters are defined for calculating the sol-air temperature or, even better, the *radiant air temperature* [14] at exposed surfaces.

On the basis of such assessments, the preliminary design concept could then reflect the reasoned commitment to a particular solar design strategy and, furthermore, allow the contextual analysis of generic options for deciding which primary solar systems – passive and active – may be implemented most effectively in further design stages. Solar profiles for guiding decisions up to this point focus on potential results mainly for identifying critical situations as well as staking out reasonable performance ranges based on a minimum of specific design information.

Once the profile of the amount of solar energy that an overall design strategy has to work with has been established, more complex design components such as thermal buffers – which fully utilize the diurnal characteristics of solar gain – can be optimized with the help of small-scale dynamic simulations of their thermal behavior. To this end, the results obtained from previous sketch assessments would comprise a good portion of the input data necessary for thermal simulation up through the final design stages.

Diurnal simulations under periodically assumed conditions are most effective for profiling the extreme situations of thermal performance, especially to anticipate overheating in the summer months and estimate critical cooling loads. For estimating the impact on annual heating energy requirements, a longer-term solar profile must be applied. Since monthly mean values of daily radiation sums are the most readily available type of data for most sites, these can be used to calibrate a plausible climate pattern to yield results that are sufficiently precise for comparative parameter studies when summed over an annual cycle.

CONCLUSIONS

Before and beyond simulation of a building's overall thermal behavior, solar radiation data can be made useful to inform qualitative design decisions if it is

- analytically modeled in parametric terms that consistently correlate geometry with radiation,
- selectively implemented in diurnal profiles that capture meaningful seasonal characteristics, and
- rendered to reveal the interdependence of solar dimensions to the building designer.

By accompanying design phases with the development of a progressively concise solar/climate model, such information brings the added benefit of applicability as ambient boundary condition data for full-scale thermal simulations.

NOMENCLATURE

d	date as day number (365 per solar year)	Q	atmospheric altitude parameter
t	mean solar time [h]	f_A	relative air mass
t'	local time [h]	r_G	ground reflectance
z	equation of time	O_G	terrain elevation [deg]
e	orbital eccentricity	I^D	direct beam flux component
j	solar ecliptic longitude [deg]	I^S	diffuse sky flux component
d	solar declination [deg]	I^G	diffuse ground-reflected flux component
I_0	solar constant [W/m^2]	a_i	azimuth of *i*-th incident plane [deg]
I	extraterrestrial solar flux [W/m^2]	$ß_i$	tilt of *i*-th incident plane [deg]
a	solar azimuth [deg]	q_i	*i*-th direct beam angle of incidence [deg]
ß	astronomical solar elevation [deg]	w	view coefficient [deg]
ß'	refraction corrected solar elevation [deg]	I_i	total solar flux on *i*-th surface [W/m^2]
H	site altitude above sea level [m]	I_N	total solar flux on normal surface
Γ	haziness factor (*Linke*)	I_H	total solar flux on horizontal surface
Π	scatter factor (*Reitz*)		

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[7] SOLRAD (SOLFEN): calculation programs for predicting solar geometries and incident radiation on planes tilted at any given orientation at any geographic location (calculated shading of incident plane by means of orthogonal flanking planes). © *TU-Wien: E. Panzhauser*

[8] GEBA, GebaControl: program package for dynamically simulating the thermal behavior of coupled interior spaces and entire buildings under periodic conditions at any geographic location. © *K. Krec & A.C. Rahn*

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