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Light Penetration Factor – A new approach towards designing for comfort with direct sunlight

DI Dr. Peter Holzer; peter.holzer@donau-uni.ac.at

Arch. DI Dr. Renate Hammer, MAS; renate.hammer@donau-uni.ac.at

Danube University Krems,
Department of Building and Environment,
Krems, Austria,
www.donau-uni.ac.at/dbu

Abstract

Daylight is increasingly understood as an important aspect of indoor comfort. Recent research proves daylight being both a crucial contribution to visual comfort and a source of health and wellbeing.

There are good reasons for integrating not only daylight but direct sunlight into the design of interiors: There's evidence for the photophysiological need for direct sunlight's levels of illumination, photometrical brightness and spectral range. Among others, direct sunlight's effects on delayed pigmentation, melatonin suppression and Vitamin D3 synthesis are of substantial importance.

In a survey amongst 119 test persons the acceptance of direct sunlight in the interior and its impact on the subjective impression was investigated. The survey showed a preference of indoor situations with direct sunlight against ones illuminated by only diffuse daylight by a significance of 84%.

The authors developed a new key figure to predict a room's interior daylight quality as regards its accessibility to direct sunlight. This new key figure, named Light Penetration Factor (LPF), indicates the proportion of a room's volume that potentially can be reached by direct sunlight within alternatively one day or one hour. The LPF allows designing for direct light from the very early design stage.

The paper in hands explains the definition of the LPF, discusses its qualities and status of development and finally offers some preliminary applications.

Keywords: Daylight, Interior Direct Sunlight, Photophysiology, Light Penetration Factor

The paper in hand suggests the Light Penetration Factor (LPF) as a new key figure to predict and properly design the direct sunlight accessibility in interior spaces.

Its content is strongly based on the findings of the Dissertation Thesis “Quality and Quantity of interior daylight supply”, carried out by the authors at Technical University Vienna up to 2009.[1]

In the first chapter a set of reasons is discussed, why the re-integration of daylight in general and of direct sunlight in in particular into architectural design is significantly important.

The following chapters propose the Light Penetration Factor as a new approach towards designing for comfort with direct sunlight.

Six reasons to re-integrate interior daylight into architectural design

Within an astonishing short period of time, going alongside urbanisation, increased indoor comfort and, not at least, better lighting technologies, our society changed to an indoor society. Recent studies indicate a proportion of lifetime spent indoors of 90% and more.[2]

Thus, aspects of indoor comfort generally play an increasing role in terms of health and wellbeing. The indoor environment has to replace the outdoor environment in its basic functions related to health.

There are crucial correlations between light exposure and health, which have been an outdoor issue throughout mankind’s history and have turned an indoor issue within the last two generations. They have been thoroughly studied and evaluated by the authors, forming a part of their Dissertation Theses.[3] Some of the most relevant correlations are very briefly outlined in the following paragraphs, formulated as “Six reasons to re-integrate interior daylight into architectural design”.

1. Daylight is for free and it’s “for ever”

Sun doesn’t render account, pouring down at thousands of lumen per squaremeter, at an expected lifespan of another 14 billions of years. Among the two forms of daylight, direct beam and diffuse light, the direct beam sunlight is the most powerful phenomenon, with intensities of two to three times as big as the ones of diffuse light.

2. Daylight is cool

Terrestric sunlight offers a luminous efficiency of 115 lm/W, behind glass up to 170 lm/W, thus beating both fluorescent light and LEDs.

3. Full spectrum daylight, including UV-A and UV-B, is crucially healthy

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[1] Hammer, Holzer (2009)

[2] German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (1996)

[3] Hammer, Holzer (2009)

UV-B radiation starts photosynthesis of Previtamin D3, what serves our health in many crucial aspects.

Since about two hundred years there's medical knowledge on the correlation between exposure to ultraviolet radiation and classical Vitamin D3 deficiency symptoms such as rachitis, osteomalacia and myopathy, being proved in recent studies. [4,5]

Additionally, there's evidence of correlations between a lack of sunlight exposure and an epidemical occurrence of number of most relevant "modern" diseases, forming non classical Vitamin D3 deficiency symptoms such as cardiovascular diseases, several forms of cancer and a number of autoimmune diseases.[6,7,8,9,10]

Finally, full spectral daylight drives spontaneous as well as delayed pigmentation, preparing our skins against erythema.

Both effects, Vitamin D3 synthesis and delayed pigmentation, rely on ultraviolet radiation. Both their sensitivity curves drop sharply at wavelengths higher than 300 nm. Furthermore, Vitamin D3 synthesis starts only if the photophysiologically effective radiation excesses a given threshold of 18 MJ/cm².[11]

If this threshold is reached, depends both on the luminous intensity and on the radiation's spectrum. Outdoors, at a cloudless spring's noon at the exemplarily place of Vienna, Austria, this threshold is reached within slightly less than one hour. At a June's noon it is reached within twenty minutes.[12]

But all types of glass, commercially used for windows, are practically intransparent against UV-B radiation. Thus, we face the challenge of developing an architecture that offers easily accessible outdoor spaces, largely openable windows and a development of glass panes with transparency in the range from 300 nm upwards. The authors are busy in research towards this aim.[13]

Against these aims it is of crucial importance to deliberately integrate direct sunlight into the architectural design decisions.

<u>High luminous intensities of visible light trigger our inner clock</u>

There's relatively young knowledge, starting from the 1980'ies, on the correlation between visible light and physiological impacts beyond visual perception.[14,15] A new

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[4] Holick (2004)

[5] Porthouse (2005)

[6] Framingham Heart Study (since 1948, ongoing)

[7] Wang (2008)

[8] Grant (2003)

[9] Garland (1990)

[10] Hayes (2003)

[11] Hollis (2005)

[12] Hammer, Holzer (2009)

[13] Hammer, Holzer (2012, unpublished)

[14] Lewy (1980)

[15] Klein (1991)

non-visual receptor in the eye was discovered only in 2001 and a sensitivity correlation of the Melatonin suppression as the physiological, non-visual reaction to radiation within the visual spectrum was developed. [16,17]

The health related aspects of light exposure follow sensitivity correlations, linked to sufficient illuminance levels, which are significantly higher than the ones necessary for visual ergonomics. The following figure shows the melatonin suppression sensitivity curve, describing the correlation between illuminance at the retina and melatonin suppression.[18]

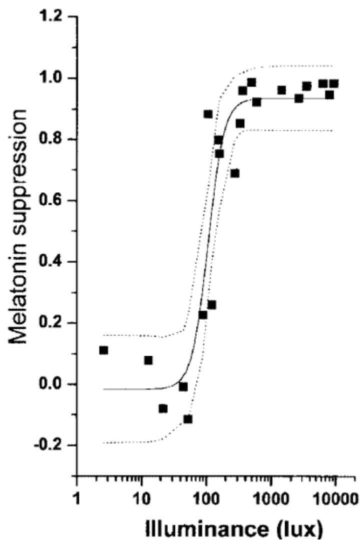

Figure 1: Sensitivity curve of melatonin supression

Melatonin suppression directly drives our subjective alertness and is closely linked to triggering our circadian rhythm. According to its sensitivity curve it starts from illuminance levels at the eye's retina of 100 lx and reaches its full performance not earlier than at 1.000 lx, again at the retina. Moreover, triggering our circadian rhythm even needs illuminance levels at the eye's retina up to 9.100 lx.[19]

Thus, illumination levels of 300 and 500 lx at the working plane may be sufficient for performing visual tasks. But in terms of photobiology they keep us in a status of a permanent November's fog.

Sure we have to be concerned about glare risk. But the nature of our eye is well prepared: While our visual perception and thus the glare risk is limited to an angle of approximately 30° from the visual task, the non-visual receptors which trigger Melatonin suppression are sensitive in a significantly wider range of angles. Thus, we may allow high luminous intensities hit our retina, as long as we keep the narrow area of our visual task glare-free.

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[16] Brainard (2001)

[17] Thapan (2001)

[18] Zeitzer (2000)

[19] Zeitzer (2000)

Direct sunlight with its luminous intensity can solve the problem. In most cases it is the only light source that offers photphysiologically sufficient illumination levels and can be guided into the depth of a room without significantly losing luminous intensity.

Direct sunlight, because it penetrates deeply into our rooms

While diffuse light indoors quickly loses intensity with the distance from the window, direct sunlight penetrates the room without losing intensity. When hitting a bright surface, it forms a highly appreciated light reflecting surface in the depth of our rooms.

Again, to make use of this benefit while avoiding negative aspects such as glare risk, it is necessary to offer tools to design for direct light.

Direct sunlight is delightful

What's true for thermal comfort is even much truer for visual comfort: It is about delight.[20] Recent investigations carried out by the authors at Danube University Krems, Austria, prove this with an overwhelming significance.[21]

An anonymous internet supported survey was carried out amongst 119 test persons that have been collected via two calls in a local Lower Austrian daily newspaper, ensuring that the sample is not dominated by experts on light or building physics.

The internet questionnaire consisted of altogether 50 photos of interior situations.

The test persons were guided through the sequence of pictures, being asked to spontaneously rank their personal sensation of the room in five steps between very unpleasant towards very pleasant. It has to be outlined that the survey didn't mention to be focused on light. It was given the neutral title of just "Cognition of interior living space".

The interior situations deliberately show substantially very different situations, with all pictures taken in the area of Lower Austria, taken within the period of ten months, thus during different seasons.

The special thing with the pictures is that they always form pairs of two, showing the same situation once with diffuse daylight only and once with a strong element of direct sunlight. By slight changes of view positions and by sorting the pictures apart from two by two, the questionnaire wasn't discovered to show pairs of always the same situation. This has been successfully pretested with 10 persons.

The following picture shows a random collection of 18 interior situations out of 25.

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[20] Heschong (1979)

[21] Radinger, Hammer, Holzer (2010)

Figure 2: Exemplarily collection of the daylight survey's interior situations

The results show a significant positive reception of the interior situations with direct sunlight, leading to some very interesting findings:

- In 21 out of 25 cases, that is 84%, the situation with direct sunlight was perceived as more pleasant than the same room with only diffuse daylight.
- Only in 4 out of 25 cases, that is 16%, the diffusely lit situations were preferred. Investigating those four pairs of pictures more closely it turned out that in those cases the situation with direct light always showed very strong contrasts causing parts of the room lying in significant darkness.
- These results applied to both the male and female test persons, with the voting of the female persons being significantly more decided than the ones from the male test persons.

The following figure displays a collection of two pairs of interior situations, both with significance towards a more pleasant perception of the situations with direct light.

Figure 3: Exemplarily collection of the survey's interior situations

Apparently we simply love sunlight, at least in Mid-European surroundings. And apparently we are somehow forgiving towards possible discomfort driven by direct sunlight, such as glare risk or non-uniformity of illumination levels.

<u>Direct sunlight keeps us linked to the day.</u>

Behind physiological effects, daylight in the room delivers information on the progress of the day. This is of special importance for us, living indoors 90% of our lifetimes. Patterns of sunlight on the floor or on the wall tell a lot about the time of the day, about the seasons and about the weather.

Requirements towards sufficient interior daylight supply

Designing for a sufficient supply of direct light, bringing together space, time and indoor life whilst avoiding conflicts with glare is a both a challenge and a forgotten art. What's desperately missing is an aid for the early stage of the design process. Within their Dissertation Thesis the authors developed a new key figure that can serve this purpose of early advice in designing for direct sunlight.

Recently, there are internationally very little requirements based in building codes as regards sufficient daylighting.

Quite minimalistic, some countries just define the minimum of a room's window area by something like ten percent of its floor area, totally disregarding the room's shape or the window's position, shape and orientation.

Already one step forward is the requirement of a minimum Daylight Factor in a room, with the daylight factor giving the proportion between the horizontal illumination inside and outside at standardized overcast sky conditions. The Daylight factor is a good indicator of a room's daylight performance under cloudy skies, thus forming a worst case scenario. Per definition it excludes any effect of direct light and ignores the influence of orientation, place and time.[22]

Last not least careful steps towards a direct sunlight criteria are defined in the DIN 5034, announcing a direct sunlight supply of living space being sufficient, if at least one single room of the dwelling gets light for at least one hour duration at the 17th of January and for at least four hours at equinox.[23]

The need for new daylight design aids

Against the needs and findings discussed before, the authors recognized a significant need for a design aid, applicable in the very early design stage: The new design aid should assist the architects in predicting and properly designing the direct light accessibility of a room. Since the design aid should guide the early design decisions on window size, shape and position, as well as on floor plans and room shapes it has to be very handy and quick in usage. As a crucial point, it must not depend on sophistic information which isn't available in the early design stage. And it finally must fit to the portfolio of an architect, rather than a building engineer. Thus, it must offer both a visual and a numeric output.

The existing method of daylight factor calculation cannot do this job, since it fully excludes the effect of direct light. The Daylight Factor is defined as the ratio between the interior and the exterior horizontal illuminance at defined overcast sky conditions. With this definition it serves well as a design aid for the worst case scenario of a cloudy sky. But, from definition, the Daylight Factor does not give any information on the effects of direct light and is not case sensitive against compass orientation.

On the other hand, dynamic daylight simulation cannot do the job either, since it is not a suitable aid for drawing decisions in the early design stage. To build up a helpful physical model in a daylight simulation program takes too much time and money and, besides, needs too much input parameters. Dynamic daylight simulation is a wonderful tool in optimizing surface qualities such as colour, texture and reflectance. It may help enormously in planning artificial light and many other aspects. But it simply comes too late for the first important decisions concerning the façade and the floor plan. And, last not least, dynamic daylight simulation is in the hands of the building engineers, while the early decisions are in the hands of the architects.

Proposal of the Light Penetration Factor (LPF)

The new key figure has been developed by the authors during the work on their Dissertation Thesis, published in Sept 2009. It was given the name of Light Penetration Factor (LPF).

The Light Penetration Factor is defined as the proportion of a room's net volume that potentially can be reached by direct sunlight.

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[22] DIN 5034-1 (2011)

[23] DIN 5034-1 (2011)

Originally the LPF has been defined as the integration of this potentially sun-penetrated volume's proportion over the period of a full day. During the first test runs it turned out beneficial to additionally analyse the time run of the Light Penetration Factors of specific moments within the day.

Discussion of the Light Penetration factor (LPF)

The Light Penetration Factor offers some intrinsic qualities that might make it a worthwhile tool for good daylight design:

Firstly, the LPF addresses light accessibility within space and not only illumination levels on surfaces. The authors regard this as an important aspect. Visual tasks may be performed on surfaces. But people's eyes and skins move in space. Furniture is placed in space and walls are done so, too. Healthy daylight conditions must be designed according to the inhabitants' needs and must not only focus visual task performance. Subsequently, the LPF indicates the three dimensional interior space which has the potential to be penetrated by direct sunlight within a given time.

Secondly, the LPF technically can be calculated with a minimum of information required, what makes it very much suitable to serve early design decisions. In fact, the LPF is a solemnly geometric key figure, depending only on a room's shape and on the room's geographical place and orientation. No additional information is needed, no additional materials' properties and no climate data. As a result, the LPF applies well to the limited information available in the early design stage. Moreover, nowadays CAD-tools already offer all functional features to calculate and visualize the LPF. If the LPF proofs suitable, it would only be a tiny step to implement it into standard CAD products, offering additional design information for the architects without causing any new input requirements.

Thirdly, the results of the LPF can be easily visualized, offering immediate information how to shape a room, where to place windows, where to apply specific functions within a room or within a flat. The LPF can be highlighted as a light flooded volume in any three dimensional perspective, which is a form of information architects may even transport to their clients easily.

First steps of implementing the LPF

After some preliminary experiments with MS Excel the authors developed a method to calculate and visualize the LPF with a finite element approach, which was then programmed within MS Visual C++.

Within this model the room is modelled as pattern of intransparent, three-dimensional elements. Sunrays are modelled as an array of "photons", moving stepwise towards and through the geometric model. Calculation and visualization is managed by finite elements in the shape of cubes. Within time steps of one hour, the array of photons passes the volume of cubes, with photons dying away when being blocked by intransparent elements while colouring the cubes when passing them. After a one day run the number of coloured cubes is divided by the total number of cubes what exactly gives the Light Penetration Factor. Alternatively the LPF can be evaluated for every single hour of the day.

There are some weaknesses in this very first approach, especially in the aspects of usability, which is miles away from a commercially acceptable level.

Recently investigations are carried out towards calculation of the LPF within commercial CAD products. Encouraging steps have been done within the Rhino and Grasshopper environment.

A first explanatory application of the LPF

The following sequence of pictures and graphs show the very first application of the LPF within the authors' Dissertation Thesis. The room of investigation was defined with the extreme dimensions of 14m x 4,6m at a room height of 2,5m, with the smaller walls treated as fully glazed facades and with an overhang of a depth of 1,2m at one of the two facades.

The following picture (Figure 4) shows a perspective of this exemplary room, drawn with the 3D-modeller of the dynamic thermal simulation software TAS, with the room's volume highlighted in red colour, forming one possible flat within a multi-storey building with access balcony highlighted in light yellow colour.

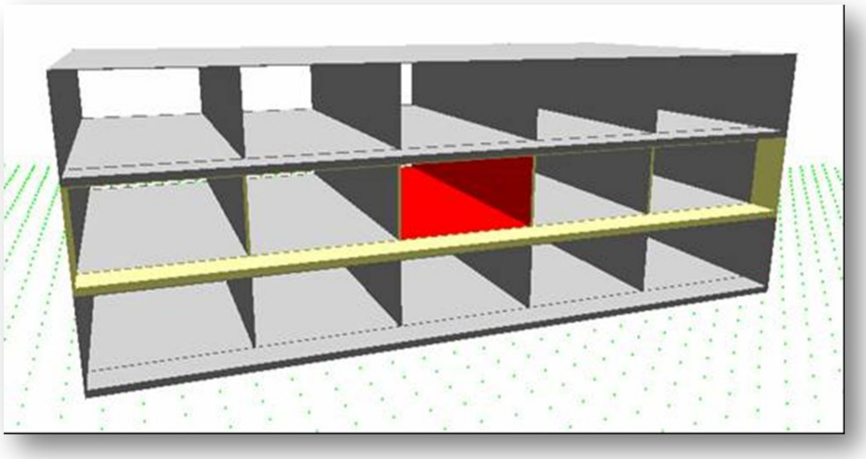

Figure 4: Perspective of the exemplary room, done with TAS

The next picture (Figure 5) shows an axonometric image of the same room, drawn within the C++ environment, with already the results of an exemplary LPF calculation, valid for mid-June at the place of Vienna. The compass orientations are indicated within the figure. The coloured areas indicate those parts of the room's volume which are potentially penetrated by direct sunlight within this single day. There's a relatively narrow directly lit space at the south façade and there's an even bigger space at the north façade, originating from the sliding light of the early morning and late evening sun. In this special case the Light Penetration Factor is 19%.

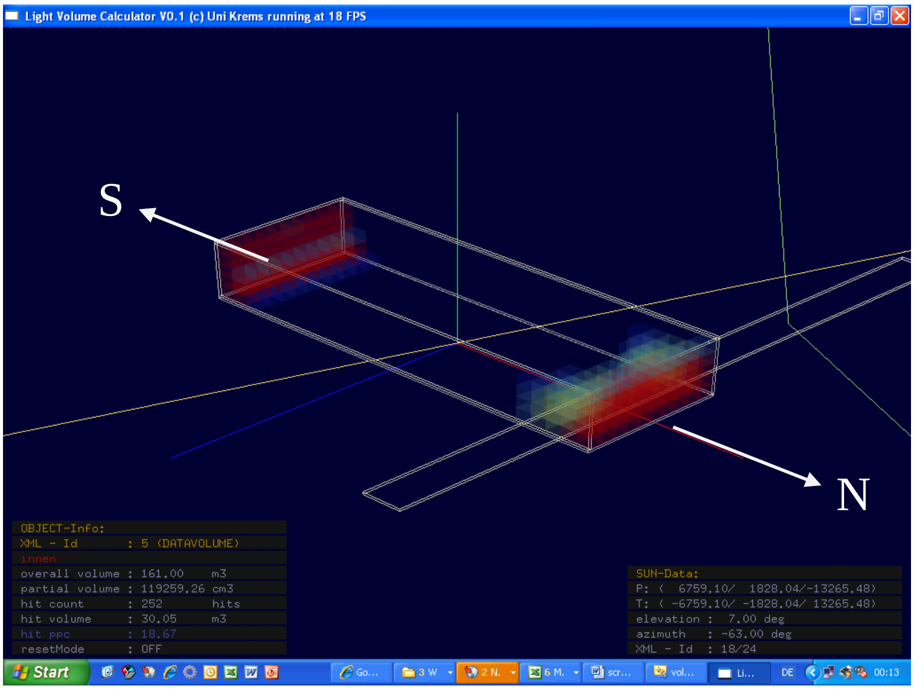

Figure 5: Perspective Visualization of a daily LPF calculation, valid for June 21st at Vienna

Repeating the same analysis for the 21st day of each month provides information on the change of the LPF with the seasons, as indicated in the following chart (Figure 6). One can see the LPF varying from only 12% in spring (April), respectively in late summer (August), up to 39% in deep winter (December).

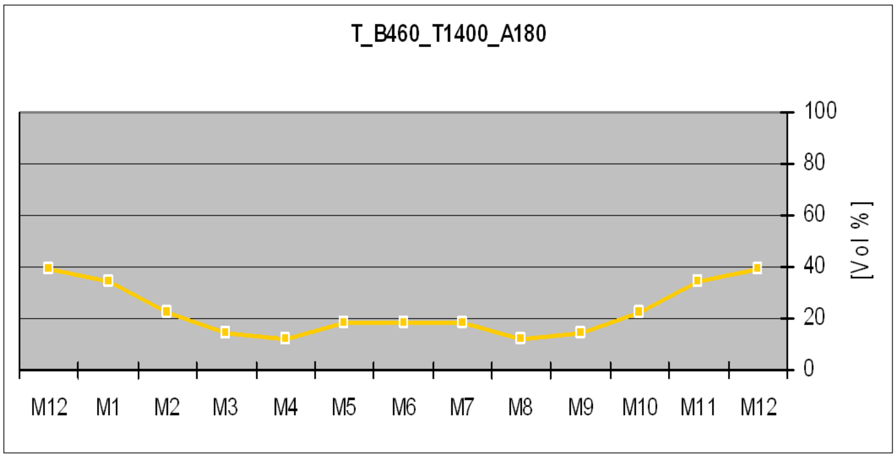

Figure 6: Time-series of daily LPF calculations, valid for each 21st day of the month at Vienna

The original definition of the LPF is the proportion of a room's net volume that potentially can be reached by direct sunlight within one day. Alternatively the LPF can be calculated for every single hour, leading to a time-series of hourly LPF calculations. Such a time series of the hourly LPF over one exemplary day is shown in the following chart (Figure 7), valid for the model indicated above, at the time of the June 21st. These time-series of the hourly LPF allow a specific analysis of the light penetration during the hours of a day, thus offering the chance to deliberately react to the results when doing the architectural design, e.g. in positioning workplaces, leisure zones and others. Note that the LPF integrated over one day can be significantly higher than the highest hourly value.

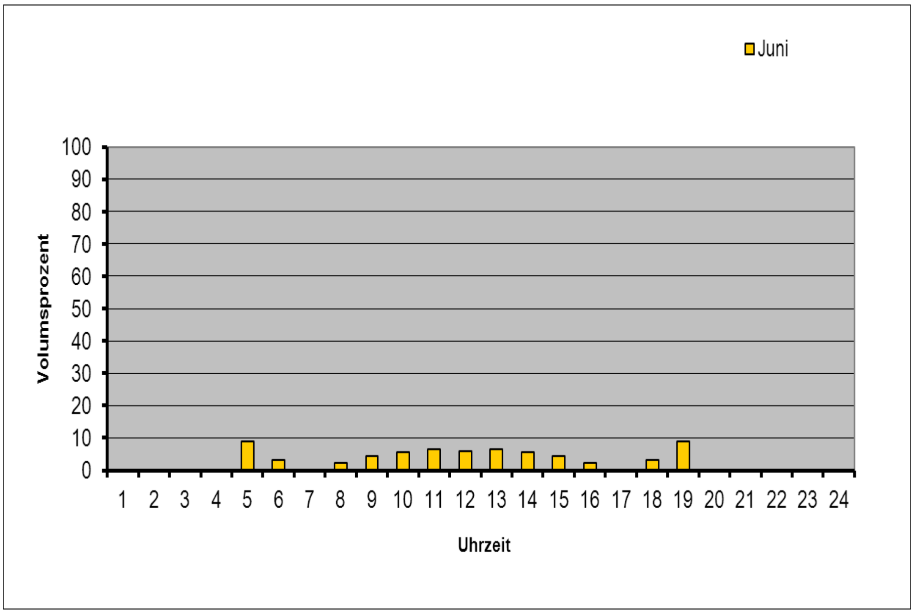

Figure 7: Time series of an hourly LPF over one day: June 21st at Vienna

Comparative application of the LPF

The following sequence of pictures illustrates a comparative analysis of the same exemplary room, once in the compass orientation North-South as already discussed before, and alternatively with its floor plan tilted clockwise by only 30°, resulting in one façade now facing SSW and the other façade now facing NNE.

The following pictures and charts illustrate the significant difference, a tilt of only 30° in compass orientation can do in terms of direct sunlight accessibility and how the LPF can be useful investigating this.

The sequence of the next two pairs of perspective pictures and charts (Figure 8 and Figure 9) show both the perspective visualizations of the daily LPF calculation and the time series of the hourly LPF calculation, for June 21st at Vienna: At left-hand side for the North-South orientation, at right-hand side for the NNE-SSW orientation.

The analysis make it more than obvious, how relevant a turn of only 30° turns out to be in terms of direct sunlight penetration potential.

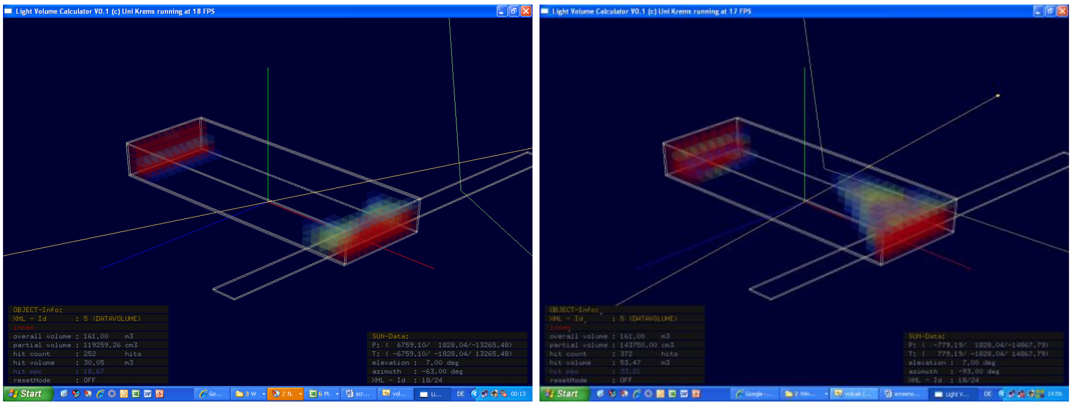

Figure 8: Daily LPF comparison between North-South and NNE-SSW Orientation, June 21st

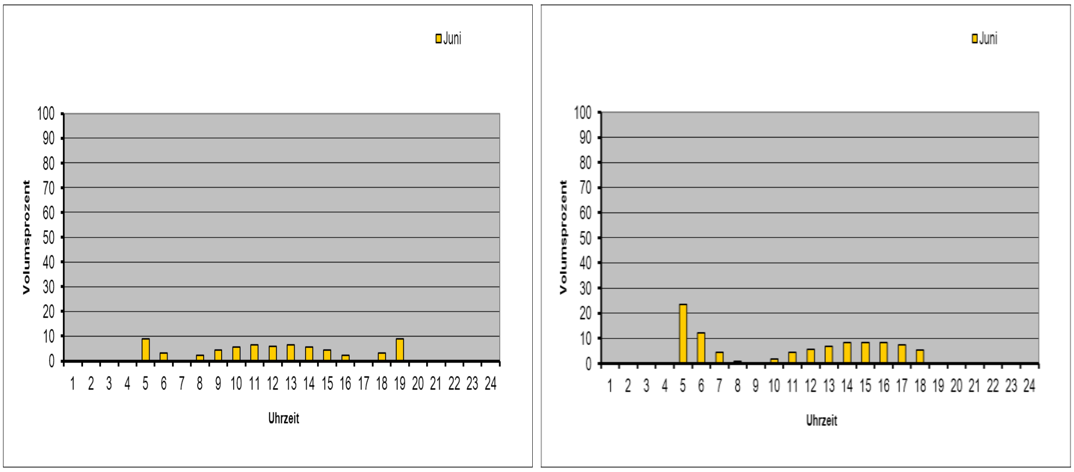

Figure 9: Hourly LPF comparison between North-South and NNE-SSW Orientation, June 21st

The sequence of the next two pairs of perspective pictures and charts (Figure 10 and Figure 11) show the outputs, but now for March 21st, equal to Sept 21st, at Vienna: Again at left-hand side for the North-South orientation, at right-hand side for the NNE-SSW orientation.

Again it shows how beneficial the 30° tilt turns out to be in terms of direct sunlight penetration potential.

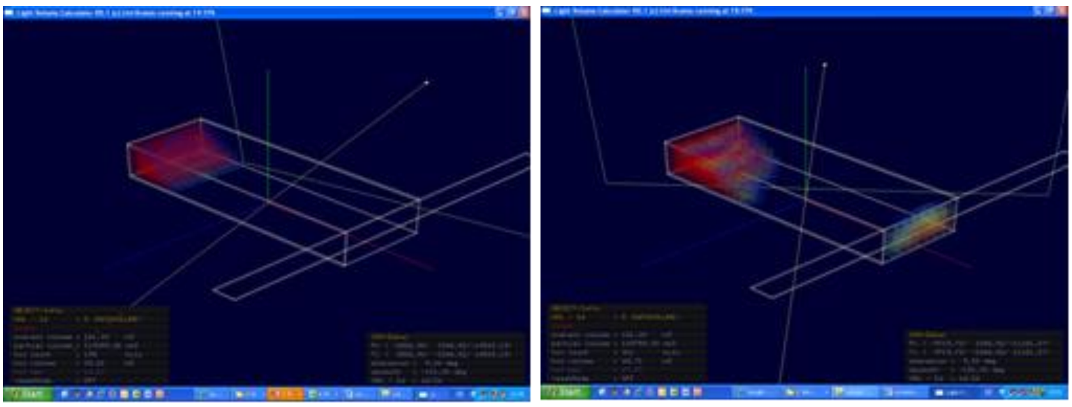

Figure 10: Daily LPF comparison between North-South and NNE-SSW Orientation, March 21st

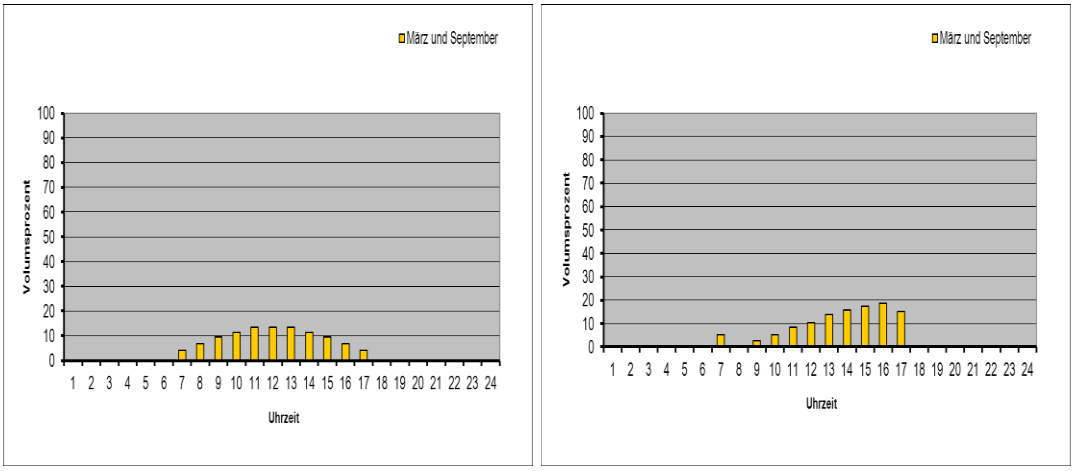

Figure 11: Hourly LPF comparison between North-South and NNE-SSW Orientation, March 21st

Finally, the sequence of the next two pairs of perspective pictures and charts (Figure 10 and Figure 11), represents the situation at Dec 21st at Vienna in right the same way as already two times before. It is obvious that the tilted room offers significantly different qualities in terms of direct sunlight accessibility than the North-South oriented one.

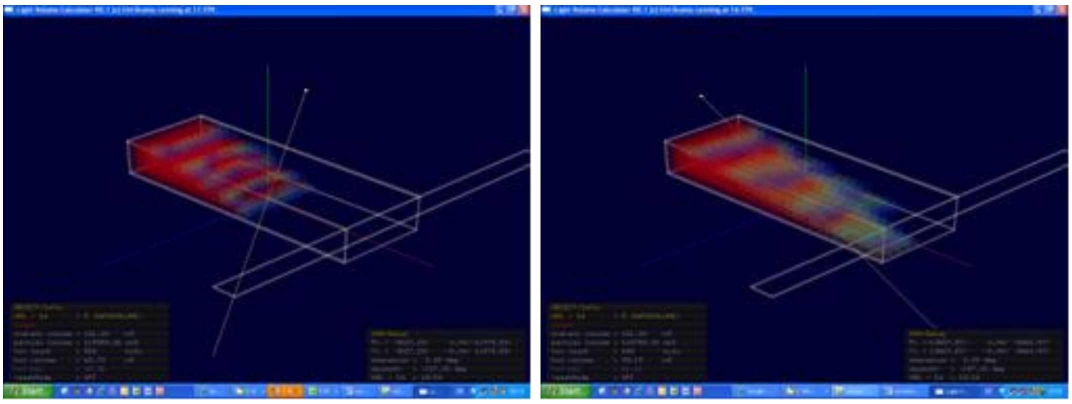

Figure 12: Daily LPF comparison between North-South and NNE-SSW Orientation, Dec 21st

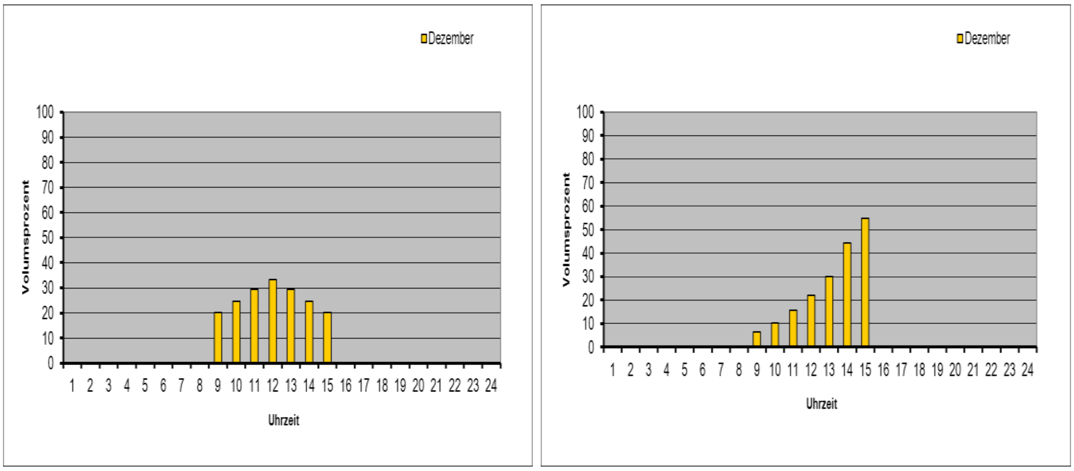

Figure 13: Hourly LPF comparison between North-South and NNE-SSW Orientation, Dec 21st

Linking the LPF to the Heating and Cooling Demand

The quality of sufficient interior daylight supply must be put in context with the aspects of thermal comfort. Again within their Dissertation Thesis the authors conducted these comparative surveys of direct sunlight accessibility and thermal comfort by investigating the monthly heating demand and the monthly cooling demand in parallel to the daily LPF at always the 21st of the month of interest.

Again, the room of investigation was defined like in the example before. The heating demand and the cooling demand have been evaluated using dynamic thermal simulation by TAS, with a sensible and well defined set of internal temperature, ventilation regime, internal gains and so on.

The following pair of charts (Figure 14) show the time-series of daily LPF calculations for each 21st day of the month (indicated as a yellow line), given in %, plus the potential monthly heating demands (indicated as red columns) plus the potential monthly cooling demand (indicated as blue columns), both given in kWh/m²a.

One can clearly see that a significant rise in LPF goes along with a stable value of the potential heating demand and with a noticeable rise of the potential cooling demand.

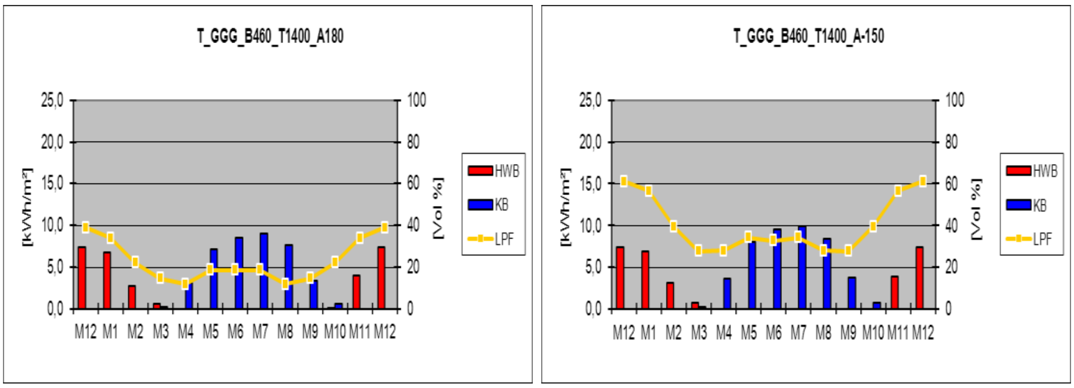

Figure 14: Time-series of daily LPF calculations, valid for each 21st day of the month at Vienna

Implementation of LPF into commercial CAD software

First steps are recently undertaken by the authors implementing the LPG into commercial CAD software. Within the Rhino + Grasshopper software it seems to be possible to investigate and visualize both the daily and the hourly LPF.

The following two pictures (Figure 15 and Figure 16) show first visualizations of these approaches, applied to “sunlight house”, an Austrian carbon neutral single family home, funded by the VELUX Company within their “model home 2020” project.

Figure 15: Photography of the VELUX sunlight house, Presbaum, Austria

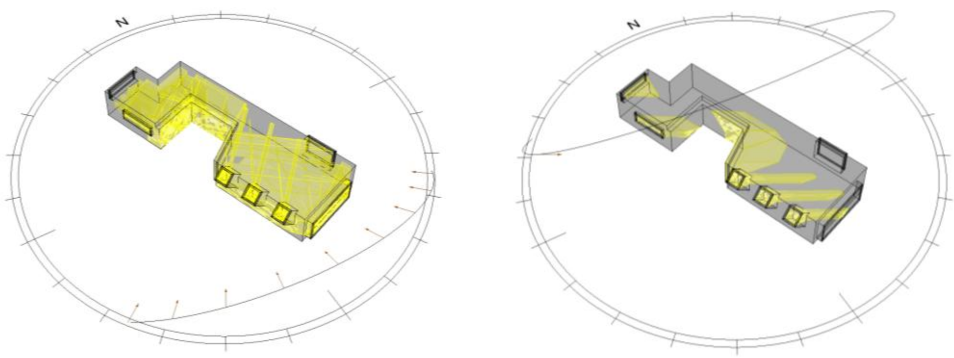

Figure 16: Visualization of preliminary LPF analysis of VELUX sunlight house

Conclusions

Daylight in general and direct sunlight in particular are strong drivers of health and wellbeing. There are more than good reasons to re-integrate them into architectural design.

Beside heavily beneficial qualities, the use of direct sunlight carries some risks, such as overheating and glare, which call for a careful optimization.

The newly developed key-figure of LPF – Light Penetration factor is suggested by the authors as an easy to use indicator of a room's interior daylight quality as regards its accessibility to direct sunlight while avoiding glare risk.

The LPF is defined as the proportion of a room's net volume that potentially can be reached by direct sunlight during a given period of typically one day. It addresses the direct sunlight accessibility within space at a given time of the year, thus corresponding to the three-dimensional usage of space by its inhabitants.

Technically the LPF can be calculated with a minimum of information required, what makes it very much suitable to serve early design decisions. In fact, the LPF is a solemnly geometric key figure, depending only on a room's shape and on the room's geographical place and orientation. As a result, the LPF applies well to the limited information available in the early design stage.

The results of the LPF can be easily visualized, e.g. as an highlighted volume in any three-dimensional perspective, which is a form of information architects may transport to their clients easily.

First test applications carried out by the authors delivered promising results.

Current development at Danube University Krems, Austria, focusses on the implementation of the LPF-calculation and visualization into commercial CAD software and on further test runs. Offers of cooperation are warmly welcome.

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