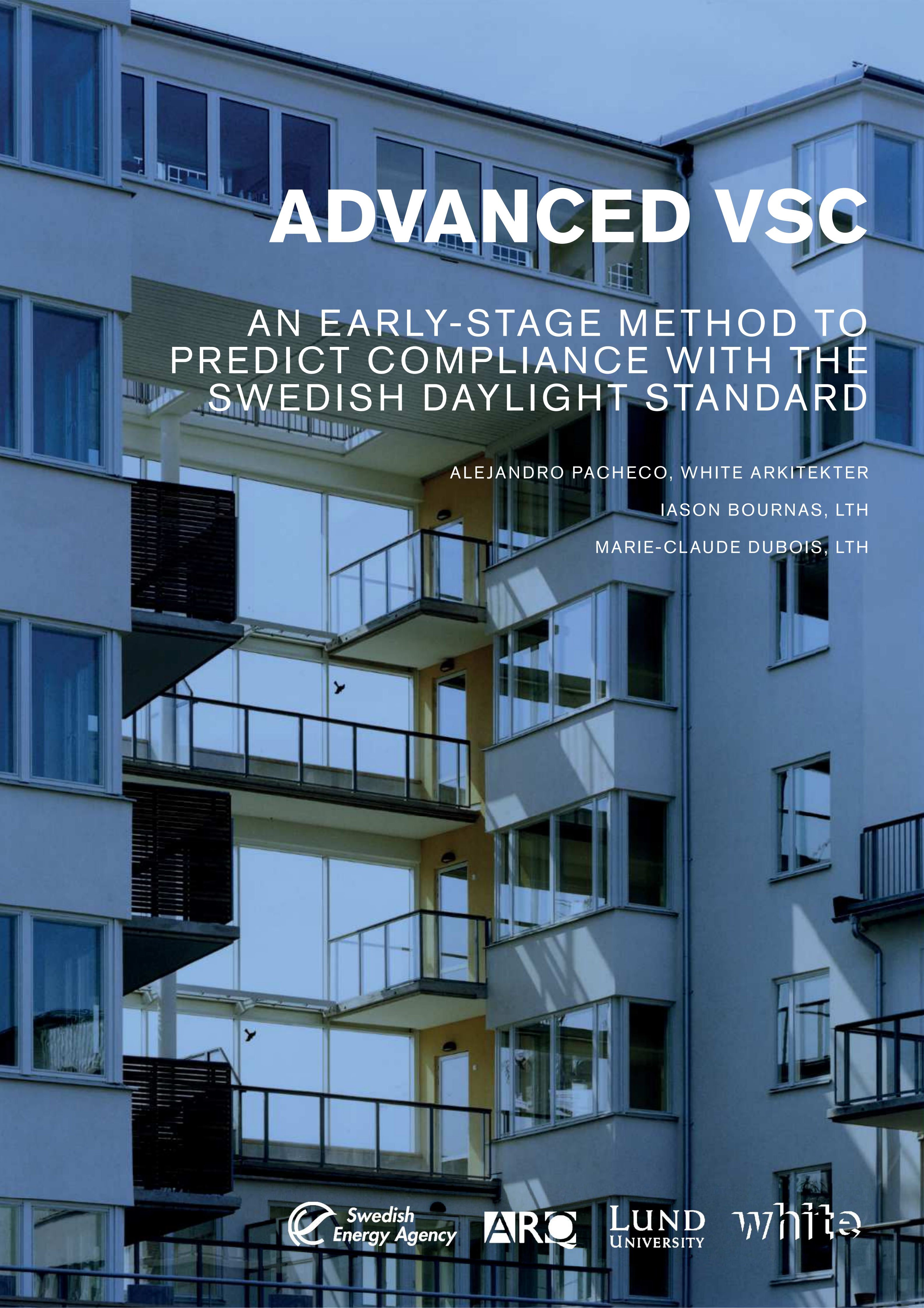

ADVANCED VSC

AN EARLY-STAGE METHOD TO PREDICT COMPLIANCE WITH THE SWEDISH DAYLIGHT STANDARD

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What is the Advanced VSC method?

The Advanced VSC method allows early design stage predictions of the maximum room depth (MRD) compliant with the Swedish daylight requirement.

It is based on a simple equation that requires information about daylight access on the window, expressed as Vertical Sky Component (VSC), and knowledge about the window size, expressed as window-to-wall ratio (WWR), and the room height (RH).

The method can be applied at a very early design stage by non-specialists (architects or engineers) once the basic massing of the project is determined. The method helps to place a spatial program into a building envelope in an early design stage without any prior knowledge about interior design or indoor partitions. The method is especially suited for overcast climates and early design stages.

$$MDR = \frac{0.2 \times (VSC \times RH \times WWR)}{(WWR + 0.7)}$$

MRD	Maximum room depth (m) allowing compliance with the Swedish daylight regulations
RH	Room height (m)
VSC	Vertical sky component on window (%)
WWR	Window-to-wall ratio, internally measured (-)

> The Advanced VSC method is a simple prediction method allowing a verification of daylight compliance of the Swedish daylight requirement at the urban scale based on exterior daylight metrics. This method was developed by White arkitekter and Lund University.

This report is a version of the article called '*Early-design daylight compliance prediction method – derivation of maximum allowable room depth from façade daylight metrics'* published in the magazine Building Research & Information (Sep 2021). This version has been adapted to be easily read by architects, urban planners, proterty developpers and other professions that work with daylighting in buildings but are not necessarily daylight experts.

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Keywords

Daylight, urban scale, metrics, daylight factor, building regulations

Acknowledgements

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Nomenclature

A_{facade}	Facade area, measured internally (m^2)
A_{floor}	Floor area (m^2)
$A_{glazing}$	Glazing area (m^2)
A_{win}	Window area (m^2)
BBR	Boverket byggnadsregler (Swedish building regulations)
CBDM	Climate-based daylight modelling
DDM	Dynamic daylight metrics
DF	Daylight factor (%)
DFp	Daylight factor (%) at a specific point located 1 m from the darkest wall, halfway along the room depth, and 0,8 m from the floor
DFm	Median daylight factor (%)
E_{indoor}	Illuminance (lux) measured indoors
$E_{outdoor}$	Illuminance (lux) measured outdoors
GWR	Glazing-to-wall ratio (-)
LT	Light transmittance (-)
MRD	Maximum room depth (m) allowing compliance with the daylight regulations
OA	Obstruction angle (degrees)
RD	Room depth (m)
RH	Room height (m)
RW	Room width (m)
VDF	Vertical daylight factor (%)
VSC	Vertical sky component (%)
WA	Window aperture (m^2)
WHH	Window head height (m)
WWR	Window-to-wall ratio, internally measured (-)

PART I:

WHAT ARE THE BENEFITS OF THE ADVANCED VSC METHOD?

Daylighting vs. urban density

An increase in urban densification is currently witnessed in many cities around the world. Denser cities are generally promoted as a good thing by environmentalists and urban planners since they translate into a higher concentration of services and infrastructure(s), and more sustainable mobility. However, higher urban density has significant impacts on the life quality and living conditions of urban dwellers. Denser cities may leave less room for green spaces, which means reduced urban biodiversity, reduced contact with nature for citizens, and a higher concentration of hard surfaces absorbing heat and solar radiation, which contributes to the urban heat island effect.

Denser cities also make it more difficult for daylight and sunlight to reach building facades and public outdoor spaces. As the height of buildings and the depth of street canyons increases, the amount of sky visible from rooms inside buildings is greatly reduced. On bottom floors, daylight levels may be so low that electric lighting inside offices and apartments needs to be switched on all day. Traditional building typologies built before the invention of electric lighting (around 1880) often had higher room heights on lower floors as a passive design response to daylight scarcity at the bottom of street canyons. However, this typology has more or less vanished in the last decades due to pressures to build more on smaller plots to secure economic profitability.

Poor access to daylight and sunlight also leads to higher energy use for electric lighting, as indicated by previous research [i] and, as a result, higher cooling loads in the warm season to remove heat from lights. Very dense cities may also create gloomy interiors and a dark urban ambience at street level, while making buildings less resilient in case of power outage. In addition, several elements of contemporary architecture such as deep balconies and exterior circulation corridors also reduce daylight penetration in buildings [ii iii].

Some studies [iv] have indicated that increasing urban density is good from an environmental point of view up to a certain point. But beyond that point, many environmental qualities start to decline. Energy use of the building stock may even increase as a result of increased urban density due to the necessity to rely on electric lighting more often, and the difficulty to use natural ventilation, which translates into a higher reliance on mechanical ventilation and cooling [v].

> " Denser cities make it more difficult for daylight and sunlight to reach building facades and public outdoor spaces.

Good daylighting: the importance of starting early

The conflict between daylighting and urban densification has started to raise concerns in many cities around the world since daylight has been linked to health, well-being, and productivity of building inhabitants [vi, vii, viii, ix, x, xi]. This aspect deserves more attention today than ever, since research indicates that people in the industrialized nations spend 90% of their time indoors [xii, xiii]. It is also especially relevant under the Covid19 Pandemic, where lockdowns keep people home all day long. This question even has high relevance in countries with an aging population, which is likely to have a more sedentary, homebound lifestyle.

As a response to the conflict between urban density and daylight access, many countries have implemented minimum daylight requirements in building codes, but when urban density increases, these requirements are increasingly difficult to meet in practice. In Sweden, for instance, the building code requires that all rooms occupied more than occasionally have direct access to daylight, with a recommendation for a minimum point daylight factor (DFp) of 1% measured at a specific point in the room. Compliance can also be demonstrated using a minimum window-to-floor ratio (WWR) of 10%, but previous research [xiv] has demonstrated that this compliance path is not acceptable for the majority (75%) of rooms in an urban context, due to geometrical limitations associated with this compliance path. Consequently, in most cases, the only way to ensure compliance is by performing time-consuming daylight factor simulations with an advanced simulation program based on the laws of illumination. Such simulations are only accessible to specialists with a few years of training.

The Swedish daylight regulations (BBR) [xv] has been the source of debates and conflicts in the building and architecture sectors mainly because compliance to the daylight regulations has to be demonstrated only towards the end of the preliminary design process, i.e. when applying for building permit. At this point, several months (or sometimes years) have already been invested in the design. Any change in the plans and elevations are likely to be costly. Moreover, calculating the daylight factor in rooms with complex geometries and building surroundings requires long modelling and simulation processes, making it difficult for design tests and iterations, which are natural in a normal design process.

There is thus a need to be able to assess daylight compliance earlier in the design process, possibly relying only on a simulation of daylight incident on building facades, without any prior knowledge of interior design and indoor configurations.

Daylight compliance made simple

There is a need to be able to assess daylight compliance earlier in the design process, possibly in a way that architects and urban planners can easily understand and integrate in their workflows.

The Advanced VSC method allows a verification of daylight compliance with simulations at the urban scale based on exterior daylight metrics. This analysis can be performed very early in the design process to determine the maximum room depth (MRD) that will ensure compliance. This method is based on a regression analysis with the following variables:

- Minimum point Daylight Factor (pDF, in %): this is the minimum indoor daylight level that wants to be achieved in the room in question.

- Maximum Room depth (MRD, in meters).

- Room height (RH, in meters).

- And window-to-wall ratio (WWR, -): indicates the window size as a percentage of the facade area.

- Vertical sky component (VSC, %): defines the amount of daylight received at the window.

The method results in the formulation of a simple equation that can be used by non-specialists (architects or engineers). The method was developed of

"The Advanced VSC method is reliable for early-stage assessments and could be implemented immediately in building practice with great benefits by lowering design costs.

this method and validated using computer simulations with the program Radiance embedded in the Honey-Bee-Grasshopper environment. The development of the equation is focused on daylight compliance path and context of the Nordic countries, using the Swedish building regulations as the starting point in the development. However, the same development could be made for any location around the world, especially in the cases where overcast skies are dominant. However, the method is less relevant for sunny locations, where metrics such as the DF and VSC are not relevant at all. A recent paper demonstrates that the Advanced VSC method is reliable for early-stage assessments and could be implemented immediately in building practice with great benefits by lowering design costs.

PART II:

DAYLIGHTING IN SWEDEN

Daylighting in the nordic context

The climate of the Nordic countries is unique in many ways. Despite regional differences, it is characterized by a high frequency of overcast skies, especially in the winter, and reversely, a rather rare occurrence of sunny conditions. Some unlucky years, sunny conditions are almost inexistent between the beginning of November and mid-February. Matusiak (2017) [xvi] summarized the typical features of natural light in the Nordic countries:

- Low solar altitudes during the whole year (compared to most other inhabited locations on Earth).

- Long periods of twilight where the solar altitude is very low.

- White nights around the summer solstice and even midnight sun in locations north of the Arctic Circle.

- Relatively low frequencies of sunny skies the whole year, especially during winter.

To this list, we may add that the high latitude translates into extreme differences in day lengths between summer and winter. The short day duration during the winter creates a daily physical and psychological challenge for Nordic inhabitants. People go to work or school in the morning in darkness and come back at the end of the day in darkness. The only opportunity to experience daylight during daytime is through windows and skylights unless one takes regular lunch walks. But even if lunch walking is possible, the dark overcast sky dominant during the winter is weak in intensity – sometimes less than 2000 lux – compared to most other locations on Earth. This aspect makes the issue of proper daylighting building interiors of significant importance to ensure proper conditions for health and well-being.

What does the Swedish building code say about daylight?

As a response to Sweden's climatic context, the Swedish building code (BBR, 2021) [xvii] contains mandatory provisions ('föreskrifter') and general recommendations ('allmänna råd') concerning natural light. These requirements cover three aspects: daylight, sunlight and a view out. The mandatory provisions state that for any room 'used more than occasionally', the design and orientation of the room should offer good access to direct daylight.

This mandatory provision is followed by a general recommendation, suggesting a window-to-floor area ratio of 10% to demonstrate compliance. This simplified method is further based on an outdated standard SS 91 42 01 [xviii], where some conditions for validity are specified, including room size, window glazing, window geometry and position and sky exposure angle. As stated above, previous research [xix] has demonstrated that this compliance path is not applicable for the majority (75%) of residential rooms in the Swedish urban context, precisely due to the geometrical restrictions associated with the standard. Note that this simplified method is also intrinsically limited since is does not consider the presence of balconies or a complex or heavily obstructed surrounding context.

Consequently, in most cases, the only way to ensure compliance is through advanced computer simulations showing that a minimum point daylight factor (DFp) of 1% is reached at a point in the room located 1 m from the darkest lateral wall, halfway along the room's depth, and 0,8 m above the floor. In cases where simulations are not feasible, a manual calculation method is also proposed, but this method is extremely time-consuming and would not be practical in any real building case with more than one room.

A general recommendation is also presented for providing a view out, with a minimum of one window in any room used more than occasionally. The window should be located such that it is possible to follow the course of the day and seasonal changes. Skylights are not considered suitable to fulfil this requirement. Access to direct sunlight is also regulated by a mandatory provision stating that at least one room where people spend longer periods of time should have access to direct sunlight. These last two recommendations (view out and sunlight) are not considered in the development of the Advanced VSC method described in the present website.

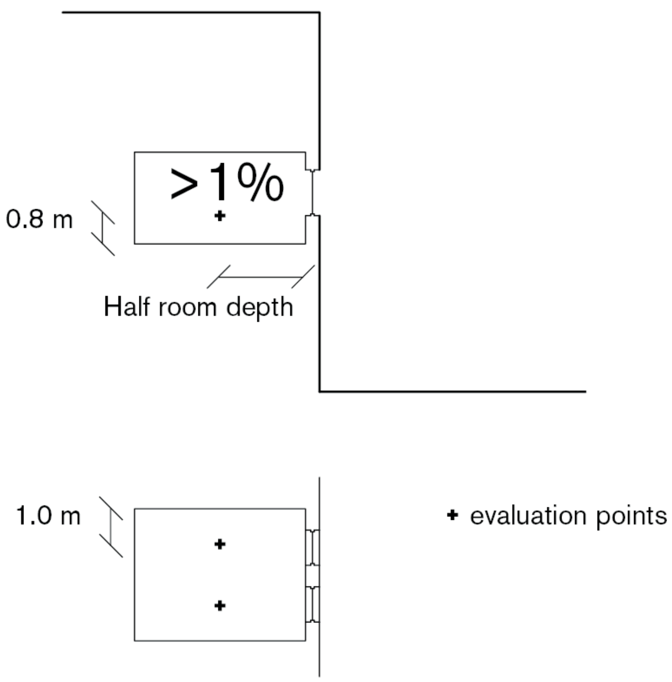

Figure 1: location of the evaluation points (pDF) according to the Swedish daylight requirement.

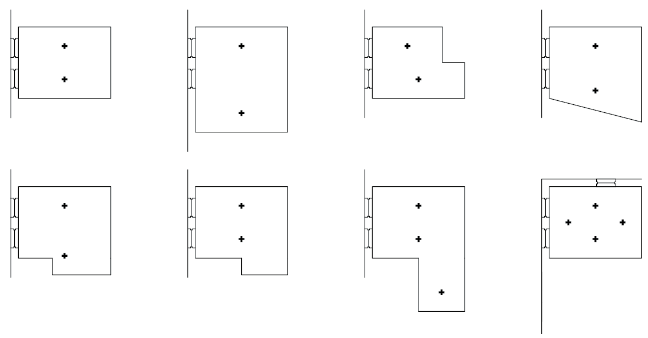

Figure 2: location of the evaluation points (pDF) in different room shapes.

How is daylight measured in Sweden?

To evaluate the performance of buildings in use and predict their performance at the design stage, one should be able to identify what the appropriate measures of performance are, when and how these measures should be collected, and how the results should be interpreted to determine success or failure of the design [xx]. A common methodology should in principle define what is measured in which way and at which point(s). Obviously, the most obvious way to measure illuminance and luminance is to use lux- and luminance-meters. However, this is hardly useful with daylighting since it varies constantly from moment to moment. Calculating average values from an annual array of data is not either very useful since the very high values from direct sunlight completely hide low illuminance values found on dark overcast days.

Over time, researchers have come up with other, more indirect ways to measure the performance of daylighting design. This common methodology is partly explained through the concept of daylight metrics. A metric is 'some mathematical combination of (potentially disparate) measurements and/or dimensions and/or conditions represented on a continuous scale; it may not be directly measurable in the field' [xxi]. Daylight metrics allow assessing either the quantity or quality of available daylight and/or visual comfort inside buildings, and some metrics address both aspects.

Daylight metrics can be simplified methods of static conditions such as the daylight factor (DF) and vertical sky component (VSC) defined below, or more advanced dynamic methods called dynamic daylight metrics (DDM). DDM require advanced computer simulations based on Climate-Based Daylight Modelling (CBDM). CBDM is the 'prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions derived from standard meteorological datasets' [xxii].

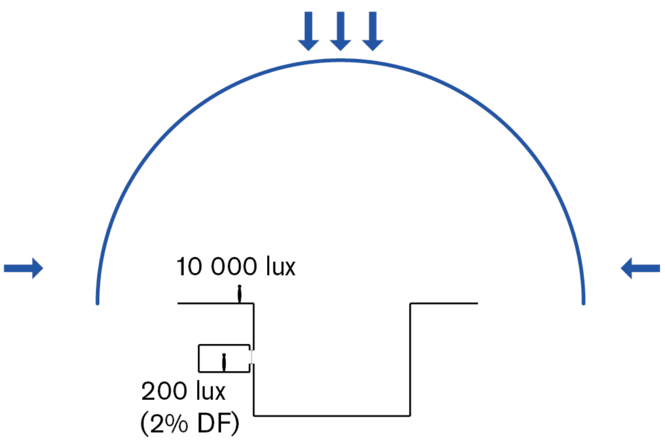

Figure 3: Daylight Factor (DF), explanatory diagram.

Daylight factor (DF)

Introduced into the British Standards in 1992, the daylight factor (DF) is 'a measure of the illuminance within a room (usually on a horizontal plane), relative to the total amount of light that would be available under an unobstructed hemisphere with an overcast sky' [xxiii].

The daylight factor remains the principal metric used in daylighting practice and guides, despite recent calls to replace it with other metrics [xxiv]. The DF is still used in many building regulations, for example in Sweden, or environmental certification systems, such as Miljöbyggnad, despite its intrinsic limitations. Some advantages of the daylight factor have been mentioned [xxv]:

- The DF allows expressing the efficiency of a room and its window(s) as a 'lighting system';

- The DF describes the relationship between interior and exterior spaces by indicating the contrast between the two environments (lower DF values correspond to higher contrasts between interior and exterior environments)The DF can be seen as a good indicator to ensure a minimum daylight level under worst case conditions (overcast sky).

Reinhart, Mardaljevic & Rogers (2006) [xxvi] also mentioned that the DF has the advantage that 'predictions are intuitive and easy to communicate within a design team'. However, many researchers [xxvii] [xxviii] claimed that the DF is clearly insufficient alone to evaluate lighting quality in a space due to its intrinsic limitations:

- Light from the sun and non-overcast skies cannot be considered with the DF;

- The DF does not allow assessing the impact of building or room orientation since the overcast sky is isotropic (same in all directions);

- DF values are very variable even under overcast sky conditions due to variable sky luminance distribution.

Therefore, the DF only really applies to a temperate climate with many cloudy situations [xxix] (which is relevant for the Nordic countries). However, note that the real climate with a large share of intermediate skies may be quite different from the overcast sky idealized model. Mardaljevic (2006) [xxx] even claimed that 'the DF persists as the dominant evaluation metric simply because of its simplicity rather than its capacity to describe reality with any degree of precision'.

The Advanced VSC method can be used to predict a certain median Daylight Factor in a room based on the amount of incident daylight on the window measured as Vertical Sky Component (VSC) and some simple geometrical variables of the room.

Daylight metrics suitable for early design stages?

The vertical-sky-component (VSC) is a static daylight metric used in urban planning. It is an accepted method defined by Building Research Establishment (BRE) guidelines [xxxi]. It is defined as the ratio of direct illuminance on a vertical plane to illuminance on an unobstructed horizontal plane, under a CIE Standard Overcast Sky [xxxii]. The BRE guidelines state that 'if the vertical sky component, with the new development in place is both less than 27% and less than 0.8 times its former value, then occupants of the existing building will notice the reduction in the amount of skylight' [xxxiii]. Note that in contrast to the Vertical Daylight Factor (VDF), the VSC does not consider light reflected from facing building facades. It only considers direct daylight from the sky incident on the façade. The main advantage of this concept is thus a much shorter calculation time since inter-reflections between facades, which is the most time-consuming operation in light calculations, do not need to be computed at all. The VSC concept thus allows a quick assessment of the quantity of direct daylight incident on the façade, without any knowledge about surrounding buildings other than their shape.

The Advanced VSC method is based on this simple indicator (VSC), which, together with other information such as window-to-wall ratio (WWR) and room height (RH) allows the deduction the maximum room depth (MRD) allowed to reach a given DF required by building regulations.

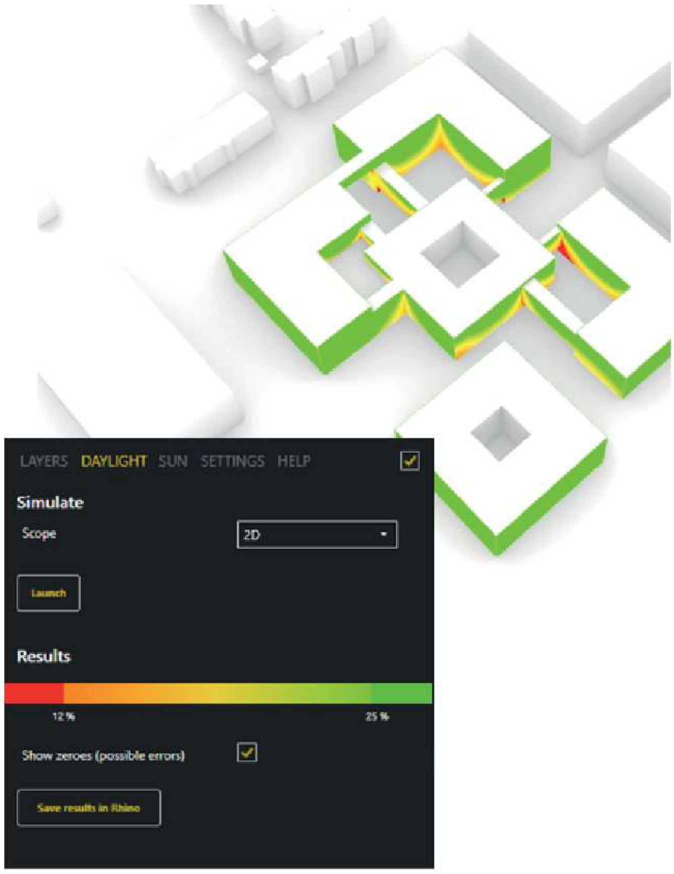

Figure 4: example of VSC simulation results. Rooms located in Green areas (VSC > 25%) are considered likely to comply with the daylight requirement. Rooms located in red areas (VSC < 12%) are considered unlikely to comply with the daylight requirement. Source: WHEAT tools, White arkitekter.

PART III:

HOW DOES THE ADVANCED VSC METHOD WORK?

How was the Advanced VSC method developed?

The overall procedure followed in order to derive the simple equation for compliance predictions is explained in Figure 5, and included four main steps. The first two steps involved generating the required data (1.selecting buildings and 2. deriving geometry and simulating daylight metrics). The latter two steps involved the development and validation of the simplified equation. The method used for the development of the equation relies on a thorough analysis of simulation results and geometrical parameters of a large building database used in a previous research and thoroughly described in other articles [xxxiv]. A number of rooms were excluded from this analysis due to their special characteristics, e.g.: corner rooms (windows on more than one façade), rooms with balconies above, windowless rooms, rooms with irregular plan (non-rectangular rooms). In other words, the method presented is valid only for rectangular rooms with windows on one side and no obstruction from balconies. The number of rooms included in this study was 6241. The settings used in the simulations are described in Tables 1-2.

Table 1: Rendering settings for each daylight metric (DFM, VSC and VDF).

Rendering setting	Daylight metric		
	DFM	VDF	VSC
ambient bounces (ab)	7	7	1
ambient divisions (ad)	2048	16834	16834
ambient supersamples (as)	512	512	512
ambient accuracy (aa)	0.1	0	-
ambient resolution (ar)	variable	300	-
ambient value (av)	0	0	-
direct threshold (dt)	0.03	0.02	0.02
direct certainty (dc)	1	1	1
direct subsampling (ds)	0.05	0.05	0.05
direct jittering (dj)	1	1	1
limit weight (lw)	1 · 10-4	1 · 10-4	-
limit reflection (lr)	7	7	-

Table 2: Surface optical properties.

Surface type	Reflectance	Transmittance
Walls (interior), closets	70%	-
Ceiling	80%	-
Floor	30%	-
Window glass	-	70%
Window frame	80%	-
Window head, jamb and sill	50%	-
Balcony ceiling	70%	-
Balcony floor	30%	-
Ground	20%	-
Surrounding facades	30%	-
Surrounding roofs	30%	-
Water	50%	-

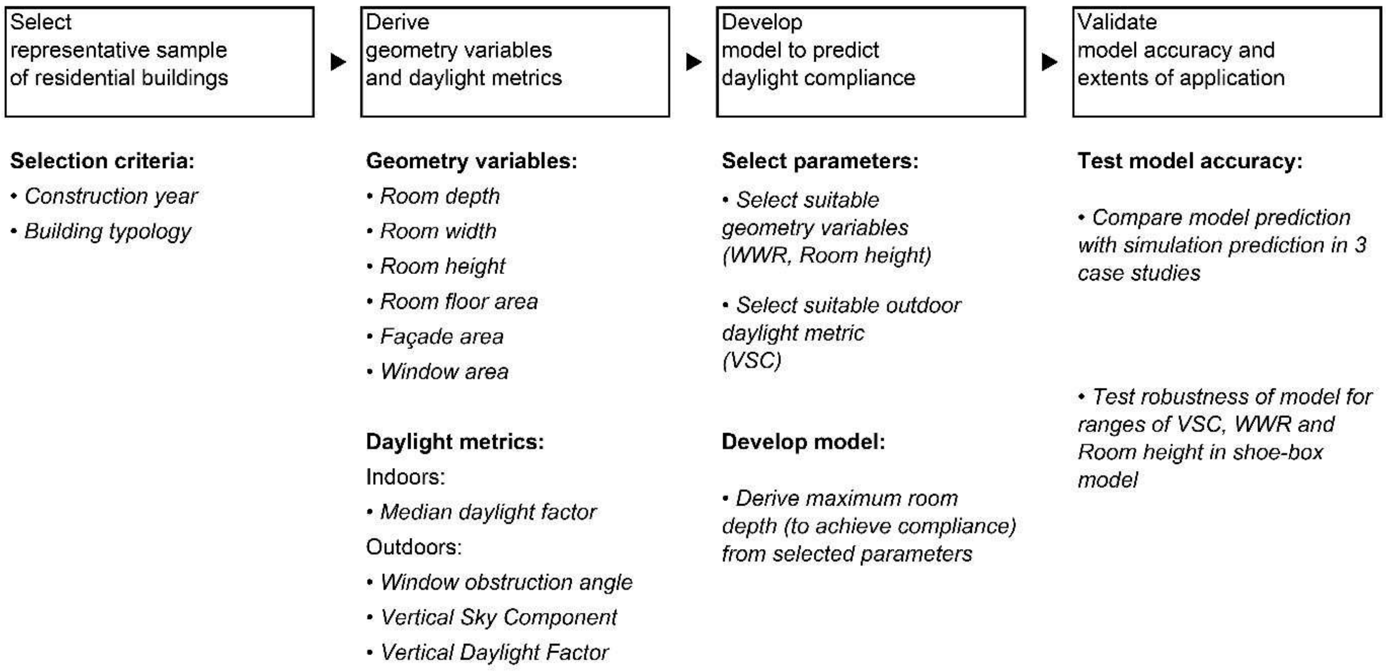

Figure 5: general workflow scheme.

Since the current Swedish regulations require that the DFp is calculated for compliance assessments, it was necessary to start by establishing the relation between DFp and the median DF (DFm) based on simulation results for the rooms in the database. The (strong) correlation between DFp and DFm revealed by this analysis is shown in Figure 6. Further steps in the development of the method entailed six distinct phases (2.1-2.6) described below:

1. Selection of façade metric combining simplicity and accuracy: one of the first phases consisted of evaluating the suitability of different façade metrics and compare them in terms of simplicity and accuracy. For this phase, the following metrics were considered: 1) obstruction angle (OA), 2) VSC and 3) VDF. Note that the obstruction angle for a window is the angle between the horizontal anda line starting from the center of the window to the highest point of the opposite obstruction.

2. Development of the equation based on a regression analysis: subsequently, an equation was developed by linking three variables: window-to-wall ratio (WWR), room height (RH) and vertical sky component (VSC). The variables WWR and RH were chosen instead of window aperture (WA, m2) [xxxv] and window head height (WHH, m) because they are more intuitive and part of the ordinary vocabulary of architects when discussing projects at early design stages. In addition, the following assumptions were made:

- WHH was assumed to be 30 cm lower than RH,

- LT was assumed to be 70%, since this is a rather usual value used in residential spaces in Sweden (assuming triple pane, clear glazing).

- WWR was used instead of glass-to-wall ratio (GWR), since architects are used to discuss window areas instead of glass areas. The range of the windows' frame factor was between 0.17 and 0.39.

3. Validation of the equation using the building database: following the development of the equation, its application was first validated using a sample of rooms (n=236) extracted from the original database. These were rooms that 1) had a rectangular plan, 2) had one window on one wall, 3) did not have a balcony obstruction and 4) approximately complied with the Swedish regulations (0.95-1.05% DFp). The room depth predicted by the equation to obtain 1% DFm was calculated and compared to the real depths of these 236 selected rooms.

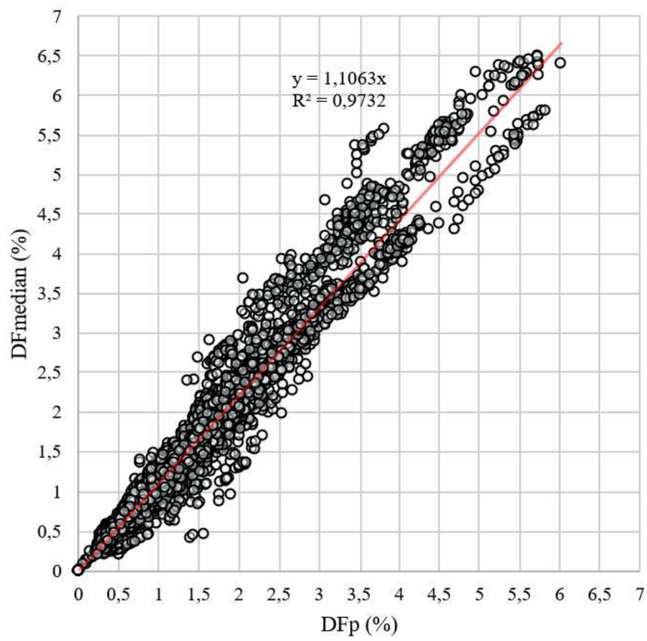

Figure 6: Correlation between DFp and DFm (n=6241).

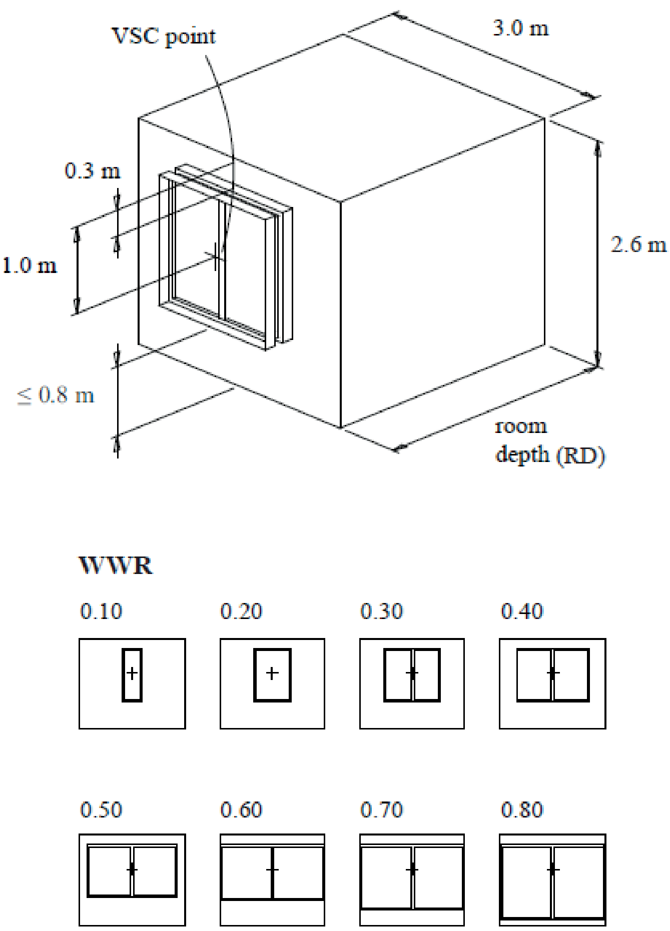

Figure 7: parametric study 1, WWR variation.

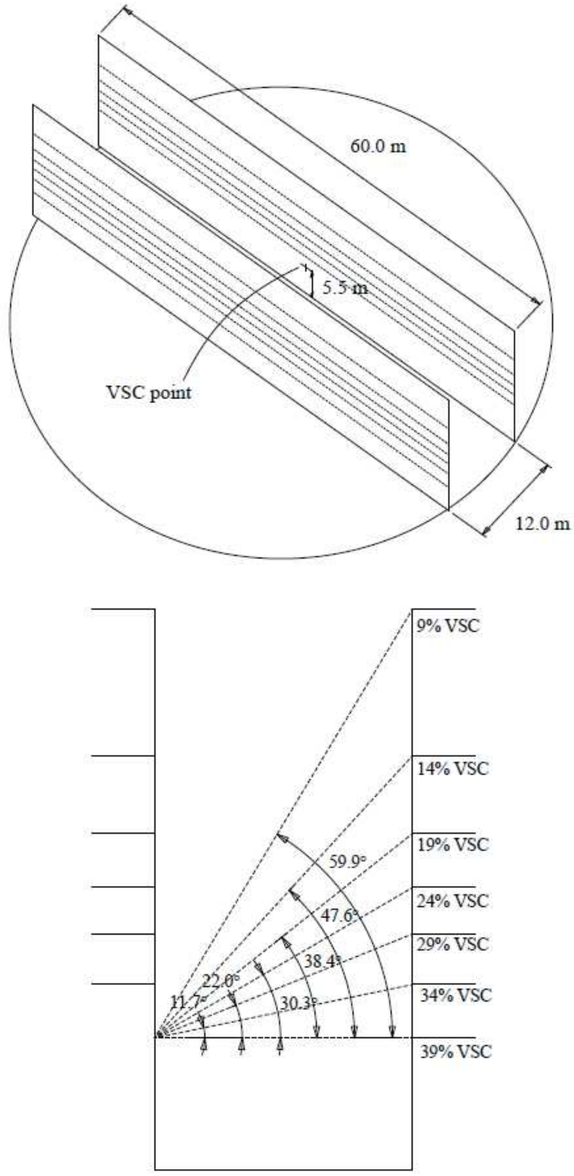

Figure 8: VSC intervals, parametric studies.

4. <u>Parametric study 1 – variation of WWR</u>: the next phase consisted of performing a parametric study to test whether the equation would be able to predict the correct MRD for larger WWR than the ones originally found in the database. The large majority of rooms in the database had WWR ranging from 25% to 40%. In this parametric study, a number of rooms with WWR varying from 10-80% (intervals of 10%) were modelled with a constant RH of 2,6 m, see Figure 7. The VSC was also varied from 9 -39% with 5% intervals, see Figure 8. Note that the VSC was always measured at a point located one meter (1 m) below the ceiling for constancy in the analysis, see Figure 7. The MRD was determined using the equation to obtain a 1% DFm. The rooms were modelled with the MRD determined by the equation and the DFm was then calculated with the simulation program. Room depths smaller than 2 m were not considered because they were deemed unrealistically shallow. As a result, a total of 47 rooms were considered in this parametric study.

5. <u>Parametric study 2 – variation of RH</u>: a second parametric study was performed to test the equation for RH not present in the original database. In this study, a number of rooms were modelled with RH varying from 2,6-5,4 m (intervals of 0,4 m), and the VSC varying again from 9-39% (intervals of 5%) while the WWR was kept constant at 30%, see Figure 9. The VSC was again always measured at one meter (1 m) below the ceiling (Figure 9). The MRD was calculated with the equation to obtain 1% DFm. Rooms with this MRD were modelled and simulations were performed to determine the DFm. Again, room depths larger than 2 meters were disregarded in this analysis since they were deemed unrealistically shallow. A total of 53 rooms were studied in this parametric study.

6. Validation of the equation in real building projects: the last phase focused on testing the equation using real case studies consisting of building projects currently designed at White arkitekter, one of the largest building practices in Europe. For this phase, the DF was calculated in several rooms of different building projects using advanced building simulations. Figure 10 shows the projects that were investigated for this phase. The points in the room with a 1% DF was determined by simulations and then the MRD was determined from this point by doubling the distance to the external wall since the building regulations take the DFp measurement 'halfway in the room'. Thereafter, the MRD obtained using the equation was calculated and drawn on the same plan drawing as for simulation results, see Figure 11 as an example for one room.

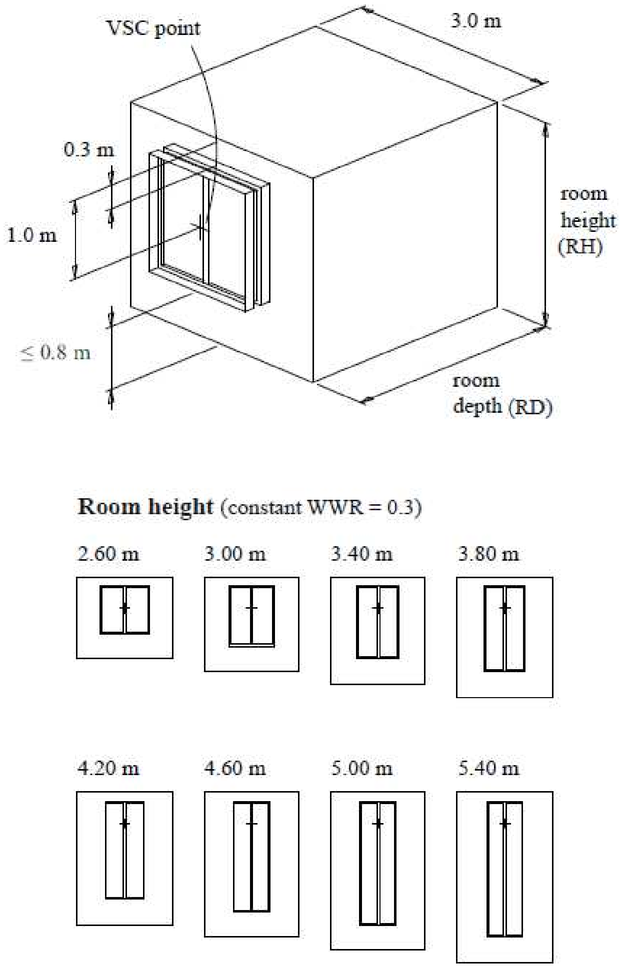

Figure 9: parametric study 2, room height variation.

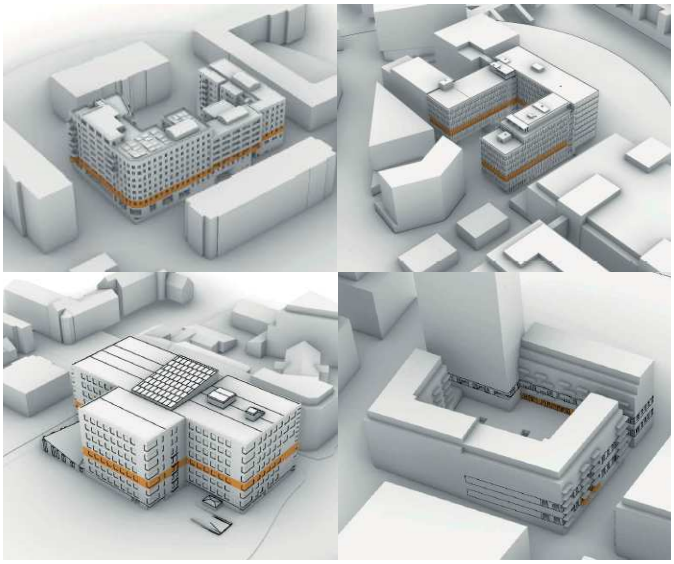

Figure 10: Real projects (3d model view), source White arkitekter AB.

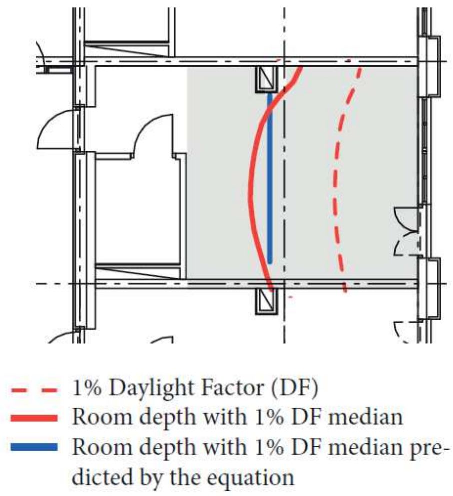

Figure 11: Example for one room only of MRD results from equation compared to results from simulation.

Why was VSC chosen as external daylight metric?

The first step in the analysis concerned the relation between the median Daylight Factor (DFm) and three external metrics OA, VSC, VDF. A similar approach was used by Eriksson [xxxvi], who specifically looked at the relation between VDF and interior DF. The results of our analysis are presented in Figure 8. The figure shows that even though VSC does not account for inter-reflections of light from surrounding objects, it relates to indoor daylight levels (DFm) similarly to VDF. The metric OA has the weakest association with DFm among the three external daylight metrics. The association between VSC and VDF is very strong (Figure 8-iv), even though VSC does not account for inter-reflections of light on surrounding objects. Given that VSC does not require prior knowledge of optical properties of surroundings, and due to the shortest simulation time required for it compared to VDF, it was preferred for the prediction model.

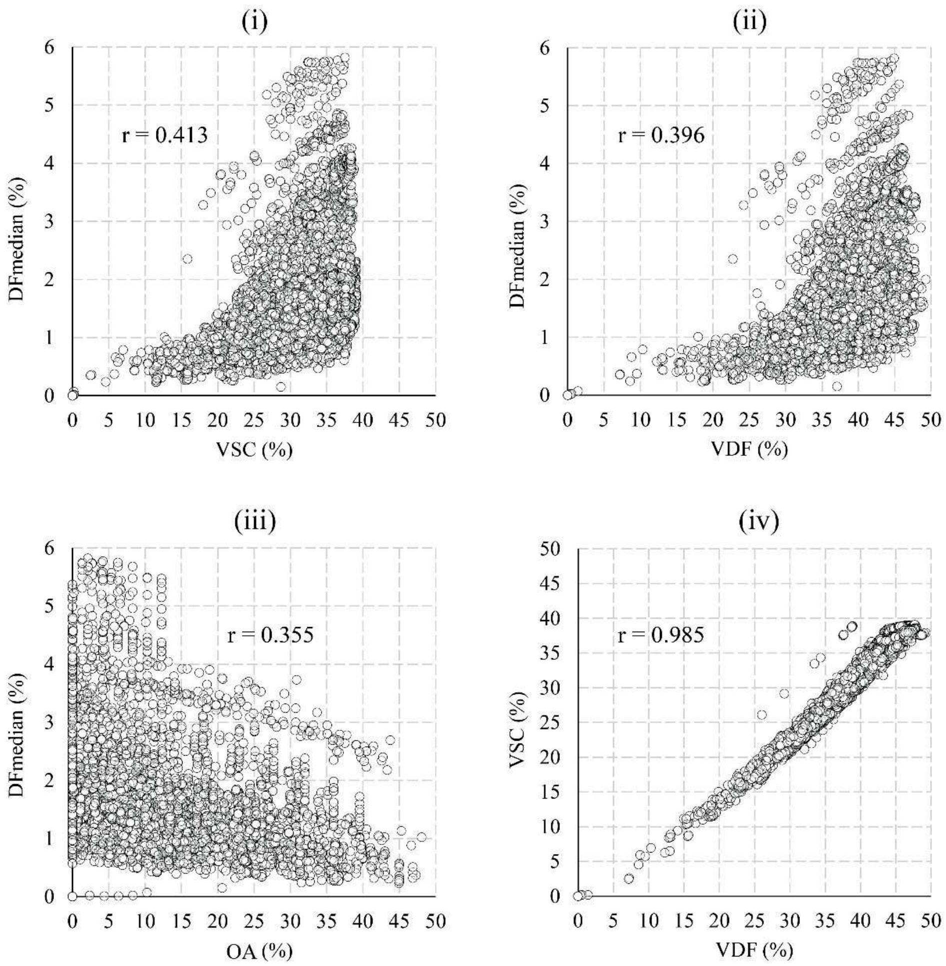

Figure 12: Association between DFm and i) VSC, ii) VDF and iii) OA. Figure 8iv shows the association between VSC and VDF. The Pearson correlation coefficient r is shown for each association.

How was the Advanced VSC equation developed?

A regression study was performed where the variables VSC, WWR, DFm, floor area (Afloor) were put in relation. The first expression and development of this equation is shown below:

$$0.2\times(VSC\times A_{win}) = DF_m\times A_{floor} \quad (1)$$

Since the DFm has been shown to be almost the same as DFp and DFp required in Sweden is 1%, we can remove the "DFm" term from the equation and write instead:

$$0.2\times(VSC\times A_{win}) = A_{floor} \quad (2)$$

Thus,

$$0.2\times(VSC\times A_{win}) = RW\times RD \quad (3)$$

$$0.2\times(VSC\times A_{facade}\times WWR) = RW\times RD \quad (4)$$

$$0.2\times(VSC\times RW\times RH\times WWR) = RW\times RD \quad (5)$$

Which can be simplified to:

$$0.2\times(VSC\times RH\times WWR) = MRD \quad (6)$$

A term (0.7) was added to the WWR to make the equation more accurate for large (>0,4) and small (<0,2) WWR. At this stage, we estimate that a three-variable regression analysis is needed to fine-tune this equation. A provisional expression of the equation is provided below:

$$MDR = \frac{0.2\times(VSC\times RH\times WWR)}{(WWR + 0.7)} \quad (7)$$

Note that the term MDR (maximum room depth) is used instead of RD since it is in reality the maximum room depth that is allowed to comply to the Swedish daylight regulations. The room height is assumed to be 30 cm higher than the window head height (WHH).

Nomenclature

A_{facade}	Facade area, measured internally (m2)
A_{floor}	Floor area (m2)
A_{win}	Window area (m2)
DFm	Median daylight factor (%)
MRD	Maximum room depth (m) allowing compliance with the Swedish daylight regulations
RD	Room depth (m)
RH	Room height (m)
RW	Room width (m)
VSC	Vertical sky component (%)
WHH	Window head height (m)
WWR	Window-to-wall ratio (-)

How accurate are the predictions of the Advanced VSC method?

1. Validation of the equation based on the original building database

The equation was used to predict the maximum room depth (MRD) that would allow meeting the Swedish daylight regulations. The results were compared to the room depth (RD) of the rooms approximately meeting the 1% median daylight factor (DFm) requirement in the building database (accepting a range of 0.95-1.05% DFm). The outcome of this comparison is summarized in a few points below:

- In 95% of the cases, the MRD predicted was within +-20% from the RD of the database.

- In 67% of the cases, the MRD predicted was within +-10% from the RD of the database.

- In 37% of the cases, the MRD predicted was within +-5% from the RD of the database.

Evaluating the discrepancy in absolute terms revealed that for 80 % of the rooms, the predicted RD did not deviate from the actual RD by more than 0.5 m. For the rest of the rooms, it appeared that two factors led to discrepancies higher than 0.5 m: 1) the asymmetrical position of the window relative to the room width, and 2) the combination of high WWR and extensive room depths. Nevertheless, these results indicate that the equation is relatively reliable for early design stages.

2. Parametric study with variable Window-to-wall ratio (WWR)

- In 100% of the cases, the DF was between 0,8% and 1,2% (<+- 0.2 deviation which is normally interpreted as "approximately 1% DF" by building authorities). Note that results with 0.8% DF correspond to rooms with a predicted RD larger than 10 meters.

- In 74% of the cases, the DF was between 0,9% and 1,1% (<+-0,1 deviation).

3. Parametric study with variable RH

In the second parametric study, the RH was varied from 2,6-5,4 m (intervals of 0,4 m), with a variable VSC of 9-39% (intervals of 5%) while the WWR was kept constant at 30%. The results of this parametric study are presented in Table 5. They can be summarized in a few points below:

- In 89% of the cases, the DF was between 0,8% and 1,2% (<+- 0.2 deviation which is normally interpreted as "approximate 1% DF" by building authorities). Note that results with 0.8% and 0.7% correspond to rooms with a predicted RD larger than 10 meters.

- In 60% of the cases, the DF was between 0,9% and 1,1% (<+-0,1 deviation).

± 0.0% discrepancy
± 0.1% discrepancy
± 0.2% discrepancy
± 0.3% discrepancy or larger

(*) Rooms below 2 meters depth excluded.

Table 3: DF_m obtained by simulation with variable WWR.

	9% VSC		14% VSC		19% VSC		24% VSC		29% VSC		34% VSC		39% VSC	
WWR	RD (m)	mDF	RD (m)	mDF	RD (m)	mDF	RD (m)	mDF	RRD (m)	mDF	RD (m)	mDF	RD (m)	mDF
0.1	0.6	*	0.9	*	1.2	*	1.6	*	1.9	*	2.2	1.0%	2.5	1.0%
0.2	1.0	*	1.6	*	2.2	1.2%	2.8	1.2%	3.4	1.2%	3.9	1.2%	4.5	1.2%
0.3	1.4	*	2.2	0.9%	3.0	1.0%	3.7	1.2%	4.5	1.2%	5.3	1.2%	6.1	1.0%
0.4	1.7	*	2.6	1.1%	3.6	1.0%	4.5	1.0%	5.5	1.0%	6.4	1.1%	7.4	1.0%
0.5	2.0	1.1%	3.0	1.2%	4.1	1.0%	5.2	0.9%	6.3	1.0%	7.4	1.0%	8.5	1.0%
0.6	2.2	1.2%	3.4	1.1%	4.6	1.1%	5.8	0.9%	7.0	0.9%	8.2	0.9%	9.4	0.9%
0.7	2.3	1.1%	3.6	1.2%	4.9	1.1%	6.2	0.9%	7.5	0.9%	8.8	0.9%	10.1	0.9%
0.8	2.5	1.1%	3.9	1.2%	5.3	1.1%	6.7	0.9%	8.0	0.9%	9.4	0.9%	10.8	0.8%

Table 4: Deviation when varying RH (and WHH).

	9% VSC		14% VSC		19% VSC		24% VSC		29% VSC		34% VSC		39% VSC	
RH (m)	RD (m)	mDF	RD (m)	mDF	RD (m)	mDF	RD (m)	mDF	RRD (m)	mDF	RD (m)	mDF	RD (m)	mDF
2.6	1.4	*	2.2	0.9%	3.0	1.0%	3.7	1.2%	4.5	1.2%	5.3	1.2%	6.1	1.0%
3.0	1.6	*	2.5	1.2%	3.4	1.2%	4.3	1.2%	5.2	1.2%	6.1	1.1%	7.0	1.0%
3.4	1.8	*	2.9	1.3%	3.9	1.1%	4.9	1.1%	5.9	1.1%	6.9	1.1%	8.0	1.0%
3.8	2.1	1.0%	3.2	1.3%	4.3	1.0%	5.5	1.1%	6.6	1.0%	7.8	1.0%	8.9	0.9%
4.2	2.3	1.2%	3.5	1.4%	4.8	1.1%	6.0	1.1%	7.3	1.0%	8.6	1.0%	9.8	0.9%
4.6	2.5	1.1%	3.9	1.3%	5.2	1.2%	6.6	1.0%	8.0	0.9%	9.4	0.9%	10.8	0.8%
5.0	2.7	1.1%	4.2	1.2%	5.7	1.1%	7.2	1.0%	8.7	0.9%	10.2	0.8%	11.7	0.7%
5.4	2.9	1.0%	4.5	1.2%	6.2	1.1%	7.8	0.9%	9.4	0.8%	11.0	0.8%	12.6	0.7%

Figure 13: Plan view of selected rooms in a residential project showing the depth of a room with 1% pDF (red line) and the room depth predicted by the equation (blue line).

Validation of the equation with real building projects

In the last phase, the equation was tested using real case studies consisting of building projects currently designed at White arkitekter. For this phase, the DF was calculated in several rooms of different building projects. Figure 10 shows the results of this study where the blue line shows the RD obtained with the equation, the dotted line the points with 1% DF and the continuous line, the MRD ensuring a DFm of 1% (by doubling the distance between the dotted line and the external façade). In general, it can be concluded from scrutinizing figures 13-15 that both methods (equation and simulations) come to similar results for the MRD in all other rooms, even in floor plans without any internal partitions.

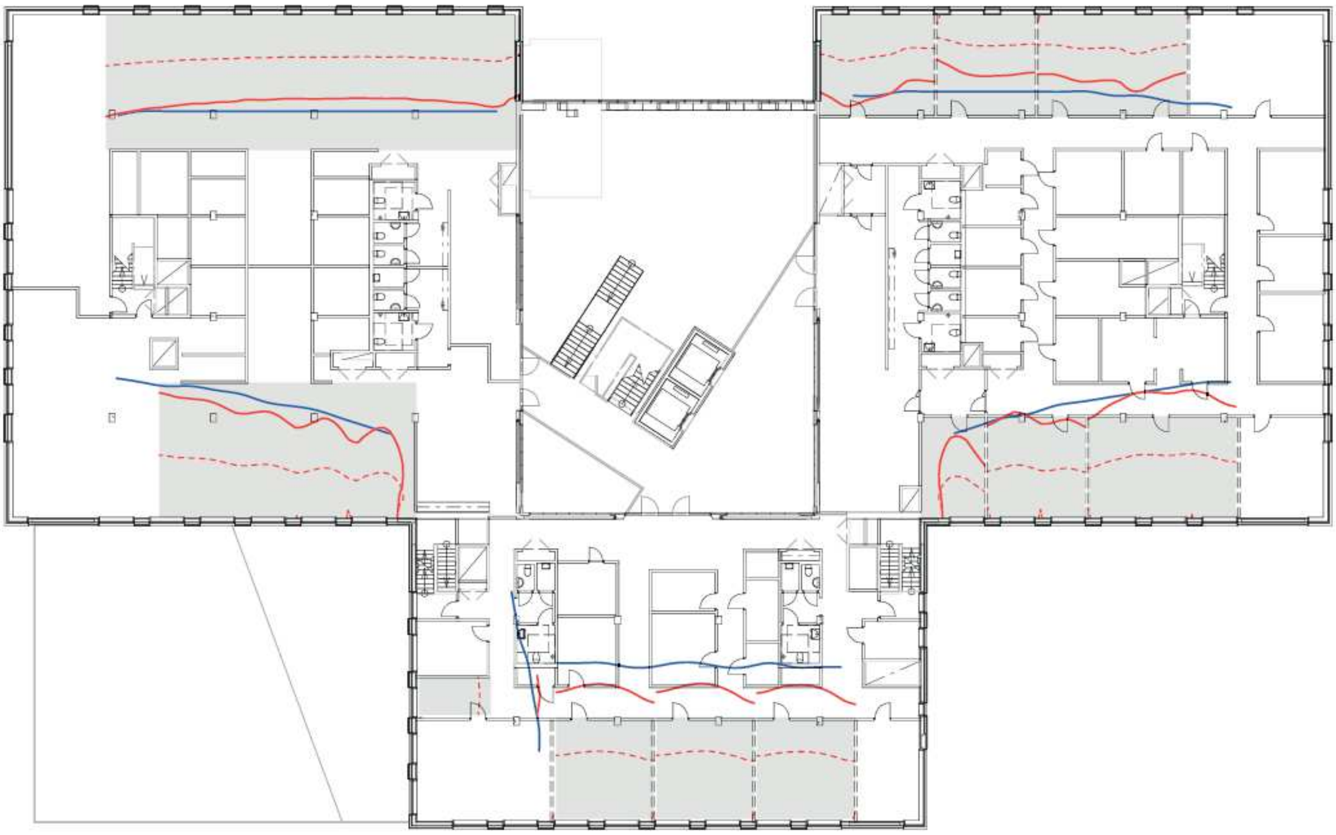

Figure 14: Plan view of selected rooms in an office building project showing the depth of a room with 1% pDF (red line) and the room depth predicted by the equation (blue line).

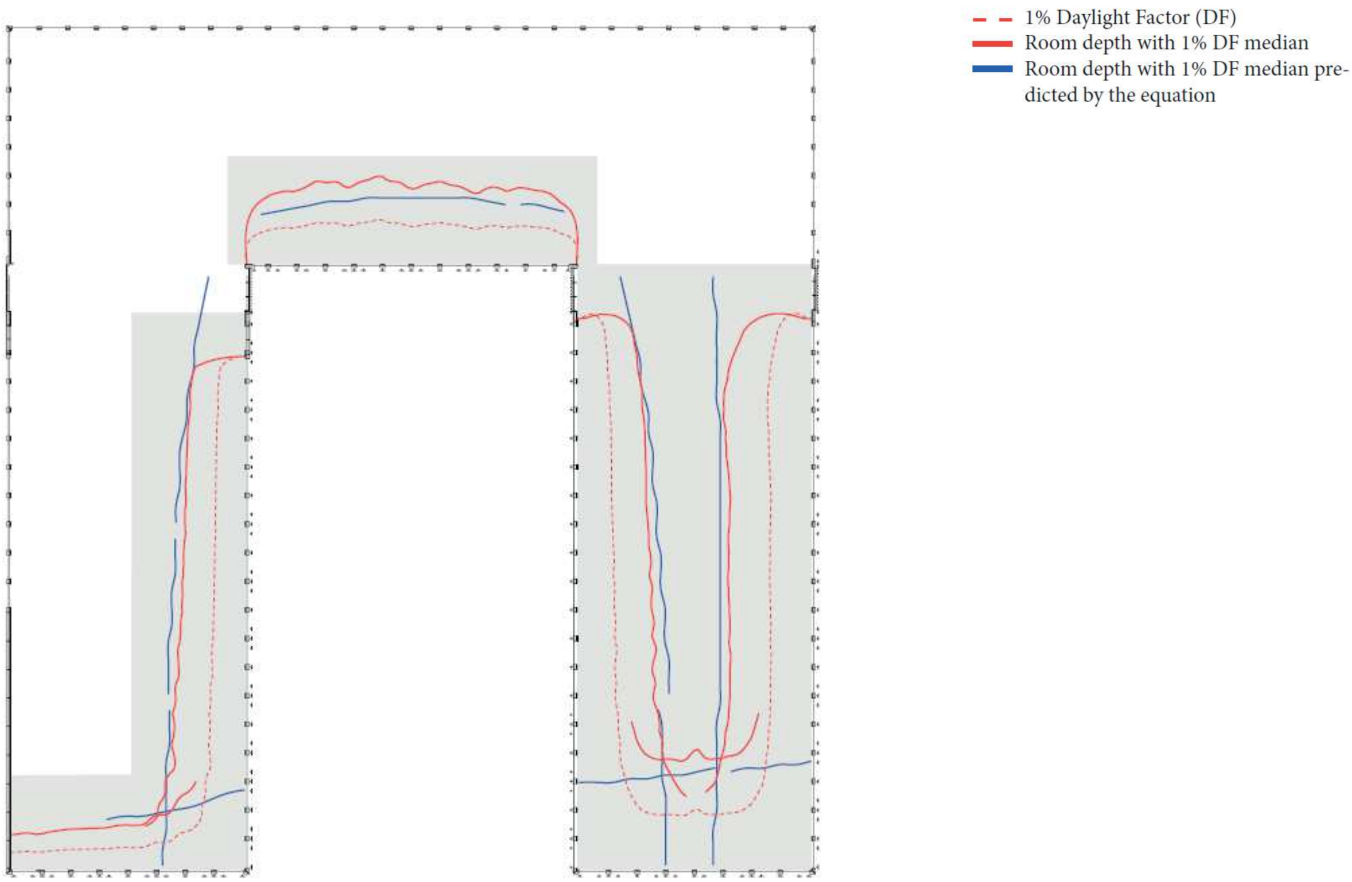

Figure 15: Plan view of selected rooms in an early design stage project without internal partitions showing the depth of a room with 1% pDF (red line) and the room depth predicted by the equation (blue line).

What about rooms with balconies above?

The two methods (equation and simulations) do not agree in rooms with balconies over the window (see Figure 16). We hypothesize that the equation could be adapted for rooms by adding a term in the equation, but this proposal needs to be tested with additional simulations.

$$RD + \text{balcony depth} = 0.2\,(VSC \times RH \times WWR) / (WWR + 0{,}7)$$

RD	Room depth (m)
VSC	Vertical sky component (%)
RH	Room height (m)
WWR	Window-to-wall ratio (-)

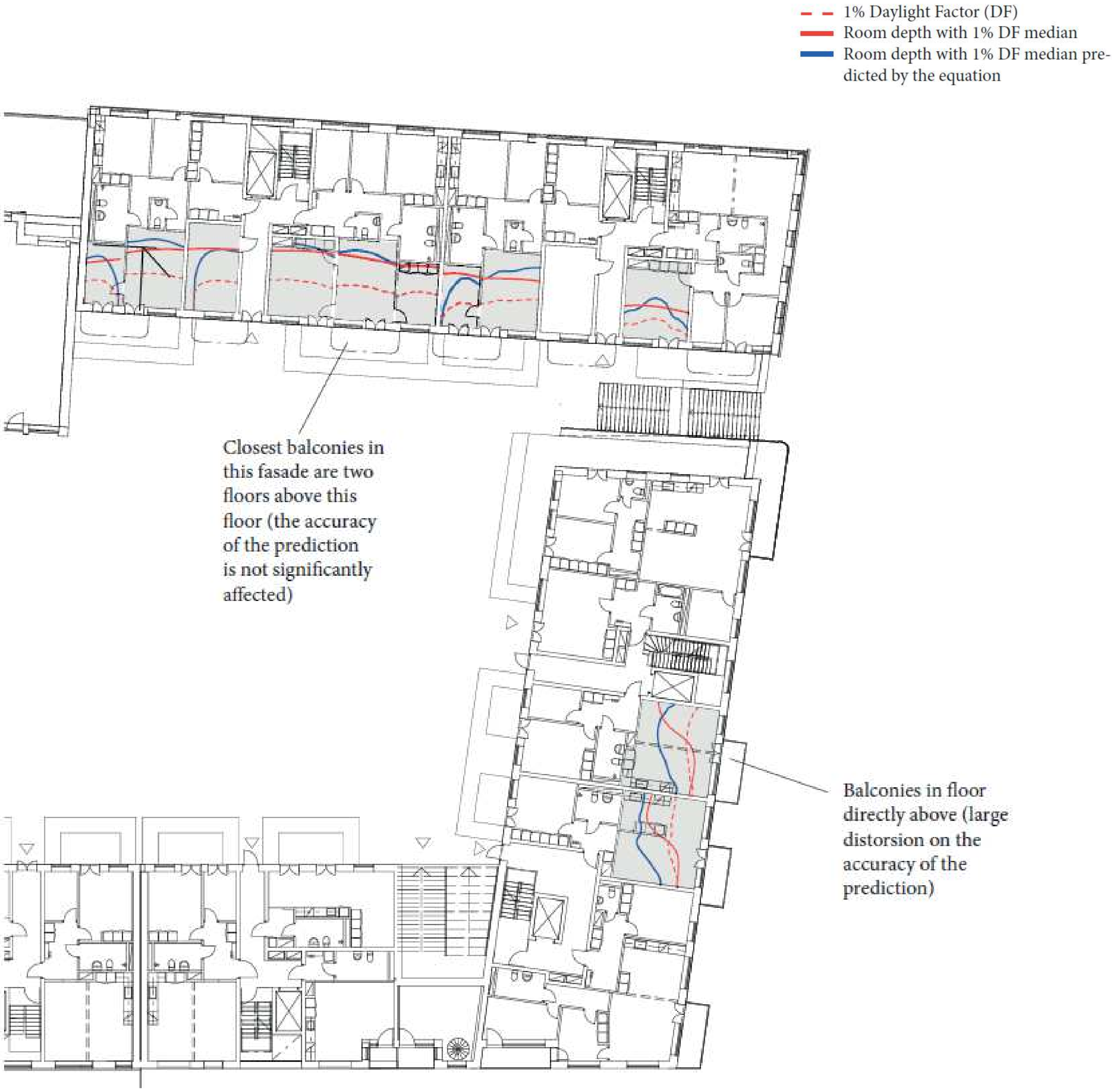

Figure 16: Plan view of selected rooms in a residential project with some baoconies showing the depth of a room with 1% pDF (red line) and the room depth predicted by the equation (blue line).

Limitations of the Advanced VSC method

The method developed in this article is mainly valid for regular i.e. rectangular rooms with windows on one side and no obstruction from balconies. Corner rooms (windows on more than one façade), rooms with balconies over the window, windowless rooms, rooms with irregular or special geometry (e.g. asymmetrical windows, very narrow windows, very high frame factors, etc.) were not considered in the development of the equation. In addition, the equation may overestimate the MRD for rooms with a combination of very high WWR and extensive depth. The equation and its use is also limited to static daylight metric predictions valid only under overcast sky conditions. Therefore, this method is not interesting for locations with sunny climates. Furthermore, the equation was mainly validated using computer simulations instead of measurements. All computer simulations have an intrinsic limited accuracy, normally +-20% with respect to reality [xxxvii]. The reader should bear in mind these limitations when using the equation in any real building project.

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