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Daylight factor prediction in atria building designs

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Abstract

This paper investigates the main characteristics of the atrium and their influence on the daylight conditions in the adjoining space and on the atrium floor. The shape of the atrium and its orientation to the sun, the transmittance of the roof, the reflectivities of the atrium surfaces and the glazed areas are important parameters in the daylighting design of atrium buildings. Several atrium cases, characterized by a different Well Index, are analysed and a simplified methodology used, to predict daylight factor on the atrium floor and in the adjacent rooms, developed through computer simulation using Radiance as a tool.

Keywords: Atrium building; Scale model; Artificial sky; Daylight factor; Radiance

1. Introduction

The atrium has become the modern trend in the architectural design of commercial or office buildings. It admits natural light, connects the adjoining spaces with the outside world and creates a meeting point between people; in other words it becomes the focal point of trade and human activities, increasing the qualitative value of the indoor spaces.

Moreover, the possibilities of having a view, even in a semi-open space, and of having natural light enter the rooms are important assets.

An atrium building design involves the analysis of several characteristics: the orientation to the sun, the shape of the atrium, the transmittance of the atrium roof, the reflectivities of the atrium surfaces and the penetration of daylight into adjoining spaces.

Boyer and Song (1994) underline the importance of the development of research-based guidelines relating to daylight prediction, sunlight strategies and conceptual daylighting design that considers glare and solar control; they develop criteria for daylighting prediction on the atrium floor and summarize a step-by-step method for the daylighting design of an atrium; Liu et al. (1991) investigate the variation of daylight distribution in an atrium in relation to its geometric shape index.

Aizlewwod (1995), in his literary review, describes several prediction methods to evaluate the average daylight factor, pointing out the parameters that affect the daylight within the atrium and its adjoining spaces; Baker et al. (1993) present their data in curves relating daylight factor to aspect ratio for three atrium wall surfaces, Kim and Boyer (1986) develop a relationship between the shape of the atrium and the DF at the center of an open atrium.

Littlefair (2003) reviews current published techniques to evaluate the average daylight factor on the atrium base and walls and in the adjoining spaces.

Szerman (1992) and De Boer and Erhorn (1999) present, in a nomogram, the results of the investigation carried out on the relation between fundamental design parameters of an atrium and the average daylight factor inside the adjoining spaces.

A main atrium characteristic is the roof: a careful design of the roof fenestration system limits glare, mitigates passive solar heating effects and supplies adequate

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daylighting and minimum sunlighting (Boyer and Song, 1994). Gillette and Treado (1988) carried out a detailed thermal transport and daylighting analysis of atria buildings; the results demonstrate the benefits of roof glazing on reducing the lighting energy requirements.

The reflectance of the atrium walls and the percentage of glazing in comparison with the atrium wall surfaces are basic parameters that affect the transmission of the light in the adjoining spaces; Cole (1990) makes experiments with scale models on the effects of varying the glazed area of the atrium walls on daylight values in the adjacent atrium spaces.

Several of the works presented above are based on scale model-measurements in an artificial sky; certainly a computer simulation could give a more rapid evaluation of the design choices (Hopkirk, 1999), saving time and money provided that the software is supported by validation studies. Radiance (Ward and Larson, 1996) is in widespread use in current light research and several studies have shown good agreement with the measured data confirming its scientific validity (Mardaljevic, 1995), (Aizlewwod et al., 1997), (Fontoynont et al., 1999). Based on these previous statements, this paper provides the study of a relationship between the architectural components of the atrium (geometry, material properties, the fenestration system, the atrium roof) and the daylight conditions inside the building. The final aim is to produce, with the aid of Radiance, a simplified correlation to predict the daylight performance of the building. With this it is possible to apply a preliminary evaluation of the basic design choices in order to consider possible alternative building configurations. In fact, for a building in an early concept stage for which probably only the shape is outlined, a simplified method of making preliminary estimates of such performances for typical configurations could be helpful in the following design choices.

The analysis provides an experimental and numerical investigation on a scale model with the aim of comparing the experimental results with the numerical ones and verifying the validity of the numerical data; in a second stage, the model of the atrium building is reproduced with three-dimensional design software and modified to obtain several atrium cases. The daylight performance of the several cases is then simulated with Radiance and the results are plotted for several values of reflectance of the atrium walls.

2. Experimental and numerical investigations

Due to the fact that physical models for lighting are independent of scale, it is possible to evaluate the behaviour of light in a building using a scale model that exactly reproduces the geometry of the space and the surface properties of the materials.

Moreover, a scale model is valuable for a pre-validation of the real performances of daylighting strategies in a new building. In fact, a model allows quick changes in geometry and surface characteristics providing qualitative data from photographs, for example, and quantitative data of the illumination in the space to check the agreement between visual needs and daylighting.

The use of a scale model and of a sky simulator connected with a video recording system makes it possible to obtain a representation of the dynamic play of light within a space and shows the design team the quantitative and qualitative performance of the daylighting system during the design phases of a building project.

The model is made to the scale of 1:50 a symmetric atrium building of a maximum of six floors with the following characteristics:

- the structure of the model is in ply-wood and it is fixed on a stiff base,
- the area adjacent to the atrium is built as an open space,
- the wall and floor surfaces are simulated using card of different colours that specifically reproduce reflectance values: 24.3% for the floor, 50% for the ceiling, 43.7% for the walls and a completely white atrium floor with a reflectance value of about 85% to improve the light reflected to the lower storeys,
- the model simulates a building of 50×50 m with an atrium with sides of 20 m,
- the atrium has variable glazed surfaces decreasing in percentage by 15% from the ground floor (100%) to the top floor (25%),
- 90% of the external surface of the building is glazed (curtain wall),
- in the experimental investigation there is no atrium roof.

The reflectance values of the material used in the model were measured under conditions of diffused light using a reflectometer.

The scale model of the atrium building has been tested in an artificial sky simulator in Lausanne (EPFL-Ecole Politechnique Federale de Lausanne) with the aim of obtaining objective and reproducible measurements without interference from meteorological conditions; in fact the artificial sky provides the reproduction of CIE standard luminance distribution that makes it possible to compare results on an international basis (Commission Internationale de l'Eclairage, 1970; Michel et al., 1995). Moreover, the reproducibility of a sky luminance distribution using the sky simulator allows one to make a comparison of several daylighting strategies that are exposed to the same conditions.

The model was located under a luminous vault and it was fixed to a heliodom (a rotating model support) that simulated, with successive rotations, the whole ceiling vault (Fig. 2)

The measurements were carried out with photometers whose positions, referring to a vertical axis, simulate on a scale of 1:50 the height of a working plane (height of about 0.85 m). All the data were evaluated in terms of daylight factor, that can be defined as the ratio between the illuminance in a point P, on the work surface Ep and the external horizontal unobstructed illuminance Ee.

$$DF = \frac{Ep}{Ee}100$$

The horizontal daylight factor was taken in several positions (Fig. 1) on the first, third and fifth floor to evaluate the daylight levels under an overcast sky.

It is important to point out that the value of the DF is always greater than 2%. Excessive internal illuminance values with visual discomfort are evident near the glazed surface of the perimeter when the external illuminance reaches about 5000 lux. This means that it is impossible to ensure comfort even if the building is under an overcast sky and it is necessary to resort to a more efficient daylight solution that is, for example, a particular type of window-pane or a shading system but, for the moment, the evaluation of these solutions are beyond the objectives of this study.

The atrium building was then reproduced by means of a 3-D-rendering program (3-D Studio Max) that makes it possible to reproduce the reflectance values of the material used in the scale model (Fig. 3). The behaviour of the 3-D model was simulated with the Radiance software that produces, with the calculation method based on ray-tracing technique, realistic 3-D rendering of various lighting scenarios and it provides quantitative data of both electric light and daylight performances.

The diffused indirect calculation to obtain the daylight factor is very interesting for this study in order to make a daylight analysis of the atrium building. The evaluation of the daylight factor derives from the irradiance predicted by a backward raytracing technique that reproduces realistic 3-D displays of the daylight conditions inside the building. The irradiance value from the standard output of retrace is converted directly to illuminance (Ward, 1994).

Even if Radiance has already been validated by several studies (Mardaljevic, 1995), (Aizlewwod et al., 1997), (Fontoynont et al., 1999) it was interesting to analyse its behaviour in this specific case. Thus, the numerical data obtained under a CIE Overcast Sky, were compared with the experimental measurements with the aim of verifying their agreement. Fig. 4 shows the comparison between the experimental and the numerical data produced with Radiance; under a CIE Overcast Sky, the data show a maximum percentage deviation (Δ%) of 26% on the first floor with a maximum average value of 13% on the third floor. The high percentage deviation in some points could depend on a

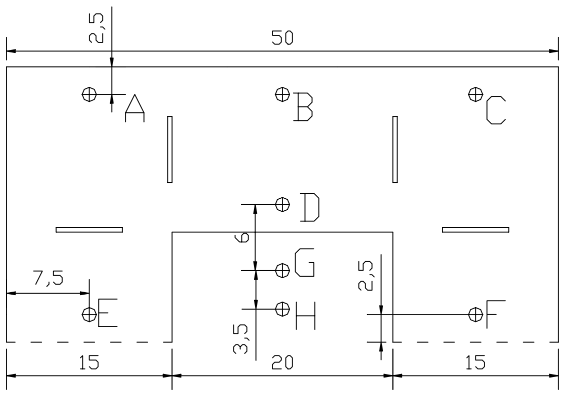

Fig. 1. Points of measurements.

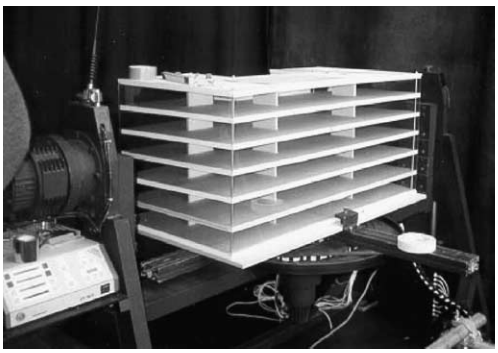

Fig. 2. Scale model fixed on the heliodom.

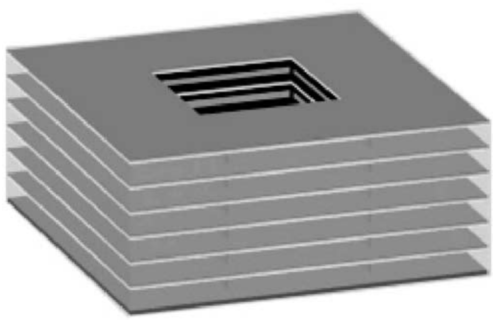

Fig. 3. Simplified 3-D Studio Max Model.

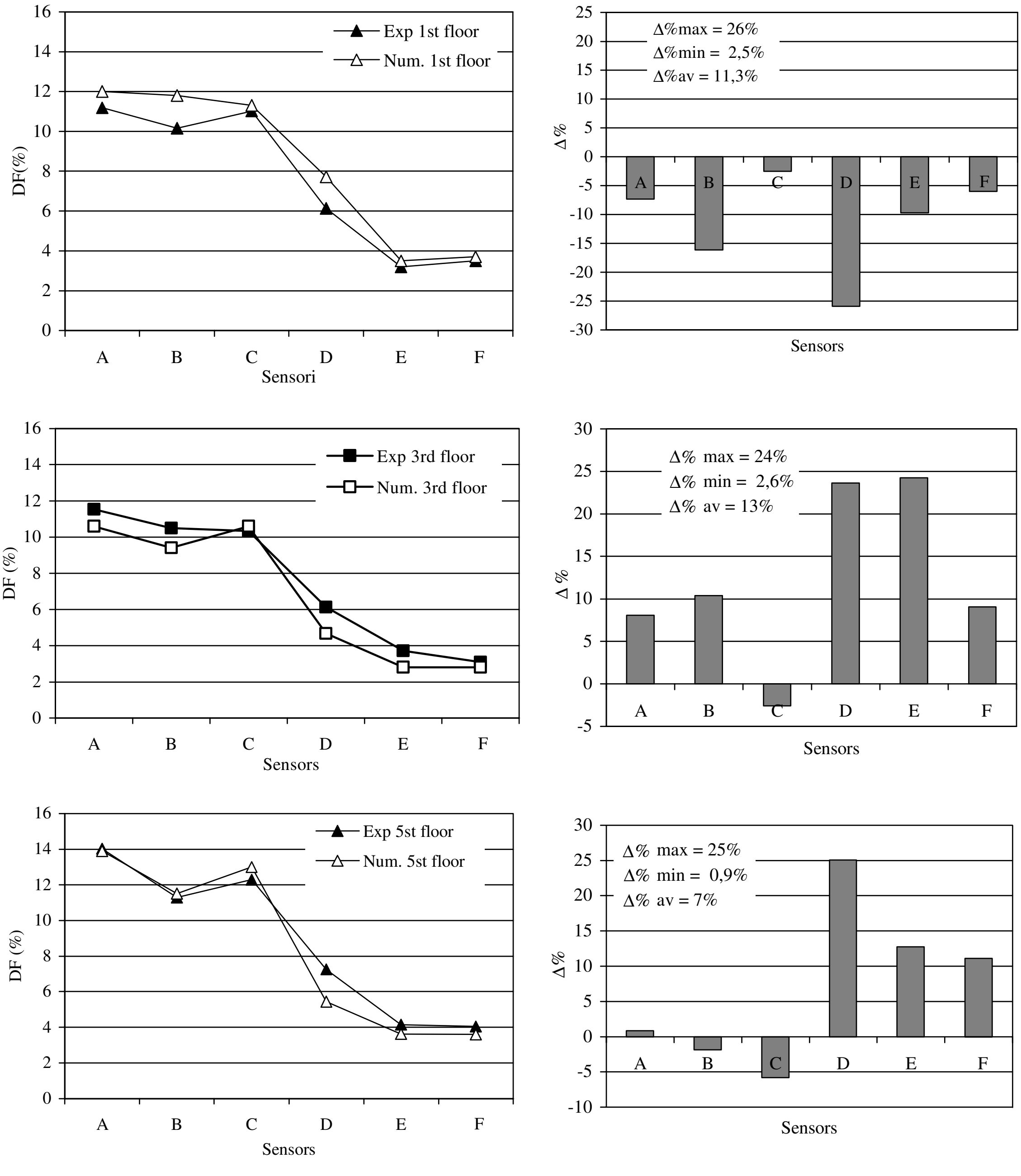

Fig. 4. Daylight factor on a working plane at the first, third and fifth floor–Comparison between numerical and experimental investigation.

shifting between the position of the sensor in the scale model and the point of measurement in the computer model or in an inexact geometrical correspondence between the physical and the numerical model. Moreover, it is necessary to consider the errors in the modelling of the surfaces in Radiance. In fact, the materials have been described with the reflectance as the specular and roughness characteristics were not available. However this paper is not the appropriate session to analyse the sources of simulation errors as the validity of Radiance was demonstrated (Mardaljevic, 1995), (Aizlewwod et al., 1997), (Fontoynont et al., 1999).

3. Design choices and variables in the atrium simulation

As briefly mentioned above, the atrium building has been reproduced by means of a 3-D-rendering programme that allows the assigning of the properties of the material used in the scale model. Several geometric types of atrium building have been obtained, varying the height of the building and the length of the atrium; moreover, changing the finish of the atrium walls, it is possible to test for each type of atrium, the effects of these alterations on the daylight conditions inside the building.

However the base model is intentionally simple in its geometry and has finishing touches to avoid any influence on the results caused by the use of a specific material or geometric element. In fact particular aesthetic choices in the atrium design should be analysed distinctly.

The following paragraphs describe the choices made in the three-dimensional models.

3.1. Atrium shape

The daylight performances of an atrium are strictly dependent on its geometrical aspect. According to Liu et al. (1991), Baker et al. (1993), Kim and Boyer (1986) the shape of an atrium can be described and quantified with a number, for example the Well Index (Eq. (1)) that represents the relationship between the light-admitting area and the surfaces of the atrium:

$$\mathrm{WI} = \frac{\mathrm{height} \cdot (\mathrm{width} + \mathrm{length})}{2 \cdot \mathrm{length} \cdot \mathrm{width}} \qquad (1)$$

This parameter permits a comparison between several atrium shapes connected with a specific height of the building.

The paper analyses eleven cases using as a parameter the "Well Index"; Table 1 sums up the atrium geometric characteristics in terms of the Well Index.

Table 1
Well Index of the analysed atria

Width (m)	Length (m)	Height (m)	WI
20	20	4.2	0.21
20	20	7.8	0.39
20	20	11.4	0.57
20	20	15	0.75
20	50	22.2	0.78
20	40	22.2	0.83
20	33	22.2	0.89
20	20	18.6	0.93
20	20	22.2	1.11
20	20	25.8	1.29
20	20	29.4	1.47

The range of validity of the analysis depends on the previous eleven cases with a WI included between 0.2 and 1.5.

3.2. The glazing system

The glazing system controls the amount of light entering the space adjoining the atrium and, while the top of the atrium receives direct light, the lower floor receives much more reflected light rather then direct light; smaller windows on the top floors mean more light being reflected by the atrium facade (Aschehoug, 1986) moreover variable glazing controls excessive illuminance at the upper floors improving the light condition at the lower floors (Cole, 1990). For this reason the walls of the atrium simulate a curtain wall surface with variable glazing surfaces decreasing in percentage by 15% from the ground floor (100%) to the top floor (25%) (Figs. 5 and 6). This solution improves the light reflected to the lower storeys because of the enlarged white walls on the upper floors.

The windowpane, in this simulation, has a transmittance value of 90%.

3.3. The adjoining space: dimensions and material reflectance

The area adjacent to the atrium is built as an open space, 15 m wide from the atrium wall to the external windows. In the scale model the wall and floor surfaces have been simulated using art card of different colours that specifically reproduce reflectance values (24.3% for the floor, 50% for the ceiling, 43.7% for the walls, 85% for the atrium floor and 1% for the atrium walls) and in the computer simulation the same reflectance values

Fig. 5. Detail of the variable glazing surface.

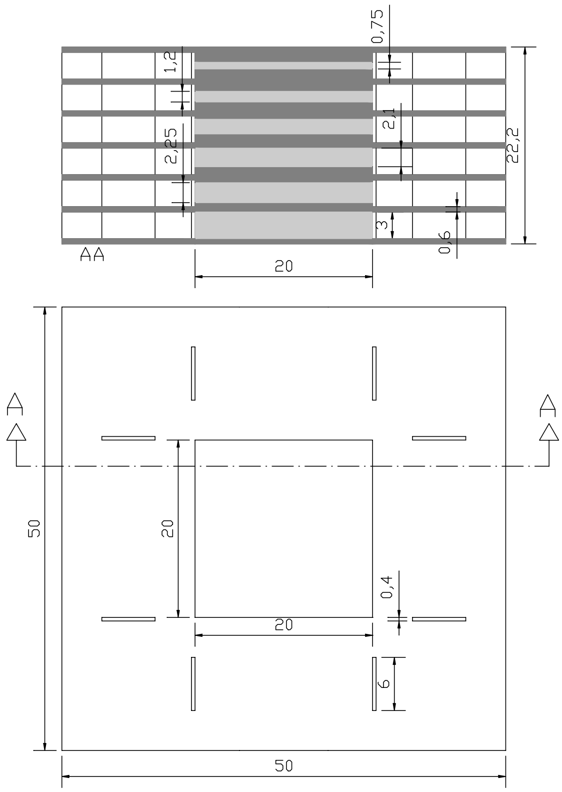

Fig. 6. Plan and section of the atrium building–WI = 1.11.

have been used. The choice of a reflectance value of 1% for the atrium walls (completely black) is due to the need to evaluate only the contribution of the atrium to the global lighting conditions without any interference of the light reflected by the atrium walls. This evaluation is made in the experimental analysis of the scale model under reproducible sky conditions. The successive numerical simulation reproduces the same conditions explained above to obtain a comparison between experimental and numerical data. In a second step the effect of five different reflectance values of the atrium walls were numerically analysed with the aim of evaluating the contribution of the walls reflected light.

In particular for each of the eleven cases specified in Table 1, the daylight factor has been evaluated with computer processing, and calculated for reflectance values of the atrium walls of 10%, 30%, 50%, 70% and 90%.

3.4. The atrium roof

In the experimental analysis the scale model is without roof while the numerical analysis investigates both solutions with roof and without roof.

The roof has been realized with a framework in steel with a side grid of 2 m (Fig. 7); a commercial solar control glass has been chosen for the roof. Table 2 summarizes the characteristics of the windowpane for the atrium roof.

The framework of the roof reduces the window area by about 11%.

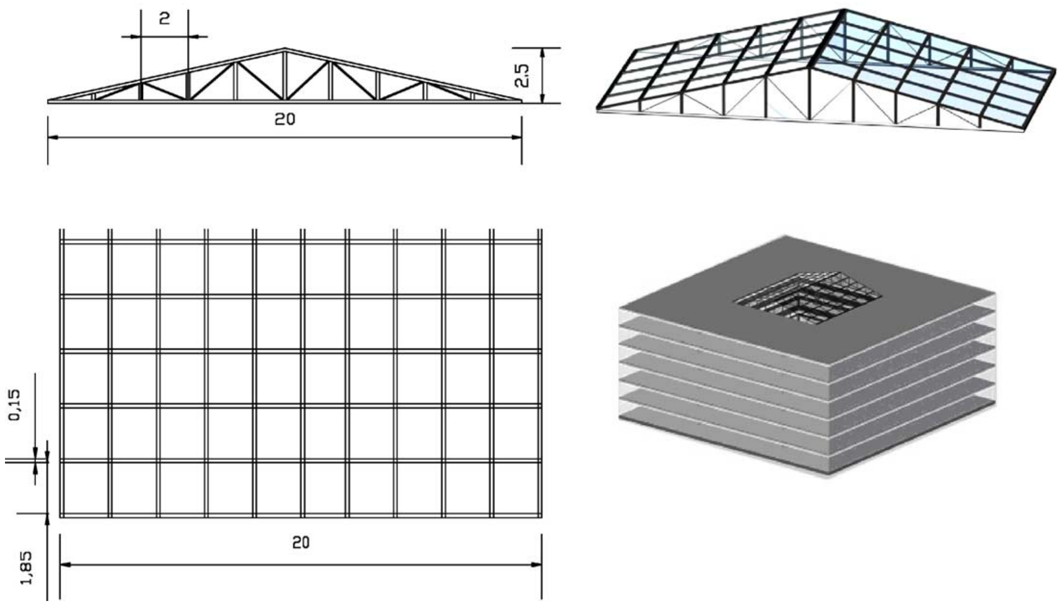

Fig. 7. Schematic drawing of the atrium roof and 3-D Atrium Model. WI = 1.11.

Table 2
Characteristics of the window-pane for the atrium roof

SGG COOL-LITE SKN 172		
Daylight	Transmission LT (%)	65
	Outdoor reflection (%)	9
	Colour rendering Index	93.9
Solar Energy	Transmission (%)	38
	Reflection (%)	35
	Absorption (%)	28
Sun factor		0.41
Shading coeff.		0.47
U-value	Air	1.6
$\mathrm{W\,m^{-2}\,k^{-1}}$	Argon 15 mm	1.1

Other types of roof are not dealt with in this study, although such analysis would be a logical extension to the present work.

4. Daylight factor analysis

Daylight Factor is the instantaneous ratio of interior illuminance at the measurement points, to exterior illuminance on a horizontal plane due to an unobstructed sky; thus, for a given sky model, any increase in sky brightness will produce a proportional increase in internal illumination directly computable with a simple multiplication of the DF by the external horizontal illumination. The DF is representative of the lighting conditions due to specific sky luminance distribution. While the CIE clear sky distribution is a function of the solar altitude and azimuth and needs a set of factors relating to all solar positions to be represented, a CIE overcast sky is a function only of the altitude of the visible sky element and it can be described by a single factor independent of time. This means that if we need a reproducible, fast and easy to handle tool to estimate daylight factor in rooms adjacent to an atrium in an early design stage it is useful to resort to an overcast standard sky independent of location and time; the evaluation under a clear sky with or without sun can be postponed to a more deepened investigation on the design parameters. The Radiance software has been used to determine the daylight factor, under a CIE overcast sky, at the center of the atrium floor and in the adjoining space at a distance of 4 m. from the atrium windows at the ground floor of the building. The choice of the ground floor and of a point 4m from the atrium windows is useful in evaluating the worst daylight conditions; in fact, for that specific dimension of the building, a band 4m from the atrium facade represents the area with the minimum DF; from that point the DF increases in the direction perpendicular to the atrium and to external windows.

Elaborating the DF obtained by the numerical simulation carried out on the eleven cases for different reflectance values it is possible to determine, for each reflectance value of the atrium walls, a correlation between the DF and the WI: the relationship makes it possible to evaluate the amount of light that reaches the space adjacent to the atrium varying the reflectance of the atrium walls.The equations below Eqs. (2)–(6) have been elaborated for the horizontal daylight factor at a distance of 4 m from the atrium windows in the adjacent space in the case of an atrium without the roof framework. The relating curves are plotted in Fig. 9a;

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 10\%$
$$\mathrm{DF} = 1.732 + 4.251 \cdot e^{-2.714 \cdot \mathrm{WI}} \tag{2}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 30\%$
$$\mathrm{DF} = 1.786 + 4.332 \cdot e^{-2.737 \cdot \mathrm{WI}} \tag{3}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 50\%$
$$\mathrm{DF} = 1.840 + 4.390 \cdot e^{-2.730 \cdot \mathrm{WI}} \tag{4}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 70\%$
$$\mathrm{DF} = 1.874 + 4.378 \cdot e^{-2.686 \cdot \mathrm{WI}} \tag{5}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 90\%$
$$\mathrm{DF} = 1.904 + 4.434 \cdot e^{-2.644 \cdot \mathrm{WI}} \tag{6}$$

The formulas for the DF for the configurations of the atrium with roof are (see Fig. 9b):

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 10\%$
$$\mathrm{DF} = 0.787 + 0.885 \cdot e^{-1.019 \cdot \mathrm{WI}} \tag{7}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 30\%$
$$\mathrm{DF} = 0.781 + 0.9115 \cdot e^{-0.9354 \cdot \mathrm{WI}} \tag{8}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 50\%$
$$\mathrm{DF} = 0.6983 + 0.992 \cdot e^{-0.7458 \cdot \mathrm{WI}} \tag{9}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 70\%$
$$\mathrm{DF} = 0.7132 + 1.000 \cdot e^{-0.7317 \cdot \mathrm{WI}} \tag{10}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 90\%$
$$\mathrm{DF} = 0.7310 + 1.036 \cdot e^{-0.7487 \cdot \mathrm{WI}} \tag{11}$$

Exponential decay relationship can be used to deal with the DF in the centre of the atrium at the ground floor. For the configuration without roof the formulas are (see Fig. 10a):

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 10\%$
$$\mathrm{DF} = -4.116 + 39.10 \cdot e^{-0.961 \cdot \mathrm{WI}} \tag{12}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 30\%$

$$\mathrm{DF} = -3.984 + 38.64 \cdot e^{-0.934 \cdot \mathrm{WI}} \tag{13}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 50\%$

$$\mathrm{DF} = -5.230 + 39.56 \cdot e^{-0.863 \cdot \mathrm{WI}} \tag{14}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 70\%$

$$\mathrm{DF} = -5.908 + 40.11 \cdot e^{-0.820 \cdot \mathrm{WI}} \tag{15}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 90\%$

$$\mathrm{DF} = -5.822 + 40.75 \cdot e^{-0.821 \cdot \mathrm{WI}} \tag{16}$$

The equations for the atrium with roof are (see Fig. 10b):

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 10\%$

$$\mathrm{DF} = -12.00 + 45.43 \cdot e^{-0.6576 \cdot \mathrm{WI}} \tag{17}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 30\%$

$$\mathrm{DF} = -11.66 + 44.87 \cdot e^{-0.6462 \cdot \mathrm{WI}} \tag{18}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 50\%$

$$\mathrm{DF} = -14.60 + 47.54 \cdot e^{-0.5768 \cdot \mathrm{WI}} \tag{19}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 70\%$

$$\mathrm{DF} = -11.44 + 44.74 \cdot e^{-0.6390 \cdot \mathrm{WI}} \tag{20}$$

with $0.2 \leqslant \mathrm{WI} \leqslant 1.5$ and $\rho = 90\%$

$$\mathrm{DF} = -17.13 + 50.65 \cdot e^{-0.5269 \cdot \mathrm{WI}} \tag{21}$$

All the equations have a Coefficient of determination R^2, which verify how well the correlation fits the data, above 0.95.

Fig. 8 shows the horizontal DF in the spaces adjoining the atrium. The daylight levels decrease when the height of the atrium increases ($0.21 \leqslant \mathrm{WI} \leqslant 0.75$ and $0.93 \leqslant \mathrm{WI} \leqslant 1.47$); maintaining the height constant and varying the length of the atrium, as expected, DF increases as the light-admitting area of the atrium increases that is, the decreasing of the WI ($0.78 \leqslant \mathrm{WI} \leqslant 0.89$).

In the Figs. 9a–b and 10a–b are plotted, as for example, the curves for a reflectance of 30%, 70% and 90%. The configuration with roof reduces illuminance in the adjoining spaces of about 45% for the several reflectances of the atrium walls with a $\mathrm{DF} < 2$ such as to require an integrative artificial lighting. The atrium walls with a reflectance of 70%, compared with a reflectance of 30%, produce an increase of the DF in the confined workspaces of an average value of about 4.8% for the several WI; the increase of the DF at the increase of the reflectances of the atrium walls is limited due to the large windows that reduce the reflecting surfaces. Tables 3 and 4 analysed the differences between the numerical data derived from the computer simulation and the DF values calculated with the correlations for the several configurations. The exponential decay relationships provide a good approximation of the numerical data in all configurations. The maximum percentage deviation of 13% was observed on the atrium floor in the configuration with roof and of 10.6% for the DF in the atrium adjoining spaces in the configuration without roof.

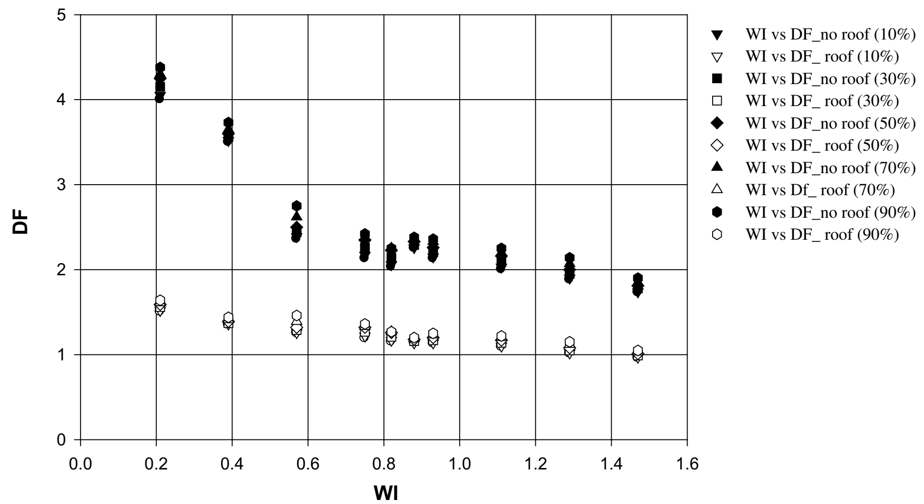

Fig. 8. DF in the adjoining spaces for different reflectance values of the atrium walls.

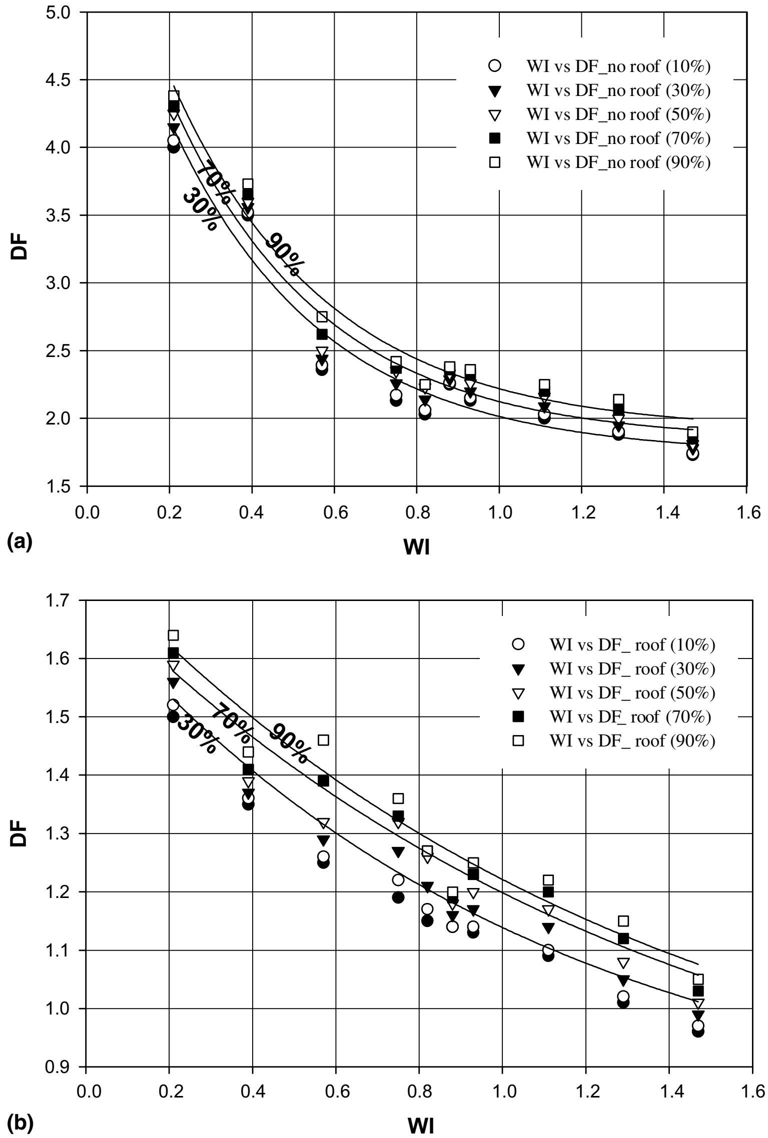

Fig. 9. (a) DF curves for different reflectance values of the atrium walls (atrium without roof). (b) DF curves for different reflectance values of the atrium walls (atrium with roof).

5. Conclusions

Simplified formulas based on Radiance computer simulation have been developed for preliminary prediction of daylight conditions in atria under a CIE overcast sky. The method presented can be applied in an early design stage of the building on square and rectangular atria and it makes it possible to evaluate the daylight factor in the center of the atrium floor and in the adjoining spaces at a distance of 4 m. from the atrium windows at the variations of the reflectances of the atrium walls. Eleven configurations of atrium with a WI ranging from 0.2 to 1.47 have been considered in the investigation and the relationships are valid in this interval: each type of atrium building was studied with and without a roof framework. The increase of the reflectances of the atrium surface does not produce a significant improvement in the DF levels on the ground floor due to the large extension of the windows with high transmittance so that the surfaces that could reflect light

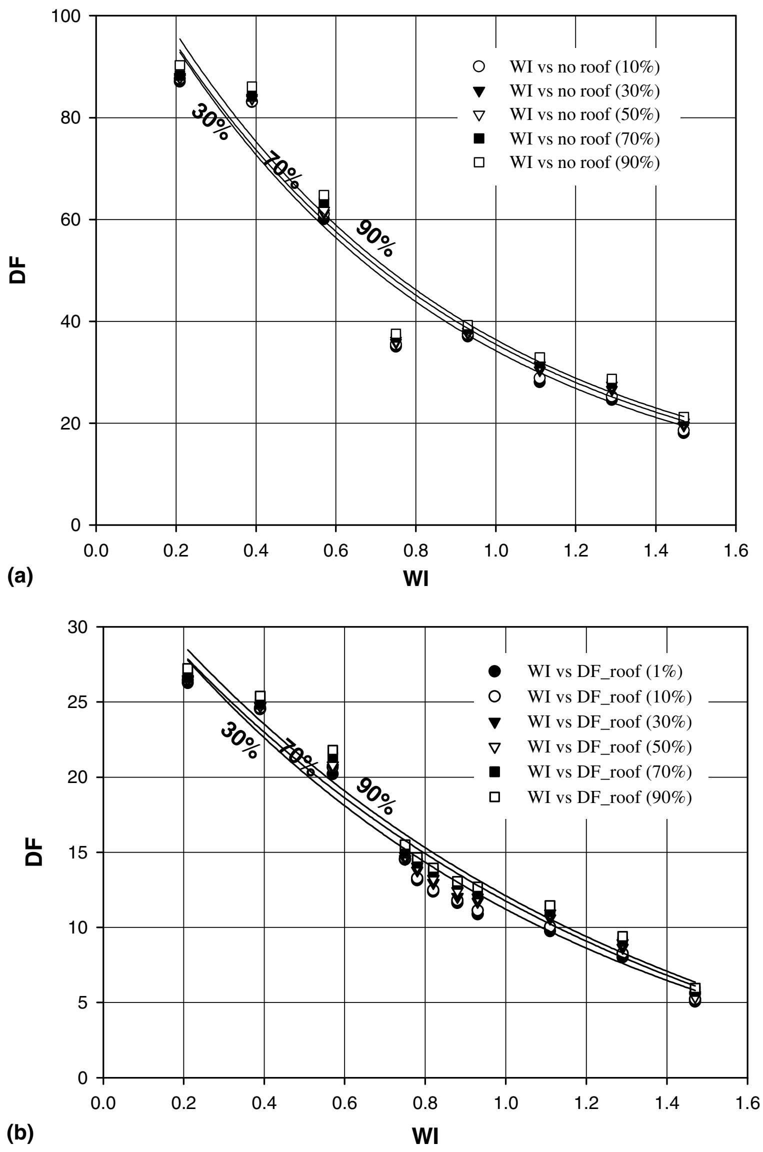

Fig. 10. (a) DF in the center of the atrium for different reflectance values of the atrium walls (atrium without roof). (b) DF in the center of the atrium for different reflectance values of the atrium walls (atrium with roof).

are very limited while the presence of the atrium roof cuts the DF by about 45% in the area adjacent to the atrium.

This investigation cannot be considered finished, as several aspects need further research. In fact, the analysis does not consider the effect of a clear sky and of the direct sun but, as in Mediterranean climates these are the norm, the analysis of the internal daylight distribution under a CIE clear sky with and without sun will be the logical extension of this work. As only one type of fenestration system and roof framework has been considered, a further development of the study would analyse several variations in roof construction and in the distribution of the internal glazing. Moreover, it would be interesting to extend the analysis to the other floors of the buildings, studying the distribution of the DF on the several storeys also with a different distribution of the working spaces.

Certainly an integrated parametric analysis of lighting and thermal characteristics in atria buildings could be desirable in the future development of research.

Table 3
Daylight Factor in the atrium adjoining spaces

WI	DF_rad	Df_corr	Δ%	DF_rad	Df_corr	Δ%
⊙ Configuration without roof						
$\rho_{atrium\ surfaces} = 10\%$						
0.21	4.05	4.14	−2.14			
0.39	3.52	3.21	8.87			
0.57	2.39	2.64	−10.36			
0.75	2.17	2.29	−5.42			
0.82	2.06	2.19	−6.39			
0.88	2.26	2.12	3.03			
0.93	2.15	2.07	1.27			
1.11	2.03	1.94	−2.12			
1.29	1.9	1.86	−2.18			
1.47	1.74	1.81	−6.93			
$\rho_{atrium\ surfaces} = 30\%$				$\rho_{atrium\ surfaces} = 50\%$		
0.21	4.15	4.22	−1.80	4.25	4.31	−1.40
0.39	3.56	3.28	7.97	3.6	3.35	6.91
0.57	2.44	2.70	−10.52	2.5	2.76	−10.58
0.75	2.26	2.34	−3.66	2.35	2.40	−2.34
0.82	2.14	2.25	−4.94	2.23	2.31	−3.42
0.88	2.29	2.18	4.97	2.33	2.24	4.06
0.93	2.2	2.13	3.35	2.26	2.18	3.33
1.11	2.09	1.99	4.59	2.16	2.05	5.10
1.29	1.95	1.91	1.88	2	1.97	1.64
1.47	1.78	1.86	−4.72	1.81	1.92	−5.88
0.21	4.15	4.22	−1.80	4.25	4.31	−1.40
$\rho_{atrium\ surfaces} = 70\%$				$\rho_{atrium\ surfaces} = 90\%$		
0.21	1.61	1.58	1.99	1.64	1.62	1.44
0.39	1.41	1.47	−4.35	1.44	1.50	−4.50
0.57	1.39	1.38	0.88	1.46	1.41	3.62
0.75	1.33	1.30	2.57	1.36	1.32	2.80
0.82	1.27	1.27	0.26	1.27	1.29	−1.71
0.88	1.19	1.24	−4.45	1.2	1.27	−5.59
0.93	1.23	1.22	0.50	1.25	1.25	0.21
1.11	1.2	1.16	3.26	1.22	1.18	3.09
1.29	1.12	1.11	1.28	1.15	1.13	2.14
1.47	1.03	1.06	−2.64	1.05	1.08	−2.45
⊙ Configuration with roof						
$\rho_{atrium\ surfaces} = 10\%$						
0.21	1.52	1.50	1.18			
0.39	1.36	1.38	−1.64			
0.57	1.26	1.28	−1.79			
0.75	1.22	1.20	1.67			
0.82	1.17	1.17	−0.10			
0.88	1.14	1.15	−0.74			
0.93	1.14	1.13	0.83			
1.11	1.1	1.07	2.46			
1.29	1.02	1.03	−0.50			
1.47	0.97	0.99	−1.57			
$\rho_{atrium\ surfaces} = 30\%$				$\rho_{atrium\ surfaces} = 50\%$		
0.21	1.56	1.53	1.92	1.59	1.55	2.35
0.39	1.37	1.41	−3.21	1.39	1.45	−3.98
0.57	1.29	1.32	−2.00	1.32	1.35	−2.38
0.75	1.27	1.23	2.92	1.32	1.27	3.84
0.82	1.21	1.20	0.47	1.26	1.24	1.56

(*continued on next page*)

Table 3 (*continued*)

⊙ Configuration without roof						
WI	DF_rad	Df_corr	Δ%	DF_rad	Df_corr	Δ%
$\rho_{atrium\ surfaces} = 30\%$				$\rho_{atrium\ surfaces} = 50\%$		
0.88	1.16	1.18	−1.83	1.18	1.22	−3.10
0.93	1.17	1.16	0.60	1.2	1.20	0.20
1.11	1.14	1.10	3.18	1.17	1.13	3.00
1.29	1.05	1.05	−0.36	1.08	1.08	0.00
1.47	0.99	1.01	−2.17	1.01	1.03	−2.18
$\rho_{atrium\ surfaces} = 70\%$				$\rho_{atrium\ surfaces} = 90\%$		
0.21	1.61	1.58	1.99	1.64	1.62	1.44
0.39	1.41	1.47	−4.35	1.44	1.50	−4.50
0.57	1.39	1.38	0.88	1.46	1.41	3.62
0.75	1.33	1.30	2.57	1.36	1.32	2.80
0.82	1.27	1.27	0.26	1.27	1.29	−1.71
0.88	1.19	1.24	−4.45	1.2	1.27	−5.59
0.93	1.23	1.22	0.50	1.25	1.25	0.21
1.11	1.2	1.16	3.26	1.22	1.18	3.09
1.29	1.12	1.11	1.28	1.15	1.13	2.14
1.47	1.03	1.06	−2.64	1.05	1.08	−2.45

Table 4
Daylight Factor on the atrium floor

⊙ Configuration without roof						
WI	DF_rad	Df_corr	Δ%	DF_rad	Df_corr	Δ%
$\rho_{atrium\ surfaces} = 10\%$						
0.21	87.62	92.60	−5.69			
0.39	83.12	73.44	11.65			
0.57	61	58.23	4.54			
0.82	37.45	36.59	2.29			
0.88	28.82	29.00	−0.62			
0.93	25.21	22.97	8.87			
1.11	18.52	18.19	1.76			
1.29	87.62	92.60	−5.69			
1.47	83.12	73.44	11.65			
$\rho_{atrium\ surfaces} = 30\%$				$\rho_{atrium\ surfaces} = 50\%$		
0.21	87.75	92.82	−5.78	88	93.03	−5.71
0.39	83.67	73.67	11.95	83.91	73.98	11.83
0.57	61.25	58.57	4.37	61.75	58.99	4.47
0.82	37.56	37.28	0.73	37.97	37.89	0.22
0.88	30.343	29.89	1.51	31.34	30.57	2.45
0.93	26.54	24.05	9.37	27.41	24.81	9.49
1.11	19.5	19.45	0.24	20.14	20.27	−0.67
1.29	87.75	92.82	−5.78	88	93.03	−5.71
1.47	83.67	73.67	11.95	83.91	73.98	11.83
0.21	61.25	58.57	4.37	61.75	58.99	4.47
$\rho_{atrium\ surfaces} = 70\%$				$\rho_{atrium\ surfaces} = 90\%$		
0.21	88.23	93.28	−5.72	90.25	95.42	−5.72
0.39	84.15	74.62	11.33	86.07	76.25	11.41
0.57	63.37	59.77	5.68	64.75	61.07	5.68
0.82	38.45	38.57	−0.32	39.2	39.52	−0.82
0.88	31.72	31.10	1.95	32.87	31.97	2.73
0.93	27.74	25.16	9.31	28.69	25.99	9.40
1.11	20.42	20.43	−0.06	21.16	21.26	−0.46
1.29	88.23	93.28	−5.72	90.25	95.42	−5.72
1.47	84.15	74.62	11.33	86.07	76.25	11.41

Table 4 (*continued*)

⊙ Configuration without roof						
WI	DF_rad	Df_corr	Δ%	DF_rad	Df_corr	Δ%
$\rho_{\text{atrium surfaces}} = 10\%$						
0.21	26.45	27.83	−5.23			
0.39	24.59	22.76	7.46			
0.57	20.64	18.49	10.44			
0.75	14.57	14.89	−2.22			
0.82	13.261	14.35	−8.23			
0.88	12.478	13.66	−9.44			
0.93	11.795	12.66	−7.33			
1.11	11.12	11.87	−6.76			
1.29	10.04	9.33	7.06			
1.47	8.264	7.19	12.95			
$\rho_{\text{atrium surfaces}} = 30\%$				$\rho_{\text{atrium surfaces}} = 50\%$		
0.21	26.47	27.78	−4.94	26.55	27.77	−4.61
0.39	24.71	22.87	7.46	24.77	23.03	7.03
0.57	20.62	18.71	9.25	20.8	18.96	8.82
0.75	14.56	15.20	−4.41	14.77	15.49	−4.85
0.82	13.784	14.67	−6.45	14.064	14.96	−6.35
0.88	12.974	13.99	−7.82	13.245	14.27	−7.76
0.93	12.046	13.01	−8.00	12.432	13.29	−6.89
1.11	11.7	12.24	−4.57	12	12.51	−4.23
1.29	10.6	9.73	8.24	10.94	9.96	8.99
1.47	8.65	7.61	12.07	8.95	7.77	13.15
$\rho_{\text{atrium surfaces}} = 70\%$				$\rho_{\text{atrium surfaces}} = 90\%$		
0.21	26.62	27.86	−4.65	26.62	28.48	−6.97
0.39	24.84	23.22	6.51	24.84	23.76	4.33
0.57	21.334	19.23	9.88	21.334	19.70	7.67
0.75	14.936	15.78	−5.62	14.936	16.19	−8.41
0.82	14.276	15.25	−6.81	14.276	15.66	−9.67
0.88	13.665	14.57	−6.59	13.665	14.96	−9.49
0.93	12.876	13.58	−5.49	12.876	13.96	−8.44
1.11	12.224	12.80	−4.71	12.224	13.17	−7.71
1.29	11.05	10.23	7.41	11.05	10.56	4.45
1.47	9.06	8.02	11.52	9.06	8.31	8.31

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