Daylight in Urban Canyons: Planning in Europe

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ABSTRACT: Daylight calculations are commonly based on the daylight factor method regardless of prevailing weather conditions. While this method may be used for overcast sky conditions, it can be argued that it is not appropriate for clear skies. Furthermore, reflected sunlight from obstructions and ground is a major contribution to the illumination of buildings in orientations and at times when the sun is behind the building. A simplified calculation that takes into consideration reflected sunlight may be used for quick calculations in the initial design stages of the project. Two different set of criteria for daylight and urban planning are presented. They apply to predominantly overcast and clear sky conditions. Both, individually or combined, allow for daylight design in European climates.

Keywords: daylight, reflected sunlight, urban canyons, planning

1. INTRODUCTION

The ultimate source of all daylight is the sun. However, weather conditions and climate, building orientation and time of the day can suppress sunlight access to buildings. In these cases, interiors are dependent on light from the sky and that reflected by surrounding surfaces.

In urban canyons, facing buildings provide considerable obstruction to daylight access by reducing the skylight contribution and blocking sunlight. However, reflected sunlight from the obstructions or the ground can play an important role in the illumination of buildings, particularly in orientations and at times of the day where sunlight is not incident on windows. Furthermore, obstructions and ground can redirect the light to other interior surfaces rather than the horizontal plane, and lead to a greater uniformity of the light inside the space.

Under sunny conditions, physical measurements collected in an urban canyon in Lisbon showed a linear relationship between the global horizontal illuminance and the total vertical illuminance on the facade when it is not receiving direct sunlight. Further studies carried out with computer simulations with RADIANCE as well as an analytical calculation confirmed this relationship, which is shown to be relatively stable throughout the year, with latitude and orientations and time of day when sunlight is reflected off obstructions and ground. [1]

A simplified calculation to apply for urban canyons under sunny climates is presented. The calculation is analogous to the average daylight factor concept but takes into consideration sunlight reflected from obstructions and ground. It is based on the principle of the integrating sphere and the ratio between the total vertical illuminance on the facade of an urban canyon and global horizontal illuminance. [2, 3]

2. ILLUMINANCE IN THE CANYON

It is possible to define three scenarios regarding sunlight availability on a vertical facade. In the first scenario, the sun is in front of the building and is providing direct sunlight on the facade. In the second scenario, the sun is still in front of the building but the obstruction is sufficiently high to block direct sunlight. Any point on the facade will receive light from the sun after it is reflected from other parts of the facade and then from the obstruction and ground. As this involves a minimum of two reflections, the sunlight contribution is significantly reduced. Furthermore, it will be mainly dependent on the reflectance of the surfaces. In the last scenario, the sun is behind the building and sunlight reaches the facade after it is reflected from the obstruction and ground.

Besides the sunlight contribution, the illuminance on the facade will be a result of direct light from the visible part of the sky and from other parts of the sky vault by reflection at the obstruction and ground.

Lastly, the illuminance on the facade includes the contribution from interreflections within the canyon due to reflected sunlight and skylight.

2.1 Fieldwork

Real data collected in Lisbon in urban canyons showed a linear relationship between the global horizontal illuminance, E_{gh}, and the total vertical illuminance, E_{tv}, at the building facade when the facade is not receiving direct sunlight. The 'total vertical illuminance' is defined as the sum of sunlight, skylight and the interreflected component that falls on a vertical plane per unit of area. This relationship can be described by a linear equation of the form

$$E_{tv} = k \times E_{gh} + C \qquad (1)$$

where the slope k mainly depends on the reflectance of the obstruction, the geometry of the canyon and the position on the facade. The constant C is mainly the contribution of the diffuse sky illuminance to the building's daylight and is more significant at higher floors.

Figure 1: Global horizontal illuminance versus total vertical illuminance on the first and fifth floor windows of a building facing north in 9th – 10th August 2000 in a 1:1.5 canyon (ratio height/width) in Lisbon.

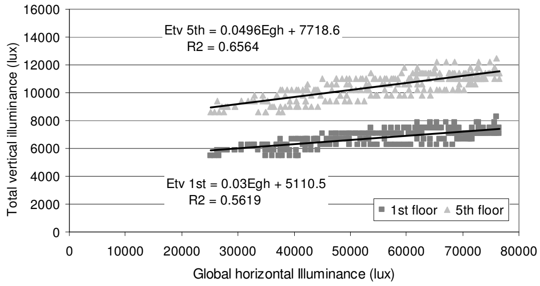


Figure 1 present linear trendline between the horizontal and vertical readings when the sun is behind the building. A few variations are result of the building not being perfectly oriented due south, provoking different angles of incidence in the obstruction for similar solar altitudes. Also surfaces of the canyon are not free of irregularities and setbacks that create shadows and points of lower luminance.

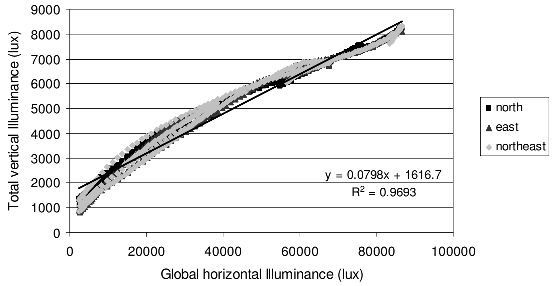
2.2 Computer simulations and analytical calculations

Further studies undertaken with RADIANCE and an analytical calculation confirmed that an approximately linear relationship existed except under specific conditions occurring mainly in the summer when the ground was fully sunlit. However, they do not weight significantly on the average. Depending on the accuracy of the calculation, this relationship can be representative for the whole year. Computer simulations allowed for a modification of the canyon geometry, the building orientation and reflectance of surfaces. It was also possible to look at the separate contributions from the sky, ground and obstruction to the illuminance on the building for overcast and clear skies in Lisbon and in London.

Although the percentage of the contributions to the illuminance of a north façade may vary significantly throughout the day (sky and obstruction) and year (obstruction and ground), the reflected light from the obstruction and ground is higher than the contribution of the sky, except in early hours of the day. The reflectance of the surfaces (ground and vertical planes) was taken as 0.2. Higher reflectance of surfaces will increase the contribution of reflected light. However, typical building reflectance (where glazing has a reduced diffuse reflectance of around 14%), urban pollution, poor building maintenance, windows reveals and setbacks casting shadows make a conservative value of 0.2 more realistic.

Nevertheless, the variation of the reflectance of the surfaces is the factor that affects the most reflected sunlight access to the building in an urban canyon and should therefore be given much thought. The orientation of the building, see figure 2, the latitude of the location and the canyon aspect ratio (between 1:0.5 and 1:1.5) have a lesser effect.

Figure 2: Global horizontal illuminance versus north, east and northeast total vertical illuminance on the third floor window in an urban canyon ratio 1:1 in Lisbon on the equinox and summer and winter solstice days.



While results obtained from the three methods present significant variations, they all show a linear relationship between the global horizontal and total vertical illuminance when there is no sunlight incident on the facade. Reasons for differences between physical measurements and those obtained by the other two means may be due to irregularities of the facade in terms of window reveals, setbacks or balconies, which contrast to the perfectly flat surfaces defined in the model for the simulation or analytical calculation. Any protruding element on the facade will cast a shadow with a sharp contrast when sunlight is incident. If interreflections in the canyon are reduced, those umbras will have a very low luminance. Not only will the average luminance of the facade be significantly reduced, it may create zones of potential glare due to a harsh contrast between strongly sunlit areas and the shadows. Under an overcast sky the shadow will be much softer. Since sunlight is very directional and much stronger than light from the rest of the sky, the shadows are much softer under an overcast sky than they are under a sunny one, reducing the contrast between the lit and the unlit areas on the facade.

2.3 Internal daylight calculation

The most common method of daylight analysis is the daylight factor approach, where the diffuse internal horizontal illuminance is directly proportional to the diffuse external horizontal illuminance.

However, by definition, sunlight is excluded from the daylight factor calculation, limiting the light source to diffuse from the sky. Besides the simplicity of the calculation it has been widely accepted on the basis of its independence of orientation. It will be argued that, whereas this characterisation is appropriate for heavily cloudy climates, it should not be used in sunny climates.

In a similar way to the daylight factor, a method based on eq. 1 that relates the global horizontal to the total vertical illuminance can be used to evaluate how well a space is daylit under a clear sky.

In an urban canyon, the lower floors will tend to have a constant of relatively low value on eq. 1, due to a reduced view of the diffuse sky. If the constant is ignored, there is a direct proportionality between the horizontal and the vertical illuminance. Considering that this relationship does not change significantly during the year, a method based on this relationship could be representative of a year condition, which would be appropriate for window design.

2.3.1 Daylight factor

Daylight analysis in the UK has been traditionally associated with the CIE overcast sky for the following reasons:

- If the natural lighting is sufficient on an overcast day it is likely to be adequate during a clear day;
- The overcast sky luminance is independent of the azimuth therefore the effect of orientation is not considered in the calculation;
- The indoor illuminance is directly proportional to the simultaneous outdoor horizontal unobstructed illuminance independent of sky brightness. [2]

The average daylight factor, $\overline{D}$, is the ratio between the mean illuminance in a space and that from an unobstructed external sky, generally assumed to be the CIE overcast sky.

The average daylight factor obtained as an equation and not as an average of daylight measurements on several points in a plane was developed by Lynes. The expression is based on the average illuminance in an enclosure defined by Sumpner. Later work developed by Crisp and Littlefair derived the average daylight factor on the working plane (assumed at 0.85 m). [3, 4]

Both equations can be rearranged so as to enable the calculation of the area of the window required to achieve a given average daylight factor. As a rule of thumb, the average daylight factor may be used to characterise the perception of how well a space is lit according to:

- Below 2% the room will appear dull under daylight. Supplementary artificial light will be needed during daylight hours;
- Between 2 and 5% the room will appear increasingly daylit. Electrical task lighting may be needed for visual accuracy;
- Above 5% the room will be strongly daylit. Electrical lighting is rarely needed. However, the excessive dimension of the windows is likely to cause thermal problems.

The average daylight factor will be strongly affected by the reflectance of the interior surfaces. Good reflecting properties will improve the quantity of internal light as well as its distribution, therefore enhancing the quality of the space.

While a reference illuminance level might be maintained easily with artificial lighting, this is much more difficult with daylight due to its variable nature. However, it is accepted that people tend to prefer daylight to artificial light. Moreover, people will accept lower light levels and variability in a daylit room more willingly than they would in an artificially lit environment. Even if a visual task is performed under task lighting, it is important to have a naturally lit ambient as our circadian rhythm expects a daylit period during the daily routine.

The appearance of a room under daylight not only depends on the illuminance on the working plane, but also on the luminance of the surrounding surfaces and the view trough the window. The judgment of the interior brightness will also depend on the occupant's background and knowledge. People may tend to assume that clear skies provide higher illuminance levels than overcast ones, therefore they are more likely to assume a space is acceptably lit under a blue sky than a cloudy sky. Conversely, a room with a smaller window may appear as dull under an overcast sky as it would under a clear sky, even if the light level may be significantly higher for a sunny sky.

While these criteria can be subjective, as the apparent brightness of the room is strongly dependent on the brightness of the sky and external surfaces seen through the window, the average daylight factor representing the ratio of the indoor to outdoor illuminance is a good indicator of how well daylit a space is.

2.3.2 Total daylight factor

The 'Total Daylight Factor', *TD*, at a point is the ratio of the total internal illuminance, i.e. direct and indirect for both sky and sun, to the external unobstructed global illuminance.

It has been shown that "the ratio of internal to external illuminance varies greatly under real skies". [5] However, in an urban canyon when direct sunlight is excluded, there is a relationship between the external (vertical) and the global illuminance, as presented previously. To a certain extent an urban canyon will tend to behave similarly to a photometric integrator, where the illuminance after interreflections is uniform and independent of the angle of incidence.

The average total daylight factor can be expressed as a percentage by

$$\overline{TD} = \frac{k \times A_W \times \tau}{A \times (1 - \rho_{av})} \quad (2)$$

Where

k is the E_{tv}/E_{gh} previously defined;

A_w net glazed area (not including frames, glazing bars or other obstructions) [m^2];

A total area of the interior surfaces, ceiling, floor and walls of a room including windows [m^2];

τ is the diffuse light transmittance of the glazing, including the effects of dirt;

ρ_{av} area-weighed average reflectance of the interior surfaces.

3. PLANNING GUIDELINES

A pleasant indoor environment with low energy consumption is the major aim of good building design and planning. Establishing criteria for daylight design may prove to be critical in the initial phases of the project, when incorrect decisions quite often compromise the final design.

Although solutions to the problem of promoting daylight into buildings may be similar for both overcast and clear skies, some factors may be more relevant under one or another sky condition. The main decision to be made is to select an appropriate approach based on the dominant sky condition for the location.

The adoption of simple calculations may prove to be sufficient to prevent initial decisions that compromise the spaces in terms of daylight. If they are easy to apply, they may become more widely adopted. Average daylight factors have been used to give a simple indication of how daylit a space appear to be under overcast sky conditions. The average total daylight factor may allow the development of a similar calculation to apply for clear skies in an urban canyon when sunlight is behind the building. More detailed daylight analyses expected to be made in later stages should be carried out by experts.

3.1 Daylight availability

Daylight simulations usually use one of the four widely accepted sky distributions, namely clear, intermediate, overcast or uniform. However, they may be a limited representation for some locations. CIE has recently published a new standard general sky (S 011/E:2003), that lists 16 luminance distributions in recognition of a wider range of conditions from a heavily overcast to a cloudless sky. [6]

Ideally, daylight analysis should make use of data obtained for the location provided it is representative of the climate and not just an occasional occurrence.

The luminance and luminance distribution of the sky as a source and availability of light are the main factors in daylight analysis. Daylight design strategies should therefore be closely related to the weather conditions at the location.

Nevertheless, the strategy or approach to be used will strongly depend on the probability or frequency of occurrence of a particular sky condition.

Other important statistics for daylight design are the analysis of the percentage of hours for which a certain daylight value will be exceeded.

3.2 Daylight strategy

Daylight provision in buildings provides a sense of spaciousness and amenity, preferred by occupants. It should be the aim of the architect to design spaces where daylight is thoroughly assessed and the criteria met unless other conditions reduce or prevent their achievement. There are some steps to follow for daylight design analysis:

1. Definition of criteria according to space, function and period of occupancy if known;
2. Establishment of weather conditions prevailing for the location and selection of sky condition for daylight calculation;
3. Analysis of external conditions for light access such as urban canyon ratios, obstructions and trees;
4. Analysis of building design in terms of orientation and form;
5. Window design in terms of size, shading systems, daylight enhancement systems and view;
6. Evaluation of overall design to achieve the requirements.

3.3 Design for overcast skies

Design guidelines for use under overcast skies are well documented in standards and recommendations on daylight design. In the initial phases of building design they involve concerns with the effect of surrounding buildings on the window size and positioning. Although sunlight is excluded from the calculations, its importance is suggested in the preferred orientation of the building within 90º of due south in order to achieve a certain number of probable sunlight hours during the year and a minimum over the winter season.

Good daylight design for predominantly overcast skies may be achieved if the following rules are met:

- Building design conditioned by the angular height of surrounding obstructions or a minimum vertical sky component in order to provide good access to light from the sky. Previous research has presented values for different latitudes; [7, 8]
- A room with side-lit windows the room depth should not exceed twice the room width. This is based on equation developed by Lynes limiting the room depth, for a typical window head height of 2 m and average reflectance of 0.5; [3]
- No significant part of the working plane should lie beyond the no-sky line. In the UK 50% of the working plane should receive a 0.2% sky factor to prevent legal remedy by 'Rights of Light';
- A room will tend to have a daylit appearance if the area of the glazing is 4% of the total room area. This rule is based on achieving an average daylight factor of 2%;
- Surfaces that are closer to the window, within twice the window head height above the working plane, should receive sufficient daylight for task lighting for most of the daylight period. This figure is based on achieving a minimum 2% daylight factor on the working plane.

Under overcast conditions, the sky contribution has the most weight in the illuminance reaching a point, therefore larger solid angles of visible sky will improve daylight access, particularly to lower floors of a building in an urban canyon. From the average daylight factor calculation the window size is inversely proportional to this angular visible sky, therefore narrow canyons may compromise daylight access by imposing impractical window sizes, particularly if these are likely to cause overheating and higher heat losses during winter. Daylight design for overcast skies can be compromised if planning guidelines do not guarantee minimum sky components dependent on the latitude of the location. The increase of surface reflectance on external obstructions will not compensate significantly for a reduction of the sky component. However, the reflectance of the internal surfaces of the room may play a significant role in increasing the illuminance indoors and will contribute to a better uniformity of the light.

3.4 Design for clear skies

When designing for clear skies care must be taken to take the most advantage of the sun's positions in the sky either aiming at direct or reflected sunlight. External surfaces will then play a significant role in the way they may interfere with sunlight access to the building. Just as the reflectances of the internal surfaces are important in order to enhance the illuminance indoors, the external surfaces of the canyon can play a significant role in the illuminance that reaches the window. Urban canyon geometry may also enhance the interreflections of light within the cavity therefore increasing the illuminance in the buildings.

Surrounding obstructions may potentially have a bigger effect on the daylight access of a building under a clear sky than they would under an overcast sky. In a sunny climate, an obstruction can block direct sunlight or at least obstruct the bright sky around the horizon. With an overcast sky, the part of the sky obstructed in the sky dome is the least bright. Nevertheless, care should be taken to avoid prolonged obstruction to direct sunlight as it reduces significantly the illuminance in the building. A building whose access to daylight is obstructed may only receive sunlight after a minimum of two interreflections in the surrounding surfaces. On the other hand, obstructions can also reflect light from other parts of the sky. For some orientations or times of the day where the sun is behind the building, obstructions are an extremely important means of directing sunlight into the building which would otherwise be unavailable to the building. Sunlight reflected from obstructions and ground can contribute to around 60% of the illuminance on the mid floor of a building in an urban canyon in Lisbon. Light reflected from obstructions contributes around 50% of the illuminance on the facade in the winter and spring. The ground contribution is only around 10%. However, in the summer period, the contribution from the obstruction is reduced to around 25%, whereas that from the ground increases to 35%. Depending on the season, the times when the higher illuminance is desired may influence the decision to increase the reflectance of the ground or obstruction.

Furthermore, light reflected from obstructions and ground will reach deeper areas in a side lit room and other surfaces than the horizontal plane, contributing to a better uniformity of the light inside the room.

However, given European latitudes where the solar altitude may be low, on a clear day the contribution of reflected light from the ground may be reduced. Exceptions may occur on summer days when the sun's altitude is high, or when the solar azimuth is around the same direction as the canyon axis in which situation the ground may be fully sunlit.

The literature review showed a significant deficiency in existing design guidelines and simple calculations that can be applied for clear skies. This gave the basis to the simplified daylight calculation defined. The average total daylight factor applies for rooms in urban canyons when sunlight is not incident on the facade. This calculation was developed using the hypothesis that daylight design should not be based on extreme conditions. If the predominant sky is clear, daylight calculations should not be based on overcast distributions. Similarly, under clear skies, windows should not be sized for direct sunlight as they will be undersized when the sun is behind the building and the light levels are much lower. Furthermore, when sunlight is incident, people may close the blinds to avoid glare due to excessive contrast between the bright window and the surrounding surfaces.

The findings of this study should strictly apply to similar conditions, particularly with reference to canyon geometry. They are summarised as:

- There is a linear relationship between the global horizontal illuminance and the vertical illuminance when sunlight is not incident on the facade;
- This relationship is relatively stable throughout the year;
- The reflectance of the surfaces of the canyon, in particular that of the obstruction have the most effect on the illuminance of the buildings, for European latitudes;
- The orientation of the buildings does not affect the linear relationship when the sun is behind the building in an urban canyon;
- A variation of the latitude does not affect the linear relationship for the urban canyon;
- The slope of the linear relationship is similar for different canyon aspect ratios, but the constant of the equation tends to increase with floor height and for wider canyons due to larger angles of visible sky;
- The slope of the relationship is relatively constant at all floors for lower obstruction's reflectance, but varies with higher reflectance;
- The average total daylight factor calculation is a simple calculation similar to the average daylight factor but taking into consideration reflected sunlight in an urban canyon;
- The average total daylight factor is proportional to the window size, therefore may be a useful method for estimating window sizes in early stages of design. This is helped by the fact that the use of the average total daylight factor does not require the window shape or position to be known in advance.

In the northern hemisphere, buildings facing north will depend on reflected sunlight for most of the time. Buildings with east and west orientations will experience a similar effect during half of the day. It has been argued that windows in these orientations should be designed for reflected light, to avoid their being undersized. The south orientation is privileged in terms of number of hours during the day with direct sunlight. In practice daylight design should only be based on direct sunlight for buildings oriented south, all other orientations should be analysed for reflected light. A canyon with an east-west axis should then be dimensioned to guarantee a certain number of hours of direct sunlight on the south facade, as well as to promote reflected sunlight into buildings opposite.

Good daylight design in urban canyons for predominantly sunny skies may then be achieved if the following guidelines are met:

- The dimensions of the urban canyon should allow a minimum period of four hours of incident radiation on the south facade (depending exclusively on the latitude of the place and not on weather conditions) A recommendation of at least 4 hrs in the middle of the window has been included in DIN 5034 Part 1 of the German standard on daylight provision; [8]
- A canyon width of between half the height and one and a half times the height allows reflected sunlight to be effective for the illumination of the building;
- The orientation of the building should be within 90º of due south if direct sunlight is expected. However, care should be taken to avoid overheating and glare. Shading devices should be used;
- Buildings oriented north should take the most advantage from reflected sunlight to compensate for the reduced period during the year when they benefit from direct sunlight;

- Windows in east or west facades should be sized for reflected sunlight and not incident sunlight, to prevent their being undersized during half of the day;
- With the obstruction and ground having a reflectance of 0.2, sufficient amounts of reflected sunlight will contribute to the illuminance of a building in an urban canyon. This reflectance has been analysed for different orientations, canyon ratios (1:0.5, 1.1 and 1:1.5) and latitude (between 35º and 55º. Higher reflectances may significantly increase the illuminance levels, however they might not be realistic in real canyons. Nevertheless, a higher ground reflectance mainly contributes to an increase of the illuminance in the summer, whereas higher reflectance in the obstruction mainly increases the illuminance during winter and spring;
- An initial estimation of window dimensions for buildings which are oriented north, east or west orientations may be obtained with the average total daylight factor in eq. 2 in order to take reflected sunlight into consideration;
- If a daylit appearance is expected, an initial estimation of 0.5%, $\overline{TD}$ may be desirable.

4. CONCLUSION

The adoption of simple calculations may prove to be sufficient to prevent initial decisions that compromise the spaces in terms of daylight.

The decision as to whether to design for overcast or clear skies influences the strategy to be followed. Although some criteria may apply under both sky conditions, some factors may be more important under one sky distribution than the other.

When designing for clear skies, the first decision to be made is whether design for direct or reflected sunlight is desired. In practice, only buildings oriented south will receive sufficient quantities of direct sunlight for an extended period. North facing buildings will depend on reflected sunlight most of the time. Windows in the east and west orientations should not be sized for direct sunlight, as they will be undersized when the sun is behind the building for half of the day.

Urban planning for clear skies should guarantee a minimum distance between buildings to allow sunlight to reach the facade. If sunlight is blocked by obstructions, the illuminance on the facade will reduce drastically, as sunlight will only be available after a minimum of two interreflections in the canyon. Moreover, a poorly sunlit facade will impair reflected sunlight into buildings opposite.

Although the illuminance on the facade will vary with site latitude, the linear relationship with the global horizontal illuminance remains relatively stable for different latitudes (between 35º and 55º), therefore a single calculation may apply for sunny climates in Europe.

The factor most affecting the illuminance of buildings is the reflectance of the surfaces of the canyon. An increase of the obstruction reflection mainly affects the illuminance of the building in the winter and spring. An increase of the ground reflectance takes affect during the summer period. However, the reduced sun's altitude for higher latitudes in Europe may compromise this effect, with the obstruction-reflected component becoming more important.

Daylight calculations mainly provide ways for calculating daylight in terms of illuminance levels. The average daylight factor, as a way to characterise the perception of how well a space is lit, appears to be more appropriate to daylight analysis. The average total daylight factor was based on the same approach, promoting the development of such a characterisation for sunny climates.

Window dimensioning should make use of either the average daylight factor calculation or the average total daylight factor calculation for overcast or clear skies, respectively. A daylit appearance may be achieved with a 2% average daylight factor for overcast conditions or a 0.5% average total daylight factor for clear sky conditions.

Initial estimations proposed to the average total daylight factors are based on quantitative data obtained in this study. [1] The definition of visual comfort indices should be confirmed with experimental surveys in real situations.

ACKNOWLEDGEMENT

The first author would like to thank the financial support of INETI – Instituto Nacional de Engenharia e Tecnologia da Informação, I.P. and the FCT – Fundação para a Ciência e Tecnologia.

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