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ΣΧΟΛΗ ΜΗΧΑΝΙΚΩΝ ΠΕΡΙΒΑΛΛΟΝΤΟΣ

Εξοικονόμηση ενέργειας στο δομημένο περιβάλλον με έμφαση στο Φυσικό Φωτισμό

Energy Savings within the built environment - an emphasis on daylight control

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ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

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Διατριβή υποβληθείσα στα πλαίσια των απαιτήσεων για την απόκτηση του Διδακτορικού Τίτλου του Πολυτεχνείου Κρήτης

PhD Thesis submitted to the School of Environmental Engineering of Technical University of Crete

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στις 18 Δεκεμβρίου 2013

Εικόνα Εξωφύλλου:
Τύποι συστημάτων σκιασμού που εξετάστηκαν στα πλαίσια της παρούσας Διατριβής
Picture on the cover:
Various shading systems examined in the present PhD Thesis

Declaration

I hereby declare that the work presented here has been my independent work and has been performed during the course of my post graduate studies at the Environmental Engineering School of Technical University of Crete, Chania.

All contributions drawn from external sources have been acknowledged with due reference to the literature.

Δήλωση

Δηλώνω υπεύθυνα ότι η παρούσα Διατριβή είναι προϊόν ανεξάρτητης εργασίας μου που διεξήχθη κατά τις μεταπτυχιακές μου σπουδές στη Σχολή Μηχανικών Περιβάλλοντος του Πολυτεχνείου Κρήτης στα Χανιά.

Για ότι δεδομένα ή πληροφορίες χρησιμοποίησα που προέρχονται από εξωτερικές πηγές έχουν δοθεί οι αρμόδιες αναγνωρίσεις και αναφορές.

Μαρία Σ. Μανδαλάκη
Maria S. Mandalaki

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"The sun control device has to be on the outside of the building, an element of the façade, an element of architecture. And because this device is so important a part of our open architecture, it may develop into as characteristic a form as the Doric column"
MARCEL BREUER (1902 -1981) (Blake (ed), 1955)

0.0. PREFACE

While conducting this research a lot of people played a major role by helping improve and complete this work. I would like to especially thank some of them.

First of all I would like to warmly thank my supervisor in this research, Theocharis Tsoutsos , Associate Professor in the Environmental Engineering Department of T.U.C., for his continuous support and scientific guidance. I would also like to thank the two other members of the advisory team, Professor Vassilis Gekas, Dean of the Faculty of Geotechnical Sciences and Environmental Management of Senate, Cyprus University of Technology and George Stavrakakis, Professor in the Electronic and Computer Engineering Department of T.U.C., for their trust and support through all the stages of this research.

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Maria M., Chania, March 2013

0.1. Summary

The issue of energy balance in buildings has a significant importance nowadays, since conventional energy sources are running out and become extremely expensive. Fundamental environmental design parameters should be carefully implemented in the overall design decisions. A building's skin is the design element that has to balance all environmental dynamics between interior and exterior. Radiation control in transparent façade elements is a very delicate subject due to the fact these elements are the ones that are the most vulnerable to it.

Sun control "machines" play a major role in the control of incident solar and thermal radiation for transparent elements. Additionally, they determine the final aesthetics of the façade and constitute an expression of the architectural language of the designer. The research's starting point is the fact that the conception of shading systems as sun control "machines" introduced in the '60s, has changed. The integration of PV elements in their surfaces is the key factor that calls for a reexamination of their performance within the actual environmental standards.

The fundamental geometric rules for effective Shading Design derive from the necessity of preventing direct solar radiation from entering the interior. The main objective of this research is to resolve an energy balance contradiction that originates from fixed shading devices: the simultaneous reduction of a building's cooling loads and the increase of its electric light needs. In order to balance the positive fact of the decrease of cooling loads that fixed SD pose and the negative fact of the increase of electricity needs for lighting and thermal comfort, the electricity produced through integrated PV systems has been examined as a potential energy balance solution for various SDs geometries. We compared all SDs with integrated PV energy and comfort performance with shading systems of simple glazing.

The research focuses to a typical office building unit. We have used the office originally defined in the European Commission Joule project REVIS (VanDijk, 2001) and further refined in the International Energy Agency Solar Heating and Cooling (IEA SHC) programme Task 27 (Performance of solar facade components) (VanDijk, 2002). The same specifications are used in the EC project SWIFT (http://www.ist-swift.org/), for IEA SHC Task 25 (Solar assisted air conditioning of buildings, http://task25.iea-shc.org/) and Task 31 (Daylighting Buildings in the 21st century, http://task31.iea-shc.org/) (Nielsen et al., 2003).

The choice of examining the function of office buildings is due to the fact that office units have very specific requirements of daylight levels according to the task of the users and according to the position of the subjects in relation to the opening. The electricity needs are calculated for the worst case scenario of the minimum requirement of 500lux at the desk level and it is measured as Average Daylight Autonomy for the whole year.

Daylight Autonomy is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. It was originally proposed by the Association Suisse des Electriciens in 1989 and was improved by Christoph Reinhart between 2001 - 2004. It considers geographic location specific weather information on an annual basis and it is related to electric lighting energy savings if the user defined threshold is set based upon electric lighting criteria. The user is free to set the threshold above which Daylight Autonomy is calculated (Tzembelikos & Athenitis, 2007). For the office units examined in this research the threshold is set to 500 lux on the desk level, as mentioned before.

Most of the SDs examined are typical external fixed systems for south orientation of office buildings (Fig.0.1.).

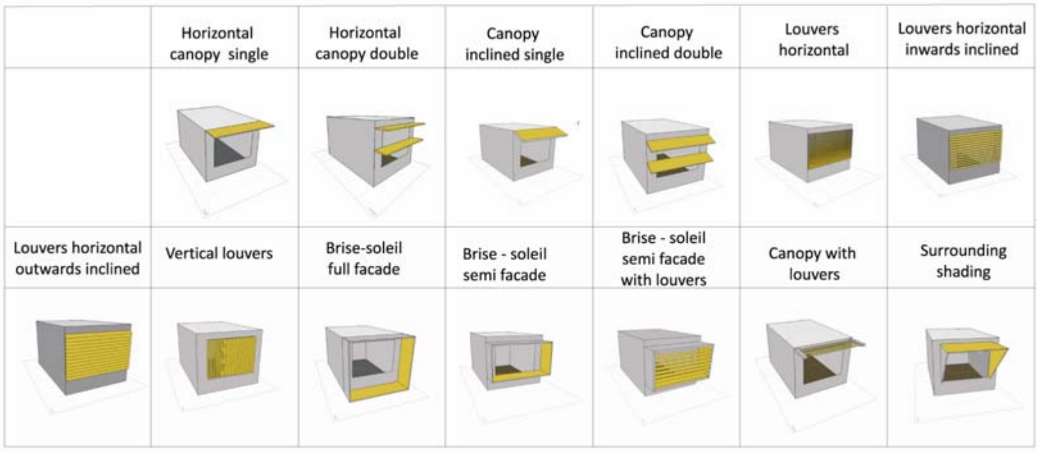


Fig.0.1. Types of examined shading systems

Objectives of the research

All shading systems are evaluated according to four factors:

- The energy consumption for thermal comfort of the office unit they shade
- The energy consumption for supporting the electric light needed into the office unit in order that visual comfort is achieved
- Visual comfort levels that each system can support
- And the energy production that integrated PV provide

In order to achieve the evaluation of the SDs besides basic equations, two main tools were used: digital models imported in simulation software and measurements taken from physical models. The comparison of the above mentioned methods, in relation to the results achieved, has been one of the main questions of this research. We searched for appropriate tools that can be used in the early design stage, when structural details are to a large extend undefined.

Two are the main objectives of this research:

- Evaluation of shading geometries with integrated PV in terms of energy savings and visual comfort
- Determination of the limitations and possibilities of each assessment method used in relation to the level of the design stage (early design stage-detail design stage)

The originality of the research is also supported by the fact that it focuses in the specific conditions of Mediterranean climate.

Innovations of the research

The main innovation of this research is the definition of geometrical configurations of Shading systems with integrated PV appropriate for Mediterranean Climate, their design and their evaluation in relation to their energy performance (production and consumption of energy for heating and cooling the space they shade) and to the daylight quantity and quality that they provide to the interior.

As we show (from the bibliographical research) there is a gap in the field of integration of PV in various geometrical configurations of Shading Systems appropriate for Mediterranean sun position and climate. Despite the rapid development of the Building Integrated Photovoltaics (BIPV) technology almost none of the Shading Systems with integrated PV examined in this research has been previously examined - Only the systems of Canopy Horizontal Single, Canopy inclined Single and double.

We define basic geometrical configurations of shading systems that can work efficiently for Mediterranean countries: provide thermal and visual comfort with low energy consumption and produce the maximum of the electricity through their integrated PV. None of the researches done in the field of Shading Systems examined various geometrical possibilities of them for increasing their energy performance, taking into account the maximization of energy production. Most of the researches are involved only on their shading performance for balancing cooling, heating loads and visual comfort or only on their performance in relation to energy production. In this research optimization points between comfort and low energy consumption through different geometries of shading systems with integrated PV are being proposed. Additionally the research focuses on a comparative analysis of various geometrical configurations and the conclusion are based on the balance of the above mentioned facts.

Another innovation is that we evaluate the influence of the integatrion of PVs within Shading Systems in relation to the visual conditions they provide and the electricity needs they create for lighting the interior. We re-examine already known geometries of Shading Systems constructed with a new material: a PV monocrystalline material. We emphasize to the specific geometry of louvers systems with integrated PV, that the thickness and the reflection of the material affect drastically their final performance. For that purpose we examine two different market PV products for the cases of Louvers Shading systems: market PV panels with an overall thickness of 3cm and of 1.5 cm. In both systems PV technology is the same: mono crystalline PV cells. We conclude that in both cases, the systems perform in a very similar way.
The third innovative action is that we evaluated different methods used for assessing visual performance and energy production of Shading Devices with integrated PV in relation to the design stage. The process of evaluating and choosing the appropriate shading system with integrate PV that corresponds to specific requirements is time consuming and regards special knowledge of the designer. In this research we proved that architects can use simple simulation tools, even though they incorporate a percentage of error and that these tools are efficient enough for the early design stages.

Methods used

Methodologically the work is divided into two main parts: The first part is a bibliography research that concerns firstly the performance of different types of SDs in relation to thermal and visual comfort, secondly the performance of shading systems with integrated PV, and thirdly the assessment methods used to evaluate that performance. The second part consists of experimental work with the use of physical models, simple and more complex simulating tools to evaluate the energy needs, daylight levels and quality, and the energy production for a reference office unit with different shading systems. All chapters of Part II, follow this structure: bibliography research and experimental work.

The research's approach is concentrated on the effectiveness of the assessment method used. We examined the balance between simple evaluating tools and more accurate complicated ones. We searched for the optimum combination of simple and accurate tools that we can use for assessing basic geometrical configurations and different color and material properties.

In order to assess the performance of SDs in relation to thermal comfort we used advanced simulation software. This is due to the fact that the simple simulation software could not measure the difference of temperature to the interior between the various types of the SDs examined.

Further on an additional parameter of energy savings from the use of daylight has been examined. We calculated daylight autonomy and the percentage of the time of the year that electric light is needed. We assumed that a continuous electric light dimming strategy is used. According to Vartiainen (1998), this system helps diminish electric light needs.

For the evaluation of daylight quality conditions we used validated simulating tools. We additionally constructed 1/10 scale physical models in order to evaluate the intricacies of the behavior of daylight and the relation between simulated sky to real sky conditions. The results of these comparisons between measured and simulated data are further connected to the daylight performance of each SD in real buildings.

Finally in order to further examine the influence of the integration of PVs in visual conditions and energy demands of the interior, we examine two different market PV products for the cases of Louvers Shading systems: market PV panels with metal frames with final thickness of 3cm the second one consists of glass louver system with integrated PVs with final thickness of 1.5 cm. In both systems PV technology is the same: mono crystalline PV cells. The main difference of these two types of PVs is their appearance and their geometry in terms of their thickness. The thickness is a crucial fact that influences the interior daylight environment.

In order to assess the most appropriate method for evaluating the energy performance of SDs with integrated PV, we compare the energy production results of the PV panels, of three different method used: a simple energy computer simulation model that uses the theoretical average PV efficiency of 12%, a more complete computer simulation model using detailed equations, and real PV installations. Each examined method refers to a different design stage according to the level of information that is available to the designer.

Conclusions

Some general conclusions can be drawn from the studies carried out within this research.

Simulation methods, measurements of physical models and real PV roof installations are used in order to evaluate the energy performance of various geometrical configurations of shading systems with integrated PV for an office unit. Even though differences between the results of the methods used have been observed and presented in the related chapters, some general conclusions have be extracted and presented here. The conclusions are either related to the method used or to the examined researched field (energy for thermal comfort, energy for visual comfort or energy production).

In relation to all examine factors (lower energy consumption for heating, cooling and lighting and higher energy production) only the shading system of Surrounding Shade can produce enough electricity to support the energy needed for all heating, cooling and lighting the examined office unit. This result can be achieved by simulation tools. Generally we can see that different types of systems perform well for different needs. The preferred selected Shading System depends on the design stage, the priorities of the design and the factors examined.

In relation to the factors and methods used appropriate for each design stage the following are concluded that concern each examined factor (thermal performance, daylight quality and quantity and energy production of the integrated PV):

For evaluating the performance of SDs in relation to the resulting thermal interior conditions and the energy needs for achieving these conditions only the complete simulation model is accurate enough and can be used. Small differences between latitude points do not affect drastically the assessment when comparative analysis is the goal.

Concerning the results of daylight quality in order to assess visual comfort conditions in the early design stage, daylight factor (DF) and daylight autonomy (DA) are appropriate values. The DGI method and UDI value for evaluating visual conditions should be used in the detailed design stage, due to the fact that they demand detailed modelling and are time consuming. Additionally the designer should be familiar with these values in order to be able to evaluate the results. Physical Models as a means to evaluate interior visual comfort can be used in the late design stage.

Concerning the evaluation of the energy production of integrated PV in Shading Systems, the results showed that the simple simulation and the more elaborated models have similar performance for most of the shading devices, apart from those with a complicated geometry. Moreover, the second simulation model uses parameters of PV modules already available on the market that can be integrated in the aforementioned shadings. This model can provide results of energy production even for complicated geometries. It is concluded that the real PV modules produce results very close to the theoretical average PV efficiency of 12%. This means that the use of the theoretical efficiency of 12% can be safely used at the early design stage.

0.2. Περίληψη

Εξοικονόμηση Ενέργειας στο Δομημένο Περιβάλλον με έμφαση στο Φυσικό Φωτισμό.

Το ζήτημα της ηλιοπροστασίας του κελύφους των κτιρίων είναι από τα θεμελιώδη που επιλύονται προκειμένου να εξασφαλιστεί ο βασικός παθητικός σχεδιασμός κτιρίων χαμηλής ενεργειακής κατανάλωσης. Ειδικότερα σήμερα που οι απαιτήσεις για χαμηλής ενεργειακής κατανάλωσης κτίρια είναι αυξημένες τα ζητήματα σκιασμού αποκτούν ιδιαίτερη σημασία.

Επί πλέον όσον αφορά στην Αρχιτεκτονική Επίλυση του κελύφους σε σχέση με τις εσωτερικές λειτουργίες τα συστήματα σκιασμού έχουν καθοριστικό ρόλο όσον αφορά το τελικό αισθητικό αποτέλεσμα και την ισορροπία μεταξύ της αρχιτεκτονικής ιδέας και της υλοποίηση της.

Όπως τονίζει ο Givoni (1969, p. 213), αναφερόμενος στη σημασία προστασίας των διαφανών στοιχείων των όψεων, τα ηλιακά κέρδη από τα διαφανή στοιχεία είναι πολύ αυξημένα σε σχέση με αυτά των αδιαφανών τοίχων. Για αυτό το λόγο και ο κατάλληλος σχεδιασμός των σκιάστρων είναι πολύ κρίσιμος σε σχέση με την ενεργειακή κατανάλωση του κτιρίου για θέρμανση ψύξη και φωτισμό, ειδικότερα για το μεσογειακό κλίμα που οι ανάγκες για ηλιοπροστασία είναι αυξημένες.

Γύρω από το πλαίσιο επίλυσης των ενεργειακών ζητημάτων και μείωσης της ενεργειακής κατανάλωσης των κτιρίων, η προσπάθεια ενσωμάτωσης ενεργητικών συστημάτων σε αυτά, έχει ήδη από τη δεκαετία του 50, αποτελέσει εφαρμόσιμη λύση. Ειδικότερα η ενσωμάτωση φωτοβολταϊκών στοιχείων στα συστήματα σκιασμού έχει εφαρμοστεί από τη δεκαετία του 80 στον κτιριακό τομέα ενώ ποικίλες εταιρείες έχουν επικεντρωθεί στην παραγωγή τέτοιων στοιχείων. Το σκεπτικό εξοικονόμησης ενέργειας, πέρα από την σκίαση και άρα μείωση της ενεργειακής κατανάλωσης για ψύξη, βασίζεται και στο γεγονός της χρήσης ενός και μόνο οικοδομικού στοιχείου για την επίλυση δύο λειτουργιών: μείωση ενεργειακής κατανάλωσης και παραγωγή ενεργείας.

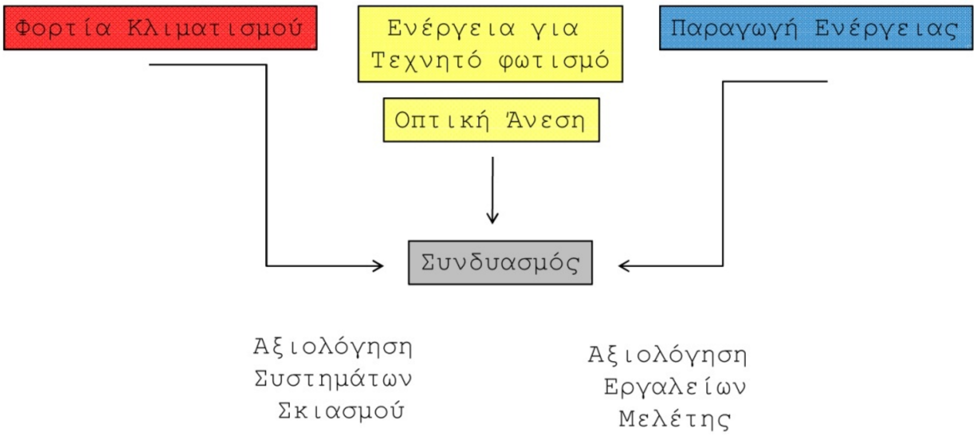
Η ενσωμάτωση όμως των φωτοβολταϊκών στα συστήματα σκιασμού επιφέρει αλλαγές στην συνολική ενεργειακή συμπεριφορά του σκίαστρου. Πέρα από τη μείωση της συνολικά καταναλισκομένης ενέργειας του κτιρίου, η συνολική συμπεριφορά του σκιάστρου απαιτεί επανεξέταση τόσο όσον αφορά τις ενεργειακές ανάγκες για θέρμανση και ψύξη όσο και τις νέες συνθήκες οπτικές άνεσης που δημιουργούνται.

Η έρευνα που θα παρουσιαστεί επικεντρώνεται στα σταθερά συστήματα σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία προσπαθώντας να επιλύσει τις ενεργειακές ανάγκες που δημιουργούν τα σταθερά αυτά συστήματα τη χειμερινή περίοδο, λόγω του ότι μειώνουν τα απαραίτητα για την εποχή άμεσα ηλιακά κέρδη. Δύο είναι η βασικοί στόχοι :

1. Εύρεση σημείων βελτιστοποίησης της ενεργειακής κατανάλωση των σταθερών συστημάτων σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία και των συνθηκών οπτικής άνεσης.

2. και η διερεύνηση των περιορισμών και των δυνατοτήτων των αναλογικών (μετρήσεις σε φυσικά μοντέλα υπό κλίμακα) και των ψηφιακών μεθόδων (προσομοιώσεις σε ψηφιακά μοντέλα) ενεργειακής και ποιοτικής αξιολόγηση τέτοιου είδους συστημάτων, σε σχέση με το στάδιο της εκπονούμενης μελέτης.

Για να επιτευχθούν οι παραπάνω στόχοι ακολουθήθηκε η μεθοδολογία όπως παρουσιάζεται στο διάγραμμα της Εικ.0.2.1., ενώ για κάθε ένα από τους τρεις τομείς (φορτία κλιματισμού, τεχνητός φωτισμός – οπτική άνεση, παραγωγή ενέργειας από τα PV) διεξάγεται βιβλιογραφική έρευνα και πειραματισμοί είτε με προσομοιώσεις είτε με φυσικά μοντέλα.



Εικ.0.2.1. *Βασική Μεθοδολογία έρευνας*

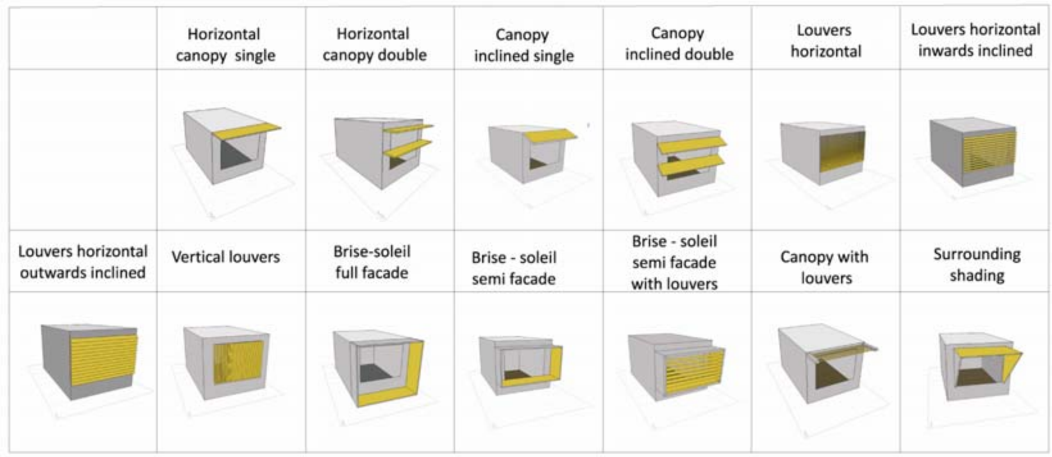
Διερευνήθηκε η τυπολογία, η κατάλληλη γεωμετρία συστημάτων σκιασμού για κτίρια γραφείων και οι δυνατότητες ενσωμάτωσης φωτοβολταϊκών πλαισίων.

Η μελέτη επικεντρώνεται στα κλιματικά δεδομένα της Μεσογείου. Ως αντιπροσωπευτικά δείγματα κλιματικών δεδομένων επιλέχτηκαν αυτά της Αθήνας και των Χανίων.

Σχεδιάστηκαν και μελετήθηκαν δεκατρείς (13) τύποι σκιάστρων με προσομοιώσεις, με τη χρήση δύο λογισμικών και με αναλογικά μοντέλα σε κλίμακα 1/10. Έγινε σύγκριση των αποτελεσμάτων όσον αφορά στα επίπεδα της εσωτερικής θερμοκρασίας, στην κατανάλωση ενέργειας για ψύξη και θέρμανση του χώρου, στην κατανάλωση ενέργειας για φωτισμό και στα επίπεδα φυσικού φωτισμού.
Αναλυτικότερα:

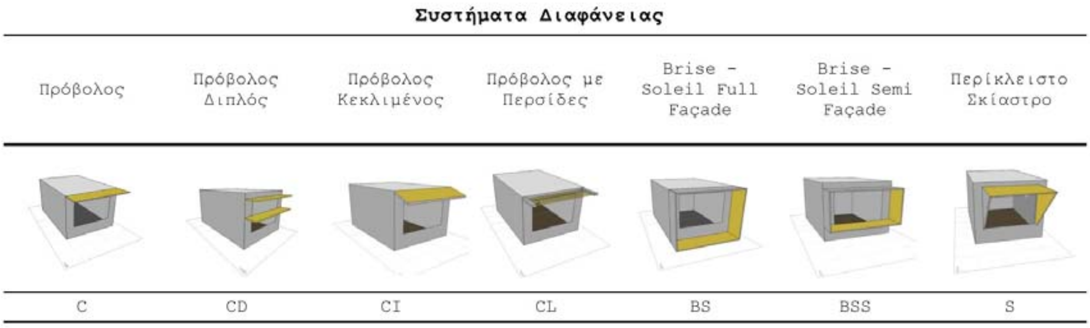
1. Εισήχθηκαν τα μετεωρολογικά δεδομένα του σταθμού της Σούδας στο λογισμικό Ecotect, για να μπορούν να πραγματοποιηθούν προσομοιώσεις για την περιοχή των Χανίων. Το αντίστοιχο αρχείο καιρού της περιοχής των Αθηνών ήταν ήδη έτοιμο για τα συγκεκριμένα λογισμικά.

2. Σχεδιάστηκαν σε τρισδιάστατα μοντέλα δεκατρείς αντιπροσωπευτικοί τύποι συστημάτων σκιασμού, για νότια προσανατολισμένα ανοίγματα, μιας τυπικής μονάδας κτιρίου γραφείων, με γνώμονα την αποφυγή της άμεσης ηλιακής ακτινοβολίας για της ώρες λειτουργίας του γραφείου, για την Αθήνα και για τα Χανιά (Εικ. 0.2.2). Προσομοιώθηκαν με δύο διαφορετικά λογισμικά σε σχέση με τις αναπτυσσόμενες θερμοκρασίες και την ενέργεια που απαιτείται για την εξασφάλιση συνθηκών θερμικής άνεσης στο εσωτερικό. Με βάση την προσομοίωση του Ecotect βέλτιστο σκίαστρο όσον αφορά την ενεργειακή κατανάλωση για εξασφάλιση θερμοκρασιών μεταξύ 18 – 26 ^{o}C για τα δεδομένα των Χανίων είναι ο διπλός κεκλιμένος πρόβολος. Με βάση το λογισμικό Energy Plus περισσότερη εξοικονόμηση ενέργειας εξασφαλίζεται με το σύστημα του περίκλειστου σκίαστρου (Mandalaki et. al, 2012).

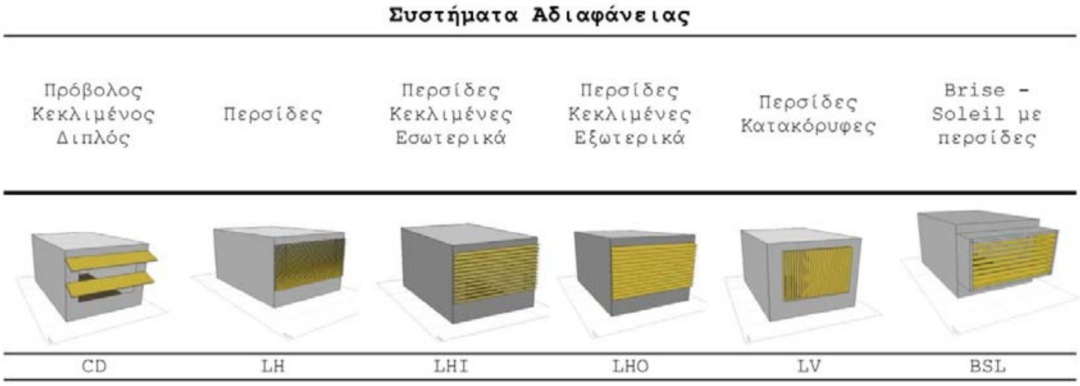


Εικ.0.2.2. *Εξεταζόμενοι τύποι συστημάτων σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία.*

3. Στους προαναφερόμενους τύπους σκιάστρων ενσωματώθηκαν φωτοβολταϊκά πλαίσια, ώστε να διερευνηθεί η δυνατότητα εξοικονόμησης ενέργειας από τη μέγιστη παραγωγή ενέργειας ανάλογα με τη γεωμετρία του σκιάστρου. Επαναξιολογούνται όλοι οι τύποι με βάση την παραγωγή ενέργειας, με βάση τις απαιτήσεις για τεχνητό φωτισμό σε σχέση με την μείωση του φυσικού φωτισμού και με βάση την ενέργεια για θερμική άνεση. Η παραπάνω αξιολόγηση γίνεται για τις κλιματικές συνθήκες της Αθήνας και των Χανίων με τη χρήση του λογισμικού Energy Plus όσον αφορά τη θερμική συμπεριφορά, ενώ για τον υπολογισμό των συνθηκών οπτικής άνεσης και παραγωγής χρησιμοποιείται το λογισμικό Ecotect. Τα συστήματα σκιασμού διαχωρίζονται σε συστήματα που επιτρέπουν την οπτική επαφή με το εξωτερικό περιβάλλον (Εικ. 0.2.3). και σε αυτά που με την αδιαφάνεια τους δεν επιτρέπουν την άμεση επαφή με αυτό (Εικ. 0.2.4).



Εικ.0.2.3. *Εξεταζόμενοι τύποι συστημάτων σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία που εξασφαλίζουν επαφή με το εξωτερικό περιβάλλον*



Εικ.0.2.4. *Εξεταζόμενοι τύποι συστημάτων σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία που δεν εξασφαλίζουν επαφή με το εξωτερικό περιβάλλον*

4. Στην παρούσα έρευνα δόθηκε έμφαση στην αξιολόγηση του φυσικού φωτισμού και του τρόπου εξαγωγής των αποτελεσμάτων των επιπέδων του στο εσωτερικό. Μετά από συστηματική βιβλιογραφική έρευνα και συλλογή στοιχείων για τον τρόπο διεξαγωγής πειραμάτων μετρήσεων φυσικού φωτισμού κατασκευάστηκε φυσικό μοντέλο μονάδας κτιρίου γραφείων στο οποίο υπήρχε η δυνατότητα να προσαρμοστούν οι δεκατρείς εξεταζόμενες όψεις που φέρουν τα εξεταζόμενα συστήματα σκιασμού. Τα συστήματα σκιασμού κατασκευάζονται με τις διαστάσεις φωτοβολταϊκών πλαίσια του εμπορίου, οπότε η νέα γεωμετρία εξετάζεται με βάση τα επίπεδα φυσικού φωτισμού στο εσωτερικό τις μονάδας.

Έξι (6) ειδικοί αισθητήρες τοποθετήθηκαν σε κάναβο στο εσωτερικό του μοντέλου. Αισθητήρας φωτός έχει τοποθετηθεί στο εξωτερικό της μονάδας που μετράει την λαμπρότητα του ουρανού. Όλοι οι αισθητήρες ήταν συνδεδεμένοι με μονάδα αποθήκευσης δεδομένων (datalogger). Πραγματοποιήθηκαν τέσσερις (4) σειρές πειραμάτων: δύο (2) για το χειμερινό ηλιοστάσιο, μία σειρά για θερινό ηλιοστάσιο και μία σειρά για την Ισημερία. Οι μετρήσεις έγιναν σε πραγματικό ουρανό για την περιοχή των Χανίων.

5. Τέλος σε όλα τα συστήματα σκιασμού εφαρμόστηκαν σε πραγματικά φωτοβολταϊκά πλαίσια του εμπορίου και μετρήθηκαν οι αποδόσεις τους σε σχέση και με τα θεωρητικά μοντέλα.

Η πρωτοτυπία της έρευνάς της επικεντρώνεται στα παρακάτω σημεία:

- Στον ενεργειακό σχεδιασμό και αξιολόγηση, σε σχέση με την εξοικονόμηση ενέργειας, μίας σειράς σκίαστρων με ενσωματωμένα φωτοβολταϊκά στοιχεία κατάλληλων για το Μεσογειακό Κλίμα
- Την αξιολόγηση των συνθηκών οπτικής άνεσης που μπορούν να εξασφαλίσουν οι συγκεκριμένοι τύποι σκιάστρων με ενσωματωμένα φωτοβολταϊκά στοιχεία, ανάλογα και με τη γεωμετρία του ενσωματωμένου φωτοβολταϊκού και
- Την αξιολόγηση διαφορετικών μεθόδων υπολογισμού της παραγωγής ενέργειας και των συνθηκών οπτικής άνεσης ανάλογα με το στάδιο του σχεδιασμού που απαιτείται.

Συμπεράσματα:

- Ο τρόπος που ενσωματώνονται τα PV μπορεί να αλλάξει με τη χρήση των σκιάστρων ως μηχανές παραγωγής ενέργειας.
- Όλα τα συστήματα μπορούν να καλύψουν τις ανάγκες για τεχνητό φωτισμό και για τα δύο ΓΠ.
- Κανένα σύστημα δεν μπορεί να καλύψει όλες τις ενεργειακές ανάγκες για θερμική άνεση.
- Το σύστημα του **«περίκλειστου σκιάστρου»** είναι το μόνο που πλησιάζει την παραγωγή των ενεργειακών αναγκών για θέρμανση ψύξη και φωτισμό.
- Το ίδιο σύστημα έχει και τις λιγότερες ανάγκες για θέρμανση, ψύξη και φωτισμό. Ενώ ακολουθούν ο **διπλός κεκλιμένος πρόβολος** και τα **Brise Soleil** συστήματα.
- Από τα βέλτιστα παραπάνω συστήματα το σύστημα **διπλός κεκλιμένος πρόβολος** και **το περίκλειστο σκιάστρο** είναι τα οικονομικότερα από άποψη

κατανάλωσης και παραγωγής ενέργειας σε σχέση με την επιφάνειας του εγκατεστημένου PV.

- Το **Περίκλειστο σκίαστρο** και ο **διπλός κεκλιμένος πρόβολος** εξασφαλίζουν καλές τιμές UDI, αλλά αυτός ο δείκτης δεν μπορεί να μας δώσει αξιόπιστα αποτελέσματα για την οπτική θάμβωση.
- Τα **Brise Soleil συστήματα** και ο **διπλός κεκλιμένος πρόβολος** εξασφαλίζουν συνθήκες οπτικής άνεση μόνο σε περιοχές μακριά από την φωτεινή πηγή (δηλ. σε απόσταση από το άνοιγμα). Ενώ το σύστημα του **περίκλειστου σκιάστρου** εξασφαλίζει συνθήκες άνεσης για περιοχές κοντά στο άνοιγμα.
- Από όλα τα συστήματα ο **διπλός κεκλιμένος πρόβολος** φαίνεται να έχει τις περισσότερες πιθανότητες να μπορεί να ανταποκριθεί ικανοποιητικά στα ζητήματα που τέθηκαν με την παρούσα έρευνα.
- Όσον αφορά την αξιολόγηση της οπτικής άνεσης, για το επίπεδο προμελέτης τα απλά εργαλεία μπορούν να μας δώσουν αξιόπιστα αποτελέσματα όσον αφορά μόνο τα επίπεδα του φωτισμού και την κατανάλωση ενέργειας. Όταν όμως απαιτείται αξιολόγηση της ποιότητας του φωτισμού και της οπτικής άνεσης εξειδικευμένα εργαλεία απαιτούνται ενώ θα πρέπει ο σχεδιασμός να έχει φτάσει σε επίπεδα λεπτομέρειας. Τα φυσικά μοντέλα μπορούν επίσης να χρησιμοποιηθούν αλλά θα πρέπει να έχουν αποφασιστεί οι λεπτομέρειες του σχεδιασμού (πχ. διατομές σκίαστρων, απόσταση του σκιάστρου από το άνοιγμα, εσωτερικά τελειώματα κτλ).
- Το φυσικό μοντέλο με τη χρήση φυσικού ουρανού υπερεκτιμά τα επίπεδα φωτεινότητας και η υπερεκτίμηση αυτή μπορεί να φτάσει και μέχρι 90% για μοντέλο κλίμακας 1/10. Η απόκλιση αυξάνεται όσο υπάρχει άμεση ηλιακή ακτινοβολία (για χαμηλό ύψος ηλίου και θέσεις κοντά στο άνοιγμα). Για μετρήσεις φωτεινότητας το φυσικό μοντέλο είναι απαραίτητο εργαλείο για τον Αρχιτέκτονα – Σχεδιαστή παρόλο που μπορεί να οδηγήσει σε υπερεκτίμηση φωτισμού
- Για την παραγωγή της ενέργειας απλά εργαλεία μπορούν να χρησιμοποιηθούν όταν το ζητούμενο είναι συγκριτικά αποτελέσματα και όχι απόλυτες τιμές.

- Τα συστήματα των περσίδων δεν λειτουργούν θετικά όσον αφορά την παραγωγή και την κατανάλωση ενέργειας ούτε όσον αφορά τις οπτικές συνθήκες. Αυτό οδηγεί στην επανατοποθέτηση μας σε σχέση με αυτά τα συστήματα που κατά κόρων χρησιμοποιούνται σε κτίρια γραφείων.
- Για αρχικά στάδια σχεδιασμού και συγκριτικές μελέτες βασικά εργαλεία μπορούν να οδηγήσουν σε αξιόπιστο αποτέλεσμα. Για πολύπλοκες γεωμετρίες όπως αυτές των συστημάτων με περσίδες, απλά εργαλεία δεν μπορούν να χρησιμοποιηθούν. Για την αξιολόγηση απλών γεωμετριών σκιάστρων με ενσωματωμένα φωτοβολταικά απλά εργαλεία μπορούν να δώσουν αξιόπιστα αποτελέσματα σε απλές γεωμετρίες.

Βασικοί προβληματισμοί που τίθεται μετά από τη συγκριτική αξιολόγηση των συστημάτων σκιασμού με ενσωματωμένα φωτοβολταϊκά στοιχεία:

Απαιτείται ο επαναπροσδιορισμός των συστημάτων σκιασμού ως πολύτιμες ενεργειακές μηχανές.

Λόγω του ότι οι περσίδες είναι σύστημα που επιλύει τον επαρκή σκιασμό για μεγάλο εύρος της ημέρας και ως αρχιτεκτονική πρόταση συνδέεται με την ενιαία όψη, επιθυμητή στα συγκροτήματα γραφείων, η επανεξέταση τους όσον αφορά την αύξηση της παραγόμενης ενέργειας τους, αποτελεί σημαντικό μελλοντικό ερευνητικό έργο.

Για την ολοκληρωμένη αξιολόγηση της ενσωμάτωσης των φωτοβολταϊκών στοιχείων στα συστήματα σκιασμού περαιτέρω έρευνα απαιτείται όσον αφορά την αποδοχή αυτών των συστημάτων από τους χρήστες των κτιρίων γραφείων.

Περαιτέρω οικονομοτεχνική ανάλυση απαιτείται σε σχέση με την εξοικονόμηση ενέργειας, το κόστος της κατασκευής και τη διάρκεια ζωής τέτοιων συστημάτων.

Η ανάπτυξη λογισμικών εργαλείων που θα ενσωματώνουν μία τέτοιου είδους πολύ-επίπεδη έρευνα σε σχέση με την εξεύρεση βέλτιστων συστημάτων ανάλογα με το εκάστωτε Γ.Π., την επιθυμητή οπτική και θερμική άνεση και την εξοικονόμηση ενέργειας μπορεί να αποτελέσει ένα επόμενο ερευνητικό πεδίο, που θα ενσωματώσει και την παρούσα έρευνα.

Part I

1.0. Introduction

The issue of energy balance in buildings has a significant importance nowadays, since conventional energy sources are running out and become extremely expensive. In addition to the development of environmentally friendly design as a basic requirement for the new EU directives, the above mentioned facts are the main reasons for establishing passive design of buildings as one of the most crucial and fundamental factors in buildings' energy savings. Basic environmental design parameters should be carefully implemented in the overall design decisions.

A building's skin is the design element that has to balance all environmental dynamics between interior and exterior. Transparent and opaque materials, the openings and the walls, affect absorption, reflection and transmission of solar and thermal radiation to the interior. Control of this amount of solar energy is one of the most crucial factors for the building's environmental balance. In opaque façade materials, radiation control is incorporated within their insulating and reflectivity properties. Concerning transparent façade elements though, radiation control becomes a much more delicate subject due to the vulnerability of these elements to radiation. According to Givoni (1969, p. 213) "heat gain through a sunlit glass is many times higher than through an equal area of an ordinary wall".

Sun control "machines", or shading devices, play a major role in the control of incident solar and thermal radiation for transparent elements. Their geometry, their position in relation to glazing, their operational strategy (in the cases of movable systems), permit the control of heat and light entering the building. Material and color are additional parameters influencing their final performance. Additionally, sun control machines, determine the aesthetics of the façade and constitute an expression of the architectural language of the designer.

"*The architectural appearance of sun control is not an effect in itself- it is the result of several other developments*" (The AmericanNautical Almanac, 1963; Olgyay, 1963, p. 6).

The fundamental geometric rules for effective Shading Design derive from the necessity of preventing direct solar radiation from entering the interior. Olgyay A.&V. (1957) developed these rules since 1957: they have been integrated in algorithmic relations which were subsequently incorporated in computer applications, in order to create various technically correct geometrical configurations. In any case, the decision for the final geometric configuration is proposed by the designer. It is what Olgyay argues about in his book "Solar Control and Shading Devices": "*This is the line where the technical method ends and creative expression takes over*". By the time Olgyay was arguing about this subject, building technology science was in its infancy. Since then, a variety of factors started to influence the geometry of shading devices (SDs). The balance between heating and cooling loads, control of diffuse radiation, visual and the thermal properties of the glazing used, required daylight environment according to the user task, energy balance between electric light needs and cooling loads are additional factors currently taken into account for the design of SDs.

1.1. Problem definition – Objective of the research

The main objective of this research is to resolve an energy balance contradiction that originates from fixed shading devices: the simultaneous reduction of a building's cooling loads and the increase of its electric light needs due to the reduction of incident solar radiation. A response to this contradiction has been introduced by movable shading systems that are able to adapt to different weather conditions and sun position, and consequently optimize the above mentioned energy balance by means of their controllable nature. But the disadvantages of implementing external movable shading systems are quite a few. The most important are the high degree of maintenance needed, the low degree of users' acceptance due to their frequent changeability especially in office buildings and the high cost of their installation.

In order to balance the positive effect of the decrease of cooling loads that fixed SD accomplish and the negative effect of the increase of electricity needs for lighting and thermal comfort, the solution of electricity produced through integrated PV systems has been examined as a potential energy balance solution for various SDs geometries.

Building-integrated PV systems have been introduced in the market since the 1980's. During this time, integration of PV systems in shading devices was proposed as an energy efficient and economic solution. This is due to the fact that by a single building element both energy reduction and energy production can be achieved.

PV integrated in shading systems can overcome the reduction of daylight that fixed shading systems impose by producing the electricity needed for the electric light. At the same time though, PV integration can cause less daylight availability than simple Shading systems. We found that all shading systems examined, are efficient enough and can cover the electricity needs to light an office unit, for the periods that daylight is falling under 500 lux. We compared all SD with integrated PV with shading systems of simple glazing.

The research focuses on a typical office building unit. This is due to the fact that office units have very specific requirements of daylight levels according to the task of the users and according to the position of the subjects in relation to the opening. Additionally, nowadays, office work is done everywhere. People work everywhere, at a waiting hall, at the station or at home. Every building is a potential office. Shading systems providing comfortable working conditions with less energy are essential for sustainable buildings.

We evaluated the performance of SDs with integrated PV facing south in relation to the electricity needs and the electricity production of the office unit that they shade. The electricity needs are calculated for the worst case scenario of the minimum requirement of 500lux at the desk level and the average daylight autonomy for the whole year. Most of the SDs examined are typical external fixed systems for south orientation of office buildings. For most of them, the metrics of their basic geometry correspond to the exclusion of direct solar radiation entering the office during the overheated period (1^{st} of June till 24^{rth} of August from 11:30 to 13:30 solar time). Due to the symmetrical movement of the sun around the summer solstice though, for the above mentioned desired shading period the opening is actually shaded from the 18th of April till the 24rth of August even if the overheated period starts later on. This is the main disadvantage of fixed shading systems: They decrease the useful solar radiation during the time period that it is actually needed.

As a next step for the design of the SDs examined, we developed all systems according to aesthetical rules and with the idea that the examined office unit is part of a high rise building and consequently it is repeated horizontally and vertically.

On top of the effective various horizontal louvers solutions, we additionally examined a vertical louvers shading system although it is not appropriate for south orientation. This was done, because very often all building facades are treated in the same way by the architect, meaning that the same shading system is incorporated in all orientations. We examined the advantages and the disadvantages of this system when used for south orientation in relation to other more suitable south facing shading systems. Sometimes, architects follow the most aesthetically acceptable solution for potential shading, thus sacrificing part of the energy savings. By evaluating vertical louvers SDs facing south we were able to quantify these losses and compare them with other, more appropriate systems for south orientation.

All shading systems are evaluated according to three factors:

- The energy consumption for thermal comfort of the office unit they shade
- The energy consumption for the amount of electric light needed into the office unit in order that visual comfort is achieved, and
- The energy production that integrated PV provide

In order to achieve the evaluation of the SDs besides basic equations, two main tools were used: digital models imported in simulation software and measurements taken from physical models. The comparison of the above mentioned methods, in relation to the results achieved, has been one of the main questions of this research. The simulation tools we used are considered appropriate for each particular case and are already validated. We searched for simple and accurate tools that designers can use in order to take decisions concerning suitable geometrical configurations able to support the sustainability of their project. We searched for appropriate tools that can be used in the early design stage, when structural details are to a large extend undefined.

Two are the main objectives of this research:

- Evaluation of shading geometries with integrated PV in terms of energy savings
- Determination of the limitations and possibilities of each assessment method used in relation to the level of the design stage (early design stage- detail design stage)

The originality of the research is supported by the fact that it focuses in the specific conditions of Mediterranean climate. We chose two different latitude points, one in Athens (37.85^{o} N) and another in Chania (35.30^{o} N). Both are coastal areas, typical examples of Mediterranean climate. This climate is characterized by mild winters with high solar radiation, long daytime and hot summers. The basic geometry of shading systems follows a concept of "protection" from hot summers.

1.2. Problem Solving Approach – Methodology

Methodologically the work is divided into two main parts: The first part is a bibliography research that concerns firstly the performance of different types of SDs in relation to thermal and visual comfort, secondly the performance of shading systems with integrated PV, and thirdly the assessment methods used to evaluate that performance. The second part consists of experimental work with the use of physical models, together with simple and more complex simulating tools to evaluate the energy needs, daylight levels and quality, and the energy production for a reference office unit with different shading systems (Fig. 1.1).

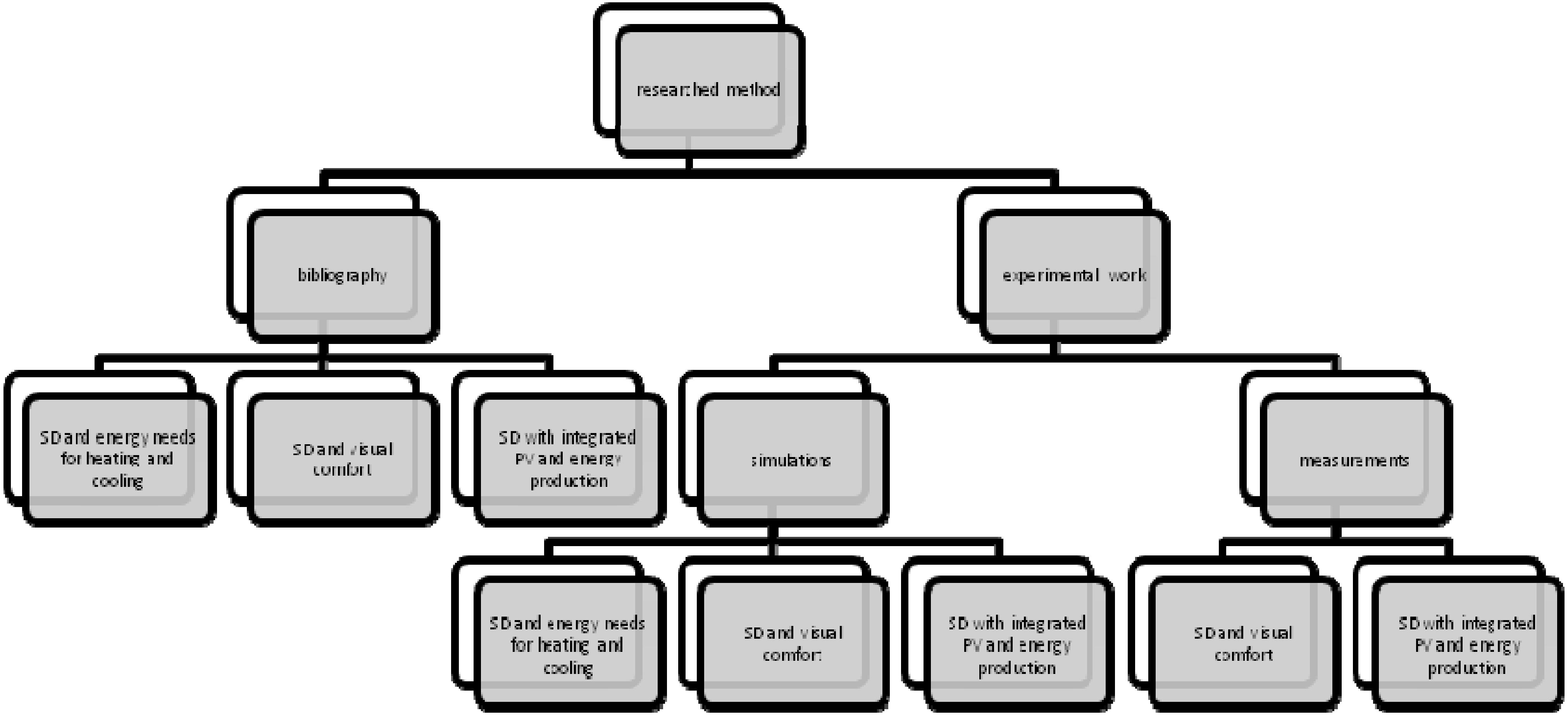


Fig. 1.1. *Methodological diagram*

The research's approach focuses on the effectiveness of the methods used. We examined the balance between simple evaluating tools and more accurate complicated ones. We searched for the optimum combination of simple and accurate tools that we can use for assessing basic geometrical configurations and different color and material properties.

Designers need these types of tools in order to evaluate their design. They need easy, user friendly tools that can be used from the early stages of the design process and provide a comprehensive image of the resulting conditions. This is one of the main reasons why we constructed scaled physical models and tested them in real sky conditions in order to evaluate daylight levels. The accuracy of this daylight measuring method has been questioned by various researchers, due to the rapid changeability of the sky and due to the need for detailed representations of the model.

We used physical models in order to assess the daylighting performance of various SDs and our main interest is not the values of daylight at each point in space but rather the relations between these values at the same interior points examined with different shading systems.

A new way of evaluating the performance of SD is introduced. It is based on the comparison between the heating and cooling energy needs of the office module examined, whose transparent south window is shaded. It has to be noted that the additional cooling and heating loads that each system demands in order to keep thermal comfort levels (18^o to 26^o C) are also being considered.

Further on an additional parameter of energy savings from the use of daylight has been examined. We calculated daylight autonomy and the percentage of the time of the year that electric light is needed. We assumed that a continuous electric light dimming strategy is used. According to Vartiainen (1998), this system helps diminish electric light needs.

For the evaluation of daylight quality conditions we used validated simulating tools. We additionally constructed 1/10 scale physical models in order to evaluate the intricacies of the behavior of daylight and the relation between simulated sky to real sky conditions. The results of these comparisons between measured and simulated data are further connected to the daylight performance of each SD in real buildings.

We focused on daylighting measuring methods and factors, in order to assess different daylighting environments. Simplifications in the calculating process and factors used can lead to unrealistic results. In order to avoid randomness in the results all SDs are examined for two window sizes for each one the two latitudes.

In order to confront the main disadvantages of fixed SDs, the SDs examined were at the same time considered both as energy reducers and energy producers. The question arising is whether they can reach zero energy impact. This means that the reduction of daylight and the increase of heating loads can be covered by the electricity produced by the integrated PV.

One of the basic constrains of PV integrated systems is concentrated in the fact that PV modules do follow specific geometrical rules. One of them is the thickness of the opaque PV panel (3 cm), another is the maximum number of PV panels connected in series. This is the main reason why all integrated PV systems are examined in relation to real PV market products.

1.2.1. Basic assumptions

Different simple fixed SD geometries have been examined, designed to exclude direct solar radiation during the overheated period for the latitude of Greece.

In order to avoid extreme glare problems, especially during the winter period when the sun angle is low, one basic assumption was taken into account: the office desk is placed 60 cm away from the façade where the ratio between the vertical to the horizontal illuminance is lower than 20 (Kittler et al., 2009). This factor is indicative of an uncomfortable daylight environment.

We calculated the average daylight values of daylight autonomy according to the weather data of Athens and Chania, Greece. In the case of Chania the values are reevaluated with physical model measurements. We found differences in values measured with the two methods, and we validated these differences in bibliography.

We used the reference office of task 27 (Van Dijk, 2001) for all measurements and calculations. We took all material and color of the interior environment from the same research.

We constructed the physical model from wood in order to represent the inner space of the office unit, carefully following instructions for constructing physical models for measuring daylight performance. We tinted the inner surfaces with color of the same properties of these followed by Van Dijk (2001). The similarities in reflectance were verified using spectrophotometer.

The PV modules were simulated with Plexiglas of dark blue color. The model was built following the worst case scenario of 3 cm thick PV so all PV surfaces in the model are constructed from 3mm Plexiglas in scale 1/10.

Two basic facts led us to test the physical models in real sky conditions: The first was the need for realistic sky and sun conditions in order to approximate daylighting of the real building. The use of physical model and its relation to real sky condition is a familiar tool for architects. In physical models daylight quality can be evaluated. The second was the need to compare the two methods of evaluation: the validated simulation application "Radiance" and the use of physical models for daylight measurements without the use of sky simulators. We assessed these methods in relation to the desirable design stage. Simple computer applications can be used in the early design stage while physical modeling can be used in the detailed design stage when almost all decisions concerning finishing and colors have been made.

Additionally we have to mention at this point that we do not compare the values of illuminance measured in the physical model and the computer simulation application. We do a comparative analysis and not an absolute value analysis in order to assess different SD geometries. This is due to the fact that physical models and simulation tools calculate different absolute values of illuminance that are related to real values with unique relations.

Finally in order to further examine the influence of the integration of PVs in visual conditions and energy demands of the interior, we examined two different market PV products for the cases of Louvers Shading systems: market PV panels with metal frames with an overall thickness of 3cm and glass louver systems with integrated PVs with an overal thickness of 1.5 cm. In both systems PV technology is the same: mono crystalline PV cells. The exact brand of the market products of framed PV used are presented in chapter 5 (Fig.5.18). The technical data for the glass louvers systems are borrowed from Schuco PorSol PV shading systems. The technical data are presented in the Appendix. The main difference of these two types of PVs is their appearance and their geometry in terms of their thickness. The thickness of a thin – film PV module is smaller (1.5 cm) because the modules are integrated in a double glazing panel. The width of the framed PV is 3 cm due to the average width of its supporting skeleton. The factor of the thickness affects the final internal visual and thermal conditions.

1.3. Thesis outline

In the following diagram we present the outline of the Thesis (Fig.1.2.):

The first chapter is dealing with the introduction to the research problem in question and the solving approach followed.

The second chapter presents the basics of Shading Design, the evolution of shading through time and the methods of evaluating appropriate shading systems according to simple geometrical rules.

In the third chapter the geometrical and material properties of the shading system in relation to thermal gains, are presented.

The fourth chapter introduces the basics of shading design in relation to both daylight quality and energy savings, through decreasing the amount of electric light needed. More specific requirements for the case of office building are being described.

In the fifth chapter the additional parameters of energy production that shading systems with integrated PV can support are presented. In this chapter we present limitations and constrains of the integration of PV influencing the energy production.

In the sixth chapter the combined approach is being presented. This approach deals with energy balance for thermal and visual comfort in relation to the energy production through the integrated PV systems.

In the seventh chapter we present the overview of the Thesis and the general conclusions related to the evaluating methods, the design stage and the potential of integrating PV in shading systems.

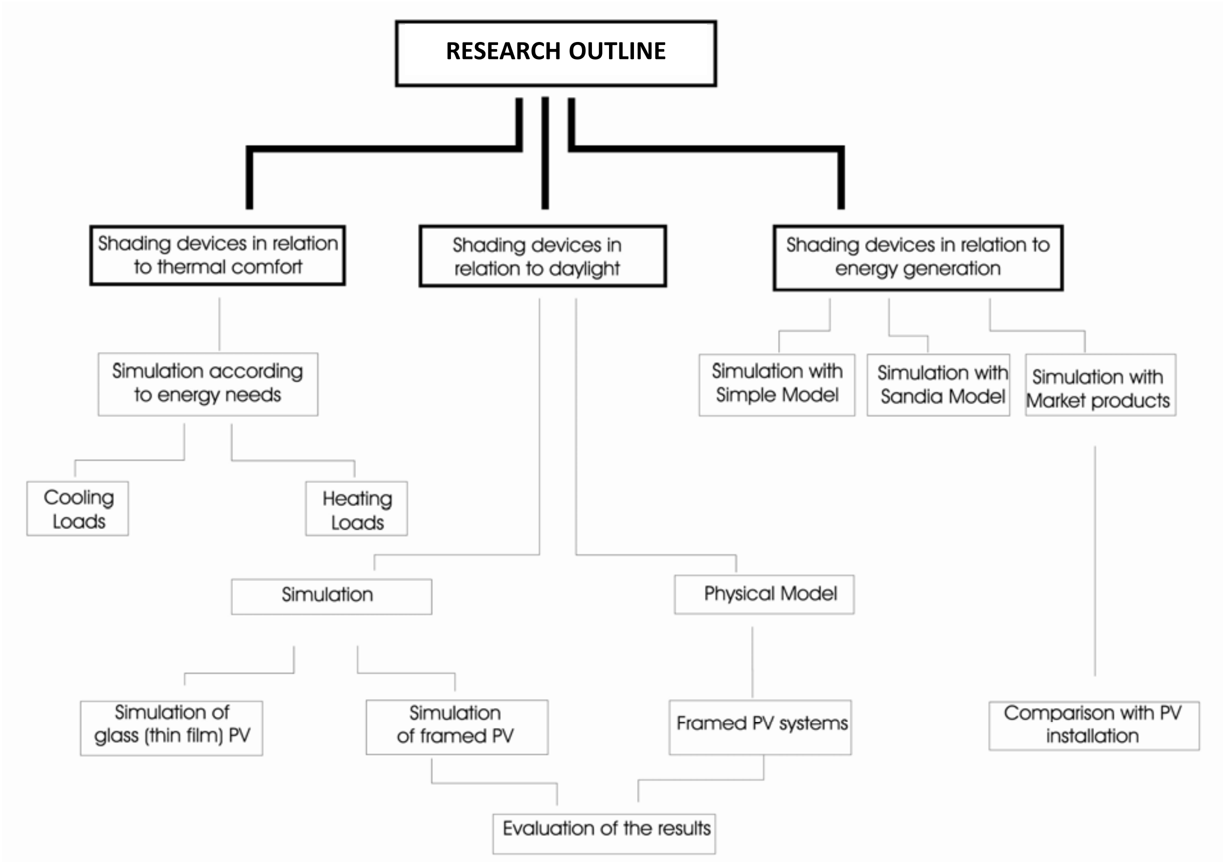


Fig. 1.2. *Thesis outline*

2.0. Design of shading systems: The basics

2.1. Introduction

Shading systems play a major role in buildings' aesthetics and energy performance. For this reason they are the focus of interest from various architects from their role as designers and researchers. Shading systems have proved to be a strong element of architectural expression. They are mostly positioned on the outside of the building and greatly define its appearance. They constitute an "outer skin" which determines, besides aesthetics, its interior environmental conditions according to technical specifications.

"The transition from masonry wall to skeleton buildings created new possibilities of expression in design elevations" (Olgyay, A. & V., 1957). Over the last few decades the transparent fraction of the buildings' envelope has increased. Thus the need for shading has increased and shading systems have become much more important for the building's final aesthetics.

It is crucial at this point to clarify the basic functions of shading systems and their role to the building's energy balance and interior comfort conditions. There are two main requirements for an effective Solar Shading: a. to significantly reduce solar gains during the cooling period while increasing solar gains during heating season and b. to ensure that there is sufficient and comfortable daylight in the interior of the building.

The basic functions of shading systems are the following:

- To minimize total solar energy entering the room and reduce the average temperatures

- To prevent sunlight from falling directly upon occupants (which would result in an increase of temperature between 3^o C to 7^{o}C)
- To reduce the illuminance of interior surfaces which are potential glare sources for the occupants
- To take off sight brightly lit outside surfaces, or the sun itself (Baker & Steemers, 2001)

A fundamental principle concerning sunlight is that it consists of two inseparable measures: heat and light (Baker & Steemers, 2001). Sunlight can also be viewed as electromagnetic radiation, in visible and invisible form (infrared and ultraviolet band respectively) (Fig.2.1). When that radiation (visible or invisible) heats a surface it is then absorbed by it, and converted into heat (Fig.2.2). When studying lighting we are interested in the visible part of the electromagnetic radiation of sunlight; however this part of electromagnetic radiation carries only half of the energy that potentially can become heat (op.cit).

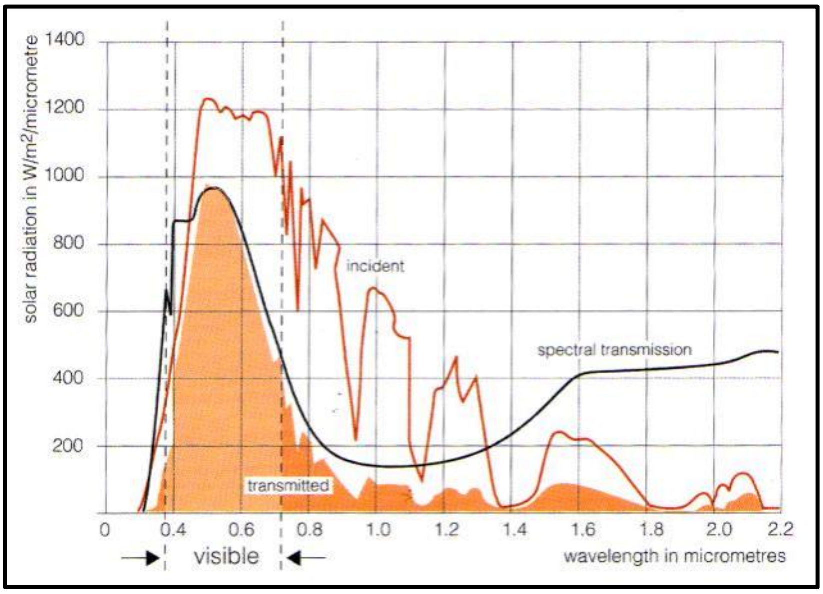


***Fig.2.1.** The radiation spectrum of sunlight: about one half of the energy is in the visible region, the remainder is found in the infrared and ultraviolet zone. The transmission curve of the clear glass shows that some of the invisible radiation is absorbed by the glass.*
(Baker & Steemers, 2001, p. 110)

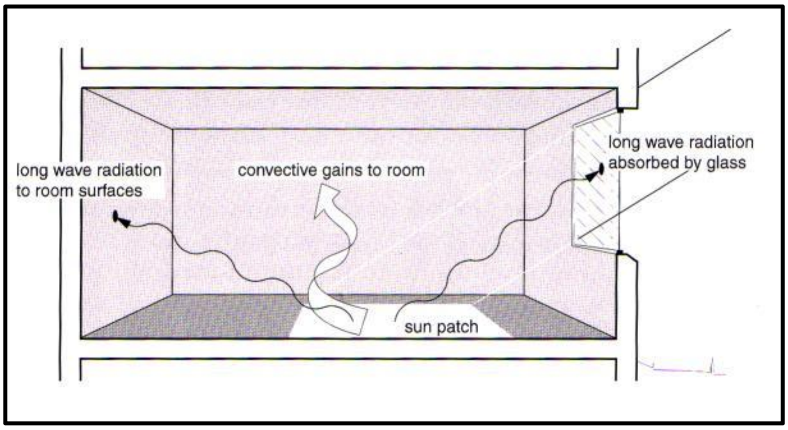


Fig.2.2.*The mechanism of solar heat gain: short wave radiation transmitted through the glass and absorbed by the surfaces in the room, where it is converted to heat. The glass is opaque to long wave radiation from warm surfaces. The rooms' surfaces also lose heat to the air by convection. The process is called "the greenhouse effect".*
(Baker & Steemers, 2001, p. 110)

Based on the facts above we understand how crucial are transparent parts of the façade in terms of heat gains and losses. Shading systems and their role as protective sun machines are influencing heat gains according to their geometrical configuration and their material. That is the reason that we examined the performance of different shading systems according to the energy needed for heating, cooling and lighting the office unit they shade in order to deliver acceptable thermal and visual comfort. We additionally examined the performance of shading systems as energy producers by an integrated active system (PV's in our cases).

In summary the aim of this research is the full assessment of the energy balance that the fixed examined shading systems can achieve in the Mediterranean climate. We will evaluate the energy needs for heating and cooling the shaded space and the energy needs to efficiently light the space. Additionally, we will assume that the examined shading devices are energy producing systems due to their integrated PV panels. We will balance the energy needs and the energy produced of the examined shading systems with integrated PV, in order to conclude basic geometrical configurations that can be less energy consuming.

2.2. Evolution of Solar shading through time

The issue of Solar Radiation in relation to a building's energy performance has been analyzed extensively since antiquity. According to Socrates, due to the movement of the sun, south oriented spaces can achieve a balance between cooling and heating loads. In "Memorabilia", Xenophon quoted Socrates's phrase: "In houses with a south aspect the sun's rays penetrate into the porticos in winter, but in summer the path of the sun is right over our heads and above the roofs, so that there is shade. If, then, this is the best arrangement, we should build the south side loftier, to get the winter sun, and the north side lower, to keep out the cold winds...presumably simultaneously the pleasantest and most beautiful arrangement".

Many large shading systems have the dual purpose of shading the interior space and creating an outdoor shaded space. The portico and the colonnades of the ancient Greek and Roman buildings can obtain shading of the facade as well as provide shaded outside spaces. Neoclassic architecture, besides its symbolic and aesthetic dimensions, was an architecture that could be successfully adapted to hot and humid climates. The need for big windows that allow ventilation is crucial for the reduction of the inner humidity but at the same time big shading systems were needed for sun protection during the summer periods (Fig.2.3).

Fig. 2.3. *The Hermitage, Andrew Jackson's home near Nashville, Tennessee, USA.*
(Lechner, 2001, p. 202)

If one would look on shading systems all around the world, he would find almost the same systems in similar climates. The Greek portico mentioned above is similar to the porch, veranda (found in India), balcony, loggia (in Italy), gallery, arcade, colonnade, and engawa (in Japan) (Lechner, 2001).

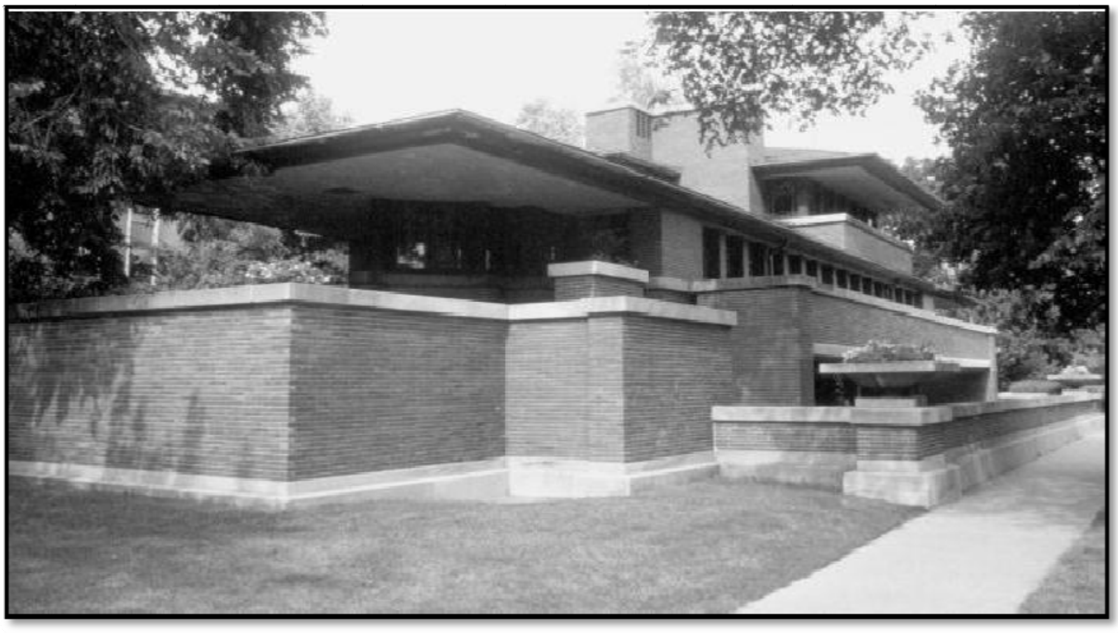


Fig. 2.4. *Large overhang of the Robbie House, Frank Lloyd Wright, Chicago, 1909*
(Lechner, 2001, p. 205)

Many architects understood the importance of shading by observing vernacular architecture in the areas that they were going to build. Frank Lloyd Wright used shading strategies in most of his buildings. In the Robbie House, he used large areas of glazing to maximize daylight and ventilation for the hot and humid Chicago summers. At the same time he used very long cantilevered overhangs to shade these glazings so as to create strong horizontal lines that also reflect the nature of the region (Fig.2.4) (op. cit.).

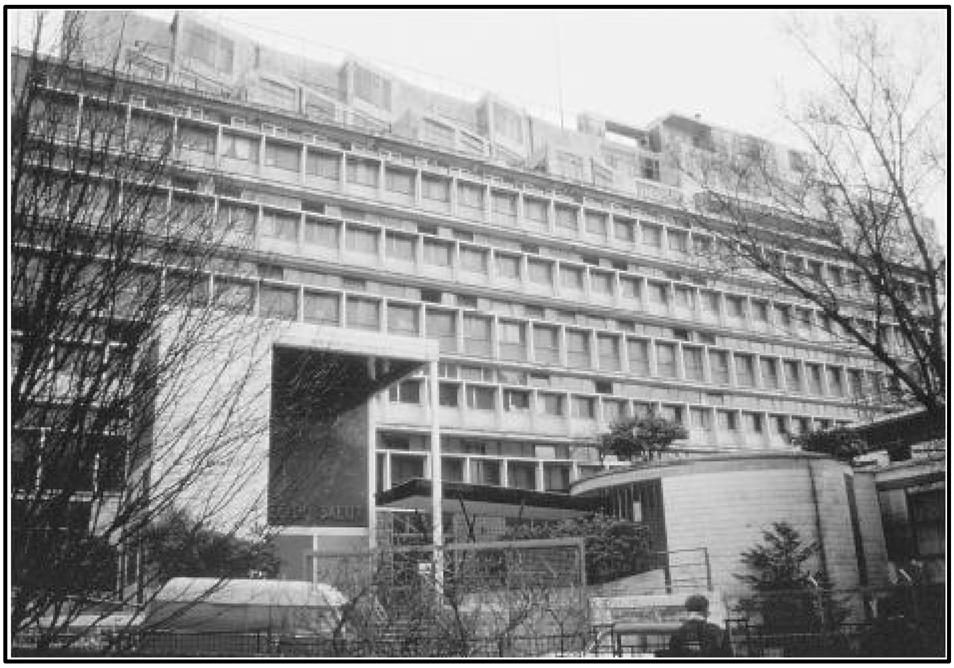


Fig.2.5. *The Brise soleil system. Le Corbusier,* Cité de Refuge, Paris, 1932
(Lechner, 2001, p. 206)

Le Corbusier is very much related with the aesthetics based on the solar shading. In his multi-storey building of Cite De Refuge, in Paris, one can trace his first attempt to design the Brise Soleil System. The building was designed with large glazed areas facing south without any shading, to allow plenty of sunlight in and to warm and cheer the residents. In winter the system performed well but in the summer it proved to be extremely hot. In order to solve this problem Le Corbusier invented the Brise Soleil (sun – breaker) or Eggcrate system (Fig.2.5). Hence Le Corbusier demonstrated the dual nature of the sun, our friend in the winter and our foe in the summer and he used this as an aesthetic opportunity of the final facade (op. cit.).

Both the geometrical characteristics of the SD, as well as geometry's relation to their performance have been extensively developed by Olgyay since 1957. He claims that the architectural appearance of the sun control systems is a result of several other developments. It is the result of the relation between the glass pane, the wall and the internal function. Their role of controlling the environmental conditions is extremely important if one considers the fact that a shaded glass transmits only about one - third (a value that depends on latitude, locality and orientation) of the heat compared to the heat transmitted by an unshaded window surface.

2.3. Types of Shading Systems

Windows have a serious impact on the indoor temperature. Heat gain via transparent elements is far greater than via massive wall systems, and this difference depends on the insulating properties of the mass systems. According to Olgyay, A. & V. (1957, p. 72), shading devices reduce the sunlight loads to one fifth of the loads that would be gained by an unshaded window (Fig.2.6).

	Sunlit	Shaded
East	1097	134
South	601	138
West	1097	134
North	305	123

Fig.2.6. Daily total Btu flowing through a square foot of single glass surface (Olgyay, A. & V., 1957, p. 72)

When shading systems are combined with areas of glazing, the interior thermal gains can be modified. One way of controlling solar gains is the use of different types of glazing, other than the single glazing (double glazing, various types of heat interrupting glazing, darkening glass). Another way to achieve this is by using solar shading systems, appropriate for the specific orientation and latitude (Fig.2.7). Shading systems can be applied externally, internally or inside the double glazing.

They can be fixed, adjustable or retractable and they are available in a variety of architectural shapes and geometrical configurations.

Internal shading devices include venetian blinds, roller blinds and curtains. They are retractable, meaning they can be lifted, rolled or moved parallel to the window. In other occasions only their inclination is adjustable. External shading devices include shutters, awnings, overhangs and louvers (horizontal, vertical or a combination of both, called Eggcrate) (Fig.2.8). Inter pane shading systems are placed between the two panes that constitute the double glazing system; they can be venetian blinds, roller shades or pleated paper (Fig.2.9). They are adjustable and retractable from the interior.

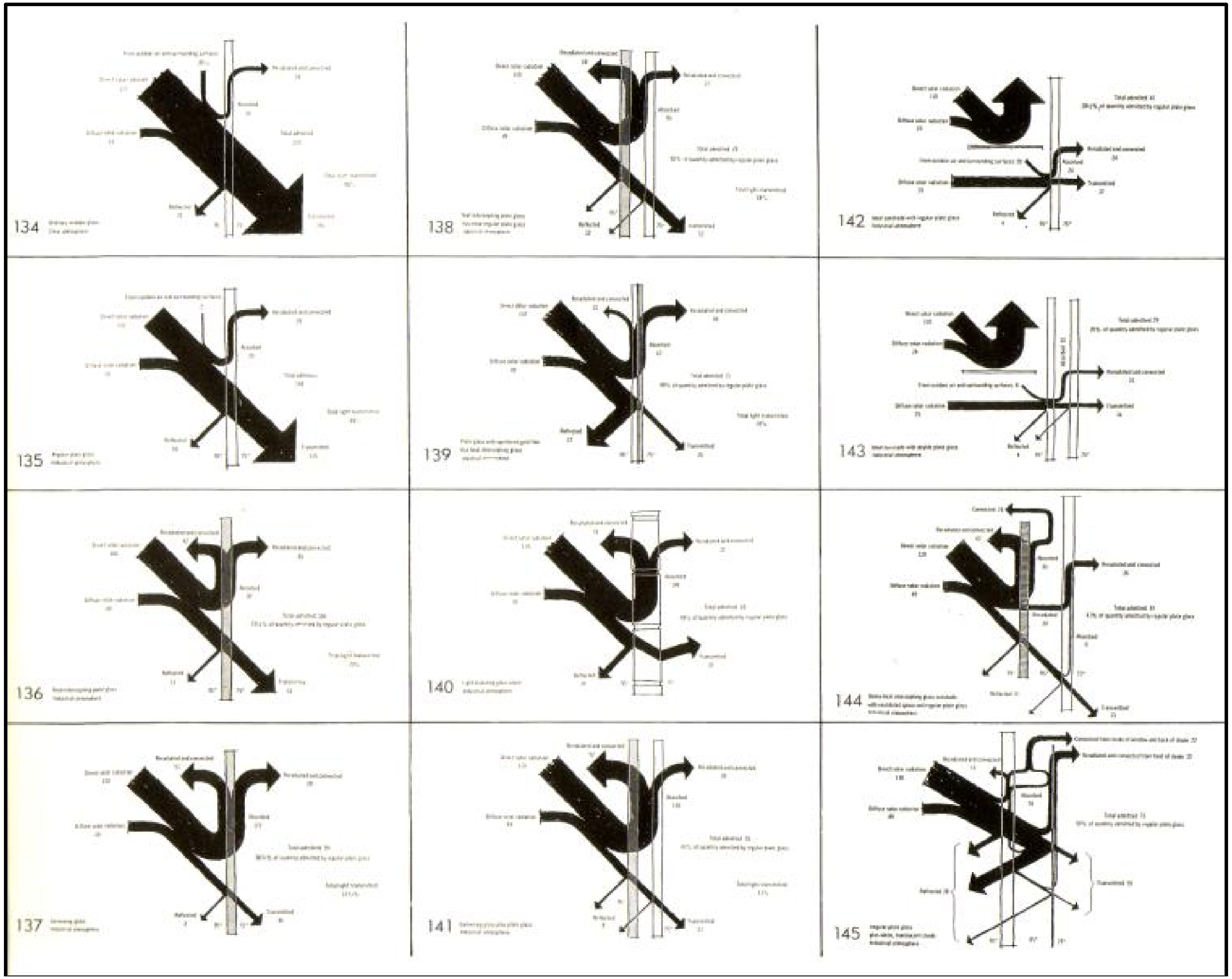


Fig.2.7. *Heat gain through different types of glass and different types of shadings* (Olgyay, A. & V., 1957, p. 71)

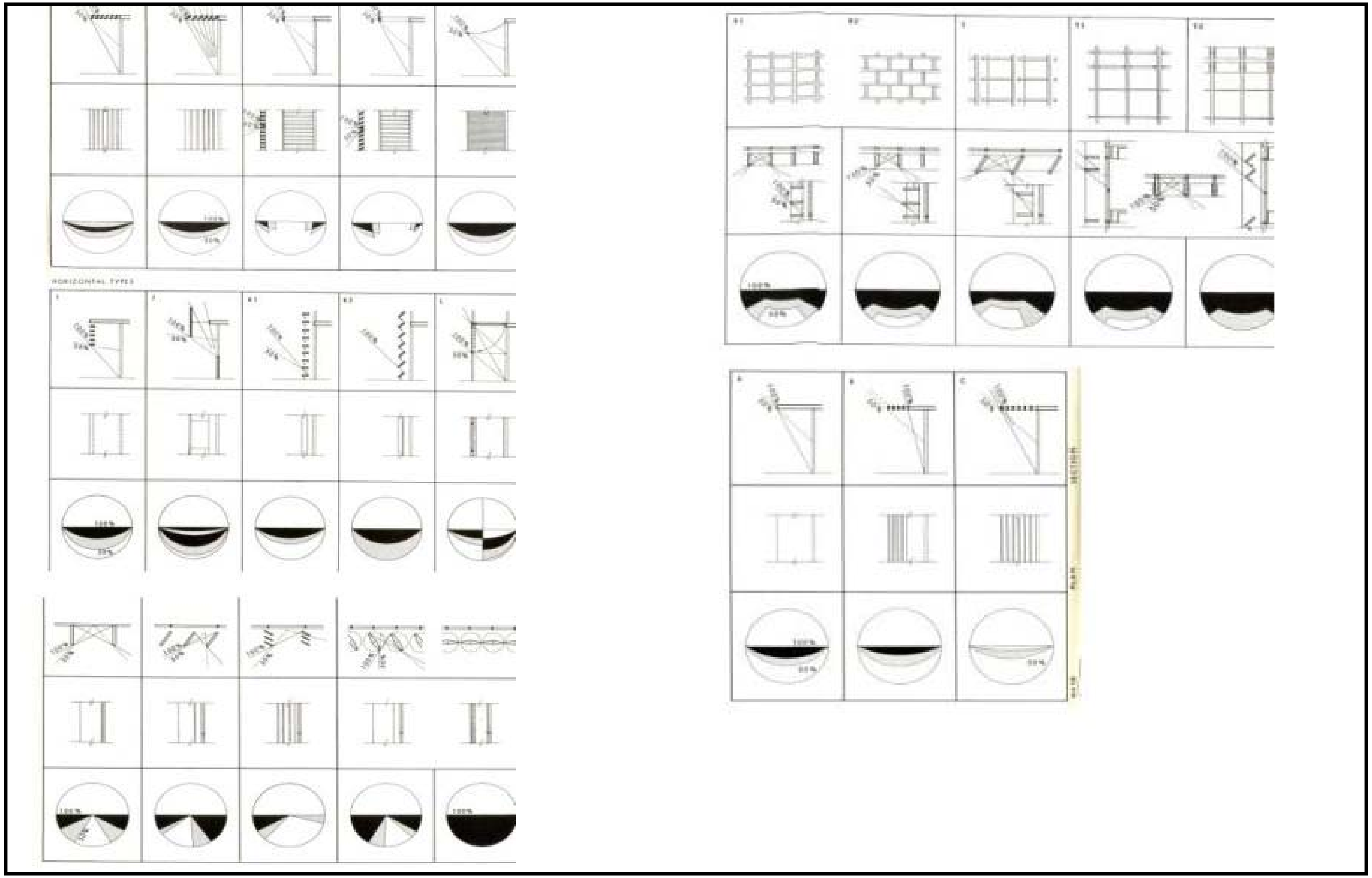


Fig.2.8. *Various types of Fixed external shading devices* (Olgyay, A. & V., 1957, pp. 88 - 92)

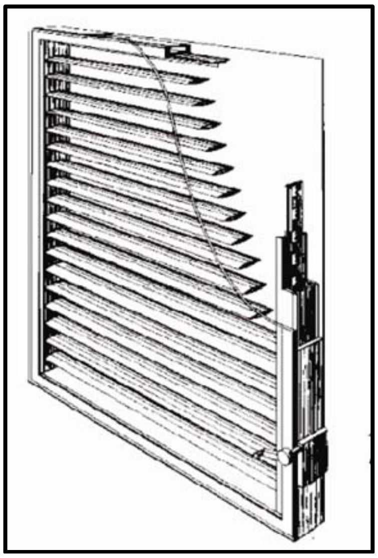


Fig.2.9. *Isometric view of an Inter-pane venetian blind system* (Olbina, 2005, p. 96)

The function of shading devices can be summarized in the following: control of heat gains during the overheated period, allowance of heat gains during the underheated period, control of daylight levels and glare, control of view to outside, and ventilation. The importance of each one of these factors varies according to climatic conditions and according to the function of the building. For a house for example, control of solar heat gains is very important during summer and winter but for an office building and a classroom both heat gains, daylighting levels and comfort are important (Givoni, 1969, pp. 213 -214).

Due to this fact we will examine the relation of the types of shading systems to both thermal and visual comfort.

2.4. Fundamental design methods and factors

Basic geometrical rules have been invented since ancient times. First, the Roman architect Vitruvius (Vitruvii, 27 - 23 B.C.) in the sixth book of his treatise "De Architectura", describes a basic geometrical method to ensure that there is sufficient daylight inside the building: "on the side that is lit we draw a straight line from the edge of the wall that seems to obstruct it, to the space that has to be lit. That space will be well lit if looking above that straight line we are able to see the sky". In general, he advised to place openings in areas where the sky vault can be seen without obstructions.

Olgyay, A. & V. (1957) propose a basic method for the design of shading systems. Their method consists of the following steps: Defining the period when shading is needed and estimating the overheated and underheated period of the year. The next step is to determine the positions of the sun for the time when shading is needed according to the latitude of the area using the "sun path diagram". The third step is to determine the type and the position of a SD which will interfere between the sun and the point of observation during the overheated period. This includes the design of the "shading mask" of the SD and the projection of that "mask" to the "sun path diagram". A decision needs to be made regarding the desired shading (either 100% or 50%). This part of the process can also be reversed. Knowing the required "shading mask" one can determine the most suitable shading device for it. The "mask" defines the type and the angle of the SD, as well as its proportions. Various technically correct possibilities can be proposed but in Architecture there is always a "*line where the technical method ends and creative expression takes over*" (Olgyay, A. & V., 1957) (Fig.2.8).

A similar method to design a SD is proposed by Givoni (Givoni, 1969, p. 218). He introduced a graphical method to depict the patch produced on the floor by the sunlight entering a shaded window. The method is based on the use of solar charts, the shadow angle protractors appropriate for the examined latitude and the design

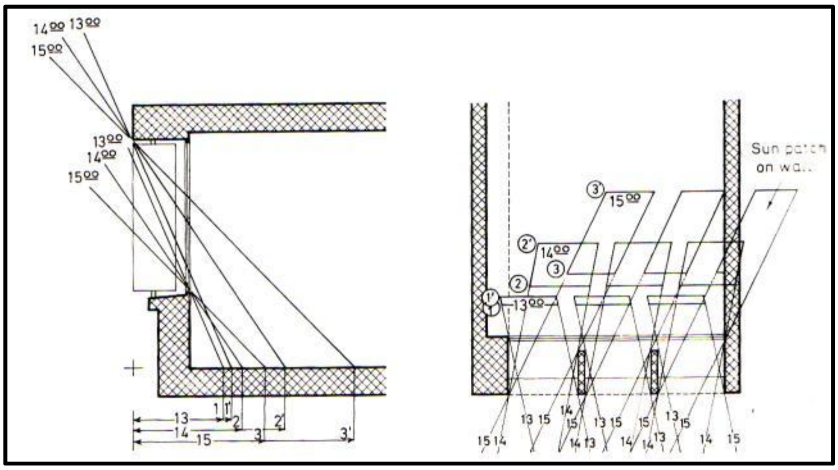


Fig.2.10. *Graphical determination of solar radiation penetration through a window and a fixed shading device as proposed by B. Givoni* (1969, p. 228)

of the corresponding solar altitude and azimuth angle, in plan and section of the examined opening – SD (Fig.2.10).

Shaviv (1975) and Radford (1981) introduced a method for designing fixed external SDs using nomograms. The method allows variations in the geometry of the sunshades. They follow the steps proposed by Olgyay with the use of a computer that generates a "family" of solutions as an envelope which satisfies the prescribed shading demands. Then a nomogram is derived of all possible solutions. The final step is to generate different forms of sunshades according to materials, the building's functionality and its aesthetics (Fig.2.11).

The geometrical rules that are followed when designing a SD have been well presented in literature. These are related to the climate and to the type of building in terms of its activity, meaning whether the main activities happen internally or externally. According to this plan articulation the shading period is decided, hence the geometrical rules for the required SDs (Lechner, 2001).

Since the beginning of the 80's, a number of computer programs have been developed to determine accurately the optimal shape of exterior shading devices—such as awnings, overhangs and eggcrated systems; these applications take into account the sunlight under clear sky conditions. Bouchlaghem (1996) and Kensek et al. (1996) developed a program called SHADING MASK, Etzion (1985) and Wagar (1984) developed a program called SUNPLOT; both these programs contributed in

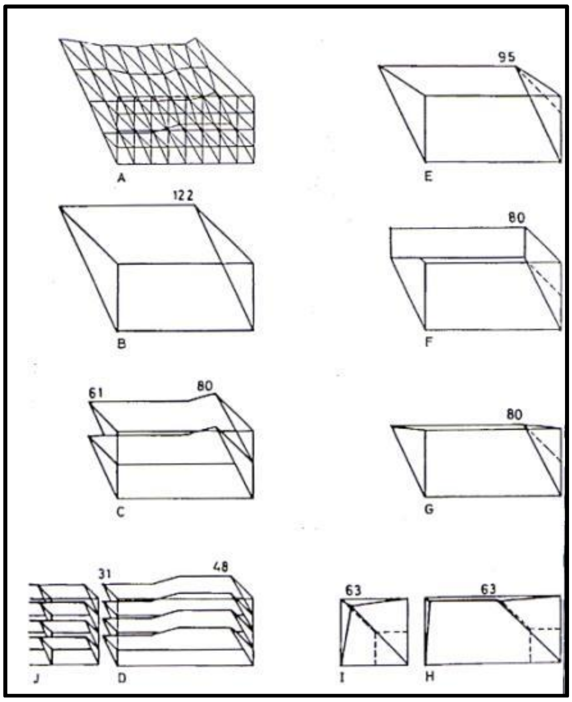


Fig.2.11. *Axonometric projection of L_{max} for a southern window and shading for the period March 21 till October 21, for hours 08.00 – 16.00 in Tel Aviv (Latitude 32^{o}N) – and alternatives for different geometrical configurations of Sun shades.* (Shaviv, 1975, p. 140)

the production of models which are mainly concerned with the geometry of shading devices and do not contain energy simulation algorithms (Dubois, 1997, p. 99).

These methods can be used as a first step towards the development of an energy calculation program. Additionally they are very helpful for the designers at the early design stage because they help visualize basic geometrical configurations of shading devices that correspond to the shading period and orientation examined.

Choosing the right geometry for the shading device is a basic step to optimise the efficiency of the proposed system. Various types of geometrical configurations of shading systems can assure the avoidance of direct solar radiation, for the same period of the year. The next step is to determine the optimum geometry of the shading system in terms of thermal, solar transmittance and daylighting performance. These depend on several factors that we are going to present in the next few paragraphs.

The balance between thermal and sunlight transmittance is the main goal of shading. This is not easily achieved due to different and complicated factors upon which this transmittance depends. For example Dubois (2001) argued that "*it is not necessary for exterior shades to provide 100 % shading for steep angles of incidence. Most important is to be able to provide shading when the sun is in front of the window*". She argues that in a smaller awning or one without covered sides the solar radiation leaking on the side of the awning (at steep angles of incidence) was insignificant with respect to annual cooling loads. Additionally the advantage of smaller awnings is that light entering from the sides of the awning can provide beneficial diffuse daylighting. The balance of thermal gains and daylight quality that a SD can achieve is mainly the subject of the detailed design stage.

We have to point out at this stage that solar radiation consists of three parts: direct, diffuse and reflected radiation (Fig.2.12). In order to incorporate the control of all these components of solar radiation more complicated computer applications are developed. They incorporate the complicated movement of solar radiation and the dependence of solar absorption in relation to the angle of incidence. Details concerning these two basic parameters of solar radiation will be developed in the next chapter.

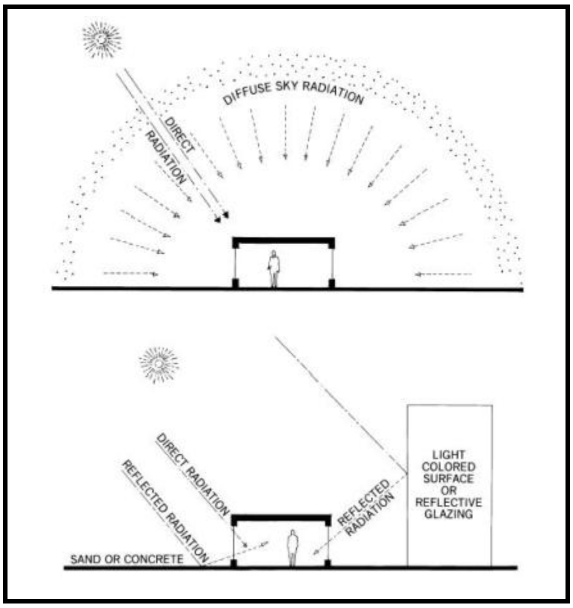


Fig.2.12. *Behavior of solar radiation* (Lechner, 2001)

Further on, in this chapter we describe the latest developed methods of assessing shading systems, included in the International and European standards. At the moment three main evaluation methods have been standardized: these are the ISO International Standards 15099 (Thermal Performance of windows, doors and shading devices, Detailed Calculations, 2003) manual and the EN 14500 (Blinds and shutters -Thermal and visual comfort - Test and calculation methods, 2008) and 14501 (Blinds and shutters —Thermal and visual comfort - Performance characteristics and classification, 2005). These manuals introduce measurement set up and procedures to evaluate thermal, optical properties, performance characteristics and classifications of the shading devices. In these manuals, only a few types of shading systems are referenced.

In the International Standards **15099** (Thermal Performance of windows, doors and shading devices, Detailed Calculations, 2003) manual, the optical properties of the SDs are defined according to diffuse reflection and direct transmission. Additionally the thermal properties are defined according to convection and radiation of heat between glazing and SD, to the ventilation ability and the SD “openness”. The thermal properties of the glazing and the relation of the framing to the glazing are examined separately in order to calculate the opening needed. Despite these definitions, there is no widely recognized procedure to measure or calculate shading optical properties (Tzempelikos, 2008).

European Standards EN 14501 (Blinds and shutters —Thermal and visual comfort - Performance characteristics and classification, 2005) introduce a number of factors in SD design that influence thermal and visual comfort. Thermal comfort interior conditions are categorized according to the **solar factor and the shading factor. Solar factor (g)** is defined as ratio between the total solar energy transmitted into a room through a window and the incident solar energy on the window. **Shading factor** (F_c) is defined as ratio of the solar factor of the combined glazing and solar protection device (g_{tot}) to that of the glazing alone (g). Both solar factor and shading factor depend on the glazing and SDs’ properties. Visual comfort depends on opacity control, glare control, night privacy, and visual contact with the outside, daylight utilization and rendering of colours. In order to quantify these quality characteristics three main factors are introduced: **normal to normal light transmittance, diffuse part of light transmittance and diffuse to hemispherical light transmittance**.

Tzempelikos (2008) explains the importance of the above mentioned values in the evaluation of shading systems. He points out that a basic difference between a shaded opening and an unshaded glazing is that in the former, the incident solar radiation may change direction while being transmitted or reflected at the surface of the Shading Device. That is the reason why we need a full matrix of transmission, to calculate forward and backward reflection and to calculate the absorption of each component for every angle of incidence. The reflectance and transmittance of transparent materials depends on the additional parameter of angle of incidence of sun –rays. The reflectance is lower when solar rays are perpendicular to the glass surface and it increases when the rays become more oblique. For Up to 60^o of incident angle the reflectance remains low; above 60^o the reflectance increases sharply and progressively with the incident angle (Givoni, 1969, pp. 212, T12.I). Tzempelikos (2008) concludes that the properties of transmittance, reflectance (direct-to-direct, direct-to-diffuse, and diffuse-to-diffuse) and absorption (direct and diffuse) are required for every angle of incidence: In general these properties depend on the wavelength of solar radiation that can be divided in visible and solar/thermal range. When a solar beam is transmitted through or reflected from the SD it is split into a direct and a diffused part and these parts continue their route through the system. That is the reason why the calculation of the diffuse-to-diffuse transmittance and reflectance and direct-to-direct transmittance and reflectance is required (see Appendix).

According to Greek legislation (Law 3661/2008, that followed the EU Directive 2002/91/EC on the Energy Performance of Buildings and the ISO 13790 (2008)) a **shading factor** (SF) is used to evaluate shading systems and their effect in the building in terms of solar radiation. It depends on solar obstructions and the position of the shading device used (if it is an overhang or a vertical element). Another indicator that is taken into account in Greek legislation is the **solar thermal gain factor (g_w)**: it incorporates the influence of thermal radiation; it is the average value of the ratios of solar radiation passing through the opening to the incident radiation falling to it during the examined period. The amount of solar radiation absorbed by the framing and transformed as thermal gain to the interior, is very little in comparison to that transmitted through the glazing to the interior; therefore it is ignored. The solar thermal gain factor depends on the percentage of the surface of the framing to the surface of the glazing within the opening and on the insulating properties of the glazing (Technical Chamber of Greece and Ministry of Environment, Energy and Climate Change, 2010, p. 1_66).

However, the above mentioned factors and geometrical equations are not sufficient when detailed research is conducted to assess complex SD, like Venetian blinds for example. In simulation models, reflected/transmitted light is usually not calculated, and some values have to be taken from measurements, so the results are not accurate enough. In these cases both experimental and simulation work is needed (Tzempelikos, 2008).

In order to thoroughly understand the basic working mechanisms of Shading Systems we will first describe solar radiation in relation to heat transfer (Chapter 3). We will then describe the shading systems' influence on daylighting (Chapter 4) and how the contradicting factors of heat and daylighting can be balanced by the geometrical configurations and the types of materials used to construct the shading systems (Chapter 6). Additionally we consider shading systems as energy producing devices and we will further on analyse their function in combination to their energy producing character (Chapter 5).

Part II

3.0. Shading Systems: their relation to thermal conditions

Although we cannot actually divide sunlight to heat and light, in this chapter we are going to focus on the basic quality of shading systems which is to reduce heat gains and ensure thermal comfort in the interior. We will analyze the quality of solar radiation and how sunlight behaves in relation to the building. We will focus on basic simulation methods that can be used in both early and late design stages of shading devices (SDs) to predict energy needs in order to achieve comfortable thermal and visual conditions in the interior.

3.1. Shading in relation to Solar Radiation

3.1.1. Direct, Diffused and Absorbed Solar Radiation

Solar radiation is divided into two types: direct and diffuse.
Diffuse radiation is the sum of scattered sky radiation and reflected direct radiation and it is not very important in terms of heat gains. According to Olgyay A. & V. (1957) the total incident solar radiation is the sum of direct solar radiation falling on a surface and diffuse sky radiation scattered by the atmosphere and by reflections from the ground and other objects (Fig.3.1).

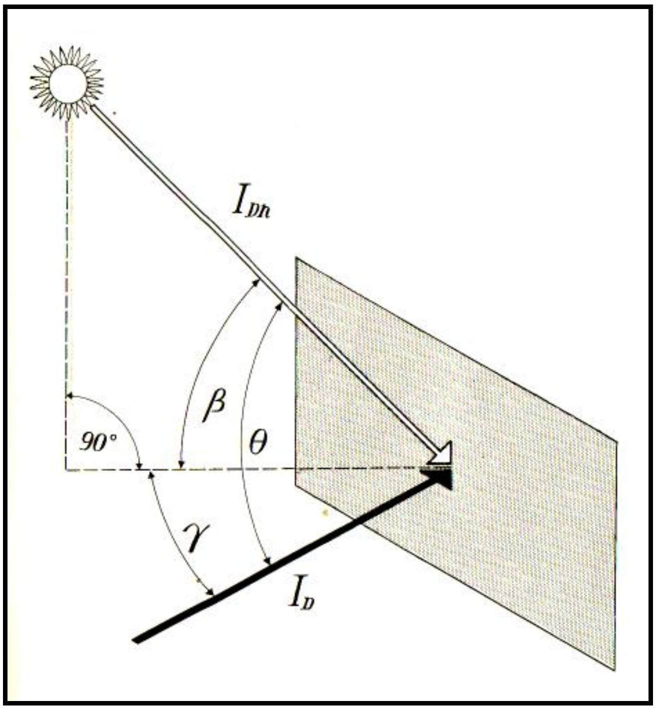


Fig.3.1. *The angle of incidence of direct radiation (I_{DN})*
(Olgyay, A. & V., 1957, p. 57)

Diffuse radiation does not have directional beaming and it has different intention for various orientations (Olgyay, A. & V., 1957, p. 56).

The reflected radiation from the ground and the surrounding surfaces depends on their reflectivity or albedo. In some cases reflected radiation can contribute to increasing heat gains. E.g. in buildings positioned near emissive surfaces, like sand or paved areas: the result is high influx of heat. Reflected radiation from the ground is slightly higher on walls facing away from the sun (Givoni, 1969, p. 180).

The amount of **diffuse** and **direct** radiation varies with cloudiness. On a clear day the amount of solar heat received from a surface is higher than the amount received during a cloudy day and on a cloudy day the amount of diffuse radiation is in turn higher than on a clear day. This does not mean that the resulting temperatures are high during clear days and low during cloudy days. The effect is rather more complicated: clear days in the summer do not mean warmer days because of increased solar energy but clear sky in the winter marks a day of lower temperature due to the fact that clear sky allows heat escape to the atmosphere. Additionally cloudy days in the summer result in higher temperatures, due to the fact that solar radiation cannot escape back to the atmosphere (Fig. 3.2).

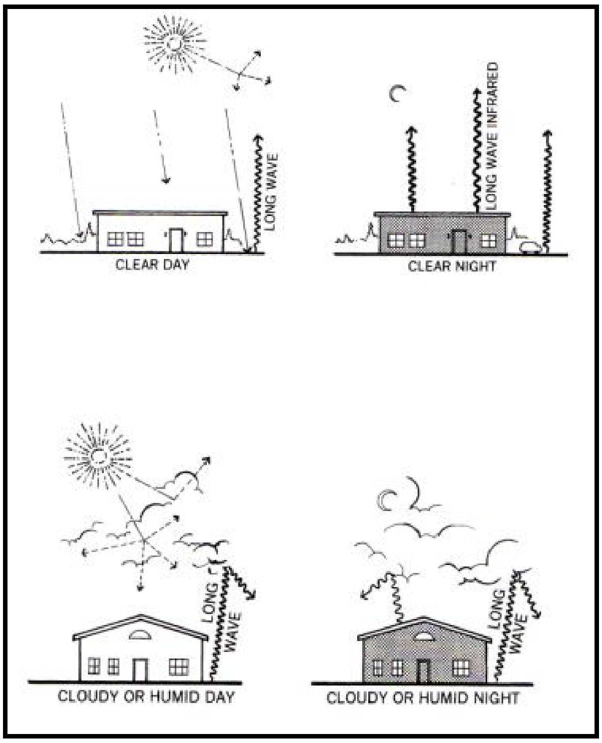


Fig.3.2. *Solar radiation in relation to clearness of the Atmosphere* (Lechner, 2001, p. 71)

That is one of the reasons why the contour isolines representing the falling total solar radiation projected on a map of an area do not run parallel to the latitude lines, since the angle of incident sun rays changes. Other reasons are turbidity of the atmosphere, topography and other local atmospheric conditions (Olgyay, A. & V., 1957, p. 58) (Fig.3.3 and Fig.3.4).

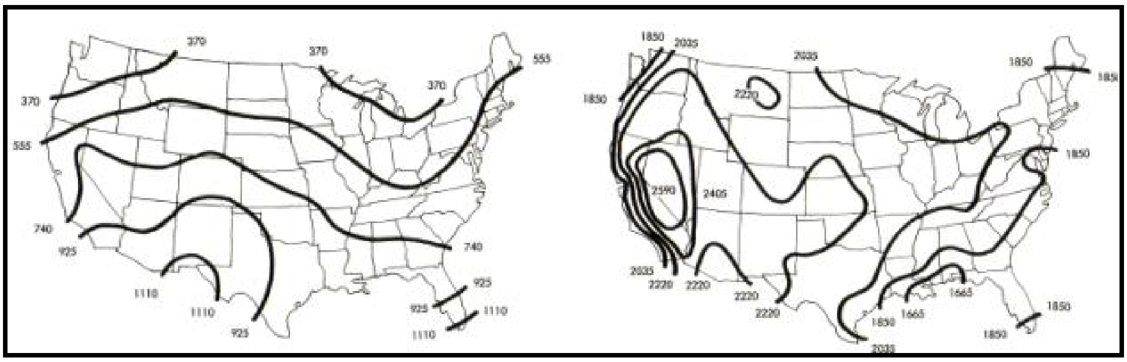


Fig.3.3. *Average daily sun energy received in January (left) and July (right image)*
(Olgyay, A. & V., 1957, p. 58)

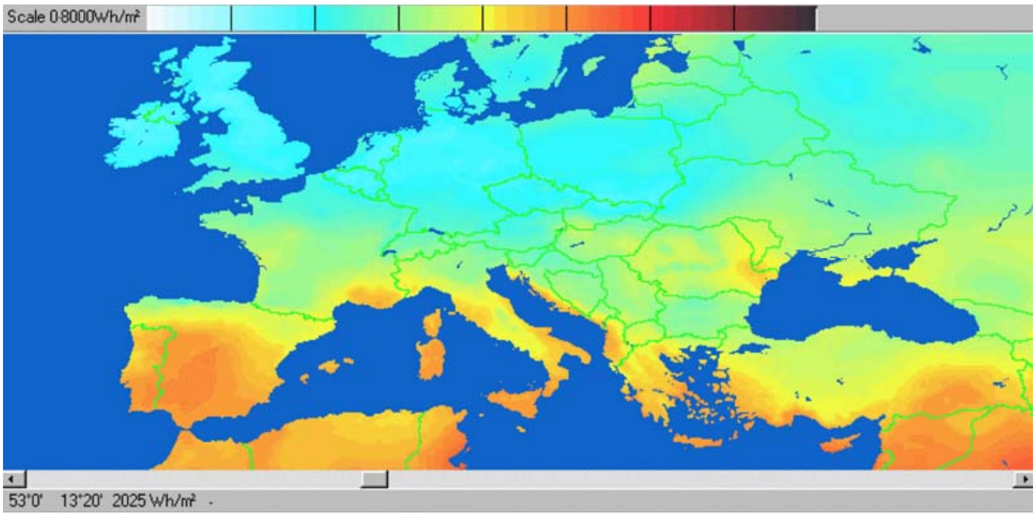


Fig.3.4. *Example of a map: average daily direct irradiation over Europe in June.*
(Scharmer and Greif (2000)., p. 56)

For Greece the contour isolines representing the falling total solar can be seen in Fig. 3.5. We can see that the annual solar energy at horizontal plane is exceeding 1.650 kWh/m2 (Kaldellis & Zafirakis, 2012).

Solar radiation is of our interest regarding two aspects: heat transfer and the resulting temperature and heat absorbed by surfaces that can produce energy, such as PV materials. This last property of solar radiation will be analyzed in chapter 5.

We can calculate the amount of heat absorbed by a surface when we know the total intensity of solar radiation that falls upon it. This depends on the absorption coefficient of the surface and on the angle of incidence of the solar beam. The absorption coefficient can be calculated by measuring the incident and reflected radiation, and the difference between these two is the amount absorbed by the surface (e.g. using pyrheliometers).

Ashbel (1942) developed equations in order to estimate the intensity of incident radiation on surfaces with different orientations and he showed that southern walls receive maximum radiation in December and minimum in June. Horizontal surfaces receive highest solar radiation in summer and less than a South East or South West wall in winter. For inclined surfaces the intensity of radiation depends on their direction and inclination (observation for Jerusalem, latitude 31. 47 by (Givoni, 1969, p. 183)).

This is one of the reasons why vertical openings are preferable for the building's envelope. They are much more easily controlled in the summer when solar heat gains are undesirable. Moreover, when SDs are used the control of solar radiation can be even more effective.

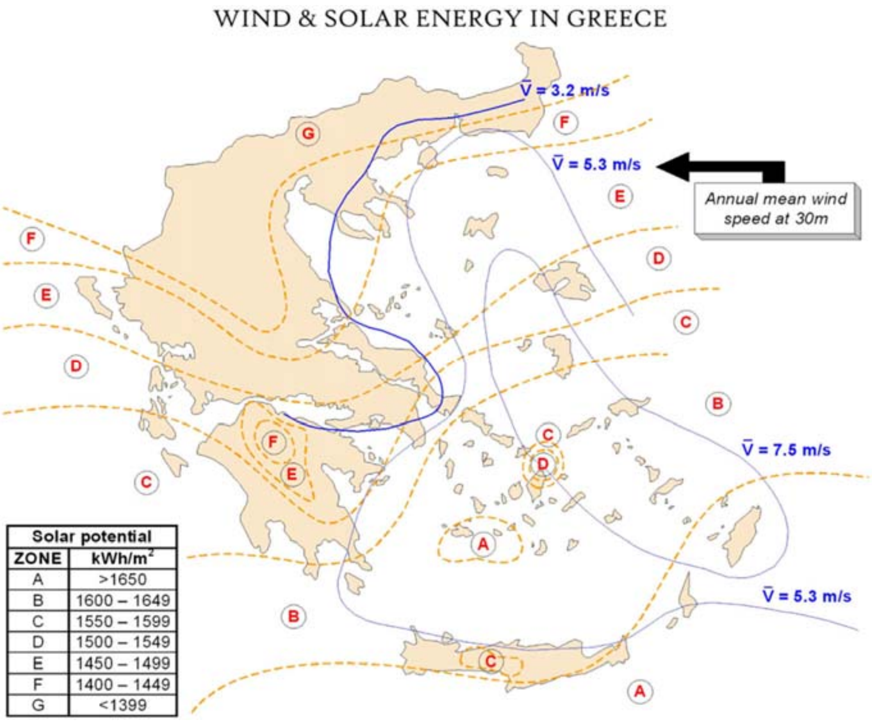


***Fig.3.5.** Wind and solar potential in the Greek territory based on data from* (HAPC, 2011) (Kaldellis & Zafirakis, (2012), p.2)

3.1.2. The influence of material and colour on the behaviour of solar radiation

The effect of the properties of windows and SDs upon the absorbed and transmitted radiation is significant: Firstly because windows' construction materials transmit and absorb radiation and secondly because the shading device's construction materials produce and absorb radiation.

According to (Givoni, 1969, p. 188) the combined effect of Solar Radiation and Ambient air is the Sol- air temperature and it depends on the absorbability of the external surface, the intensity of incident solar radiation on the surface, the overall external surface coefficient, the mean radiant temperature of the surroundings and the external radiative surface coefficient. Sol - air temperature includes three component temperatures: the first is that of the outdoor air, the second represents the fraction of solar radiation absorbed by the surface upon which it is incident and the third represents the long wave radiant heat exchange with the environment.

The absorbability of the external surface depends on the roughness of the material and its colour. Typical values of absorption coefficients for different materials are given in the bibliography (op.cit., p. 189). White smooth materials have much lower absorption than matt black ones and this should be taken into account for the design of shading systems (Fig.3.6).

New whitewashed surface	10 - 15
White oil paint	20 - 30
White marble	40 - 50
Medium grey	60 - 70
Bricks - Concrete	70 - 75
Glossy Black	80 - 85
Matt Black	90 - 95

Fig.3.6. *Absorption coefficient of various colours (%)*
(Givoni, 1969, p. 189)

This is one of the main reasons why we examine already known geometries of shading systems. Their basic difference is their construction material which is a PV, black in colour and with a glossy surface finish. These properties alter the performance of the shading system. Sol - air temperature is effected by the properties of the material and differs for the examined shading systems due to their integrated PV material in relation to conventional structural materials.

Another parameter affecting the absorption of solar radiation is the transparency of the material under examination. The heat flow of an opaque exterior wall is lower than the heat flow of a transparent glazing even if both are shaded. The single glazing for example is 30 times more vulnerable to solar radiation that an opaque wall. The exact relation depends on the latitude, the orientation, and time of the year, angle of incidence and materials' properties. We will examine these parameters in the following paragraphs.

It is important to mention here that the material of the shading system is crucial in the transfer of solar heat to the interior. For example according to (Givoni, 1969, p. 218) when a shading device is of large thermal storage capacity, such as concrete sun breakers, their heating effect may continue long after sunset. This depends on the position of the shading system in relation to the building sides. If for example the shading system is on the leeward side of the building the air passing above it flows away, removing potential heat gains from the building.

In his book "Design with climate" Victor Olgyay (1963) was one of the first researchers comparing so many types of shading systems in relation to their material and colour. He concludes that for the venetian blinds system the use of white colour adds 20% more shade protection than a dark color and the aluminium blinds add 30%. For the roller shades, he concludes that off white shades gives 40% more protection than dark color. Finally, concerning interior curtains the difference between dark and light colour is not as wide. The light one is 18% more effective than the dark one. The disadvantage of this assessment is that the author does not give any definition of shading effectiveness as he uses it. He argues that "the judgement of eye gives an approximate measure of the relation of colour to the absorption value". The definition of dark colour is light transmission lower than 20% and for the light colour higher than 50%.

A huge variety of fabrics and draperies as thermal protection devices have been examined by researchers after the 60's. (Grasso et al., 1990) review the work that has been done till then in relation to fabrics and draperies and conclude the following concerning their material and color: Tightly woven fabrics are better insulators. Drapery fabric weight and fiber content have little effect on thermal insulation. Fabrics with light-colored backings provide better insulation and among the important roller shade fabric characteristics, thickness, weight, and emissivity included, roller shades laminated with metalized material show great potential in reducing heat loss through windows.

Dubois (1997) reviewed these researches in relation to heat reduction and concludes the following: a single glazing shading system reduces heat losses to the interior between 58% to 25%, depending on the materials's properties and geometry (venetian blind, roller shade, draperies). More specifically, among others, she is referring to Grasso & Buchanan (1979) that showed that roller shade systems reduce heat losses by 25-30% while metallic coated roller shades reduce losses by 45%. Work at the Harwell Laboratory - Oxfordshire, England - Energy Technology Support Unit (Energy Monitoring Company Limited, 1990) demonstrated that thermal effects of net curtains or venetian blinds are negligible while light curtains reduce heat losses by 20% and heavy curtains by 40%.

In 2001 Dubois, expanding her research reviewed the progress on different geometrical configurations of shading systems. According to the properties of the materials used she concluded the following: for heat dominated climates the potential for energy savings is much greater with a simple exterior shading device with a low g value, e.g. a dark blue awning, than with any solar-protective glazing assembly because the shading device can be removed during the winter and the free solar heat gains can be utilized to offset the heating demand.

3.1.3. Influence of the properties of glazing to the behaviour of solar radiation

3.1.3.1. Spectral composition of radiation

Another parameter that affects the transmitted solar radiation is the material of the glazing used. The direct solar transmission of an unshaded ordinary glass is over 88%, while that of a “darkened Glass” is 30% (Elstner, 2009, p. 505).

Within the spectral composition of solar radiation three are the main sectors: the short wave, the middle band and the long – wave. Transfer of solar radiation is focusing on the control of long –wave (infra-red) range (above 0.7 micron – heat). The short waves, the ultra- violet, have a therapeutic value but most of this band range is blocked by the glass. The middle band, the visible one (0.4 – 0.7 micron), is welcomed to the interior, as long as it does not produce glare. The role of the shading system is decisive in relation to the facade and its opaqueness or transmittance, absorption or repellence.

The glass transmits radiation in a selective manner, permitting solar radiation to penetrate into the building, be absorbed by interior materials, and elevate their temperature. The heated materials in turn, emit radiation in the longer wavelength, for which the glass is completely opaque. This process, called the “greenhouse effect”, is the main reason why shading systems are needed.

A basic characteristic that influences the thermal performance of a glazing is the U-value. This is a measure of the heat flux through the window per unit surface area and degree temperature difference between inside and outside. It is given in W/m2K. It is sometimes called the dark *U*-value, since it only accounts for heat being lost through the window (e.g. nighttime) and not for incoming solar radiation.

U – values of glazing are calculated in accordance with EN 673 and measure in accordance with EN 674. For windows the U value is calculated in accordance to EN ISO 10077. The formula used includes the surface of the glazing, the U value of the glazing, the area of the frame, the extent of the glazing that takes into account the thermal bridge between glass and frame (Elstner, 2009, p.503).

The standards demand calculation and labeling of window *U*-values, total solar energy transmittance (or solar heat gain coefficient, SHGC as used in the US), shading coefficient (older term introduced in the US), daylight transmittance, and condensation. The computer tool WINDOW 5 was developed in Lund University to facilitate calculations of window performance.

A basic variable of thermal transmittance of transparent elements is the **total solar energy transmittance** of the window glazing: it is defined as the sum of the directly transmitted energy (depending on the amount of light transmitted) and the part of the absorbed energy which is transported into the room. The *g*-value (*g* for gain) or SHGC (solar heat gain coefficient) expressed as a ratio is also denoted here. It is usually only slightly lower than the corresponding light transmittance, but can be significantly lower for a special solar control glass. For single clear float glass the direct energy transmittance is approximately 83 % and total energy transmittance is 86 % (op. cit.).

We have to mention at this point, (even though it is the subject of the following chapter) that the principal parameter for the properties of glazing is the transmittance of solar energy within the visible region: the **light transmittance** (T_{vis}, but the term LT also appears in bibliographical resources). For ordinary clear float glass, approximately 90 % of the light that hits the surface at normal incidence is transmitted. Approximately 8 % of the energy is reflected (R = 4 % at each surface), and the remaining 2-3 % is absorbed as heat in the glass. The more window panes are placed parallel, the lower is the transmittance (op. cit.).

The reflectance of transparent materials depends on the additional parameter of the angle of incidence of sun rays. The reflectance is lower when solar rays are perpendicular to the glass surface and it increases when the rays become more oblique. For up to 60^o of incident angle the reflectance is low and above 60^o the reflectance increases sharply and progressively with the incident angle. (Givoni, 1969, pp. 212, T12.I) provide a table showing the heat absorption for various types of glazing with incident solar angle ranging between 0 and 45 degrees (in fig. 3.4, (Bulow - Hube, 2001, p. 61)) (Fig. 3.7.)

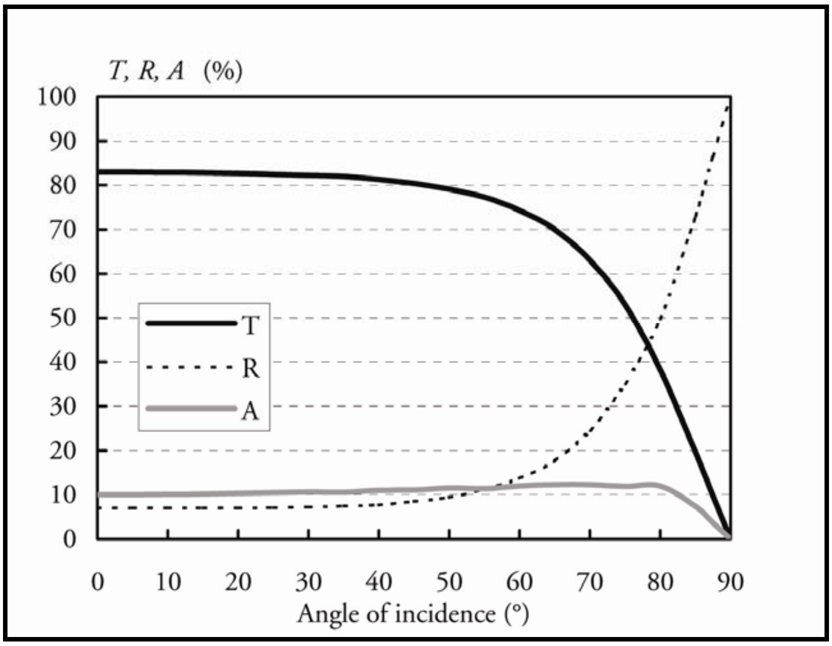


Fig.3.7. *The angle dependence of transmittance, reflectance and absorption of clear float glass for incidence angle* θ *(from the surface normal)*
(Bulow - Hube, 2001, p. 61)

If the physical properties of the glass are known (thickness, refraction/ extinction coefficients, and absorption coefficient) the angle-dependent properties can be calculated using Fresnel's equations and Snell's law of refraction (see Appendix). For coated glass the calculation the behavior of light when moving between media of differing refractive indices is becoming a more complicated task.

A crucial factor is how these physical properties are defined. When the transmittance for a single glass is calculated or measured, it is necessary to weight the results for each wavelength against a "standardized" solar spectrum. For the **light transmittance**, D65 is a widely used spectrum. For the **solar energy transmittance**, references to two solar spectra are given in the ISO 9050, and both of these are widely used by manufacturers in Europe (see fig. 3.8 (Bulow - Hube, 2001, p. 62). In the US, a different spectrum is used, ASTM E87-891, which corresponds to ISO 9845-1:1992. Standardization work is in progress with the aim to move from the spectra referred within ISO 9050 to the spectrum given in ISO 9845. Care must therefore be taken when performance data on products from different manufacturers are compared. Hopefully, this problem will eventually disappear when everyone conforms to the same calculation measures and standards (Bulow - Hube, 2001).

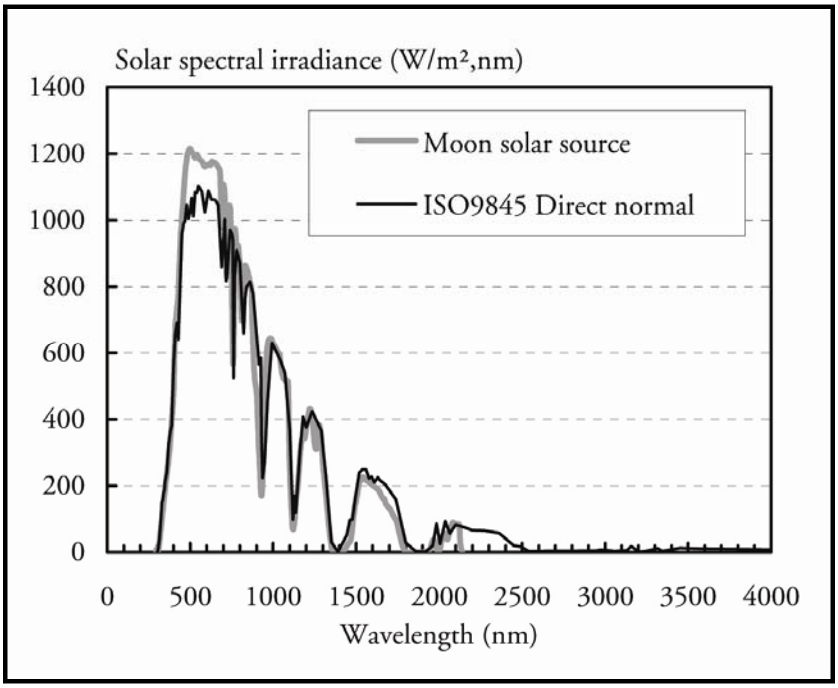


Fig.3.8. *Solar spectral irradiance for two spectra: Perry Moon and ISO 9845 Direct normal irradiance, Tab 1, col. 2. The source for Perry Moon was found in Optics5 from LBNL.* (Bulow - Hube, 2001, p. 62)

This last characteristic of glazing is the main reason why the shading coefficient is not the most accurate factor of solar transmittance of a combination of shading systems in a glazing. It does not take into account the changeability in the solar absorption according to the angle of incidence. This fact led to the development of algorithms that relate solar radiation to solar angle. We will describe this with more detail in Chapter 4.

3.1.3.2. Types of glazing as shading systems

There are several types of glass, which are distinguished by their spectral selectivity, their clarity, their absorbance or reflectance of heat and their colour: grey or coloured glasses. The heat absorbing and reflecting glazing absorbs and transmits infra-red radiation to a greater extent than ordinary clear glass. Heat absorbing glass, absorbs more infra-red and at the same time transmits more the middle - visible waves. The infra –red absorption is due to successive layers with a primary layer of silver among the other ingredients of glass (low –e). There are mainly used for reduction of solar heat gains and not for the shading. We are mentioning them here due to the fact that they can serve one function of the Shading Systems; the function that refers to the reduction of heat gains. Internal solar gains are due to two factors: due to the direct transmission of visible and long wave radiation to the interior and to the inward heat flow by convection and long wave radiation from the heated glass surface (Fig. 3.9).

For assessing the energy performance of a glazing three values are important to be used: Solar Heat Gain Coefficient (SHGC) or Shading Coefficient (SC), U-Value (W/m2·K) and spectral selectivity. Solar Heat Gain Coefficient (SHGC) is the ratio of total transmitted solar heat to incident solar energy and U – value is a measure of heat transfer through the glazing due to a temperature difference between the indoors and outdoors. We will explain more in the next paragraph.

Spectral Selectivity refers to the ability of a glazing material to respond differently to different wavelengths of solar energy, to admit visible light while rejecting unwanted invisible infrared heat. High tech products on the market have achieved this characteristic, permitting much clearer glass than previously available for solar control glazing. A glazing with a relatively high visible transmittance and a low solar heat gain coefficient indicates that a glazing is selective. Various types of glazing in relation to their coating and their layering are presented in Fig. 3.10 and are informed by the Design Builder Software.

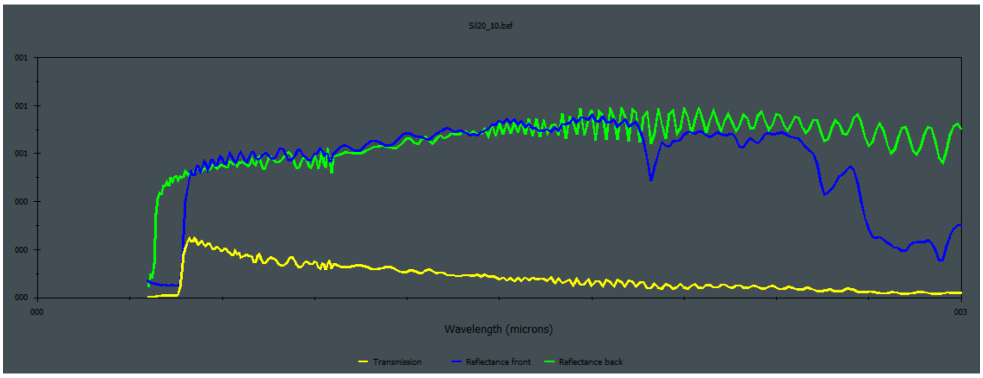
The heat reflecting glass has a very fine semi transparent coating upon its surface. That coating is very sensitive, and that is the main reason why it is usually integrated into a double glazing system with an air gap or protected by special lamination. Coloured glazing can influence the interior thermal transmittance and absorb more of the visible part of the solar spectrum according to its colour.

Printed glass reduces interior solar gains, and this reduction depends on the density of the print; sand blasted and engraved glass increase the diffusion of solar rays.

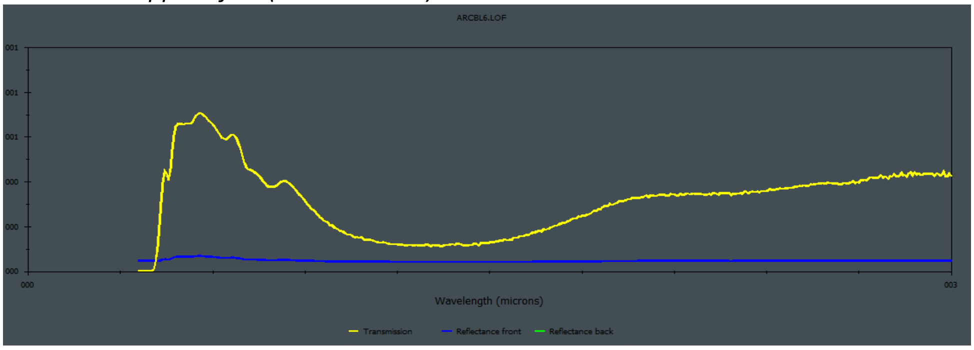
Other high technology glazing products that incorporate the additional parameter of changeability according to the required interior conditions in relation to the exterior temperature and sun position are the electro chromic, the gazochromic and the thermo chromic glazing. Electrochromic glazing is coated with an active layer of crystals, which alter their transparency and colour when a current passes through them. Gazochromic glazing works in the same way, but in this case a gas material is incorporated between the two layers of glazing (Ritter, 2007). Thermo chromic and thermo tropic glazing function passively. When the temperature exceeds a specific level, they change their transparency or their colour (Kaltenbach, 2004, pp. 14 -25).

Photo sensitive glazings when exposed to solar radiation change their texture and shape, so they can be more translucent to specific waves of solar radiation. Their changeability is not reversible, so this property is used before their final implementation to the opening (Kaltenbach, 2004).

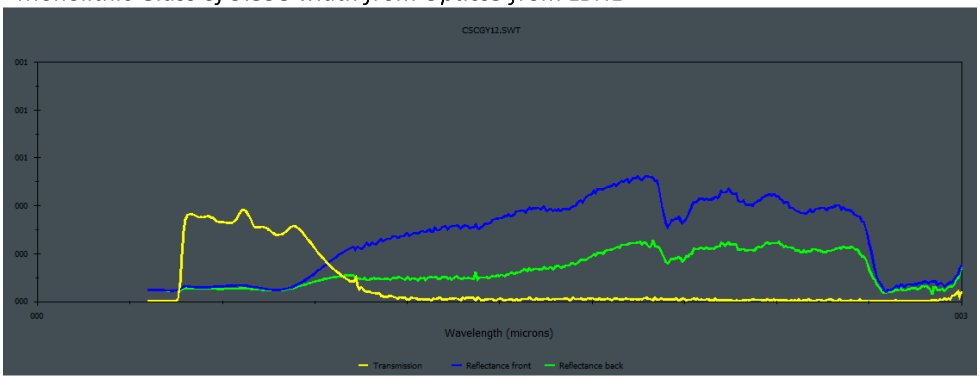
Other methods of changing the original properties of glazing are the positioning of specific materials that affect the deflection of light and are positioned in between two plains of glass. These types of materials reflect, transfer and diffuse the light. They redirect direct light outside and transmit the diffused light to the interior. Such materials are for example the lighting meshes, reflecting vents, prismatic sheets, and holographic glass of reflecting components (op. cit.).



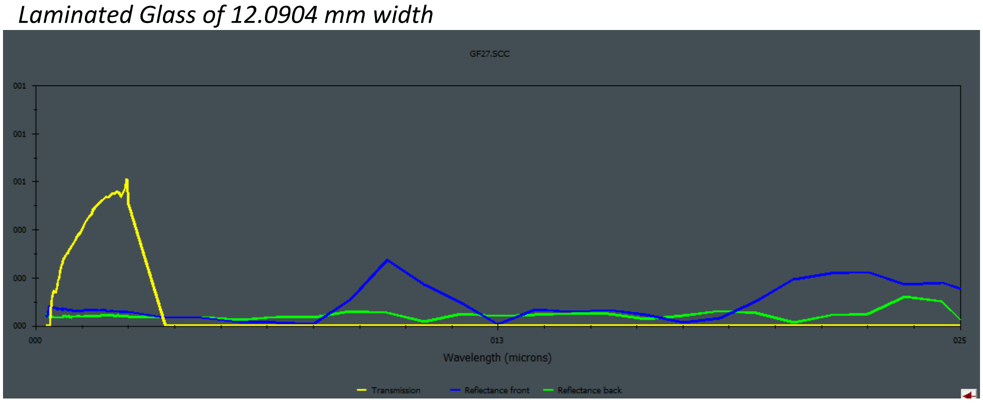
Glass with applied film (3.2mm width)



Monolithic Glass of 9.398 width from Optics5 from LBNL



Laminated Glass of 12.0904 mm width



Coated Glass of 2.5mm width

Fig.3.9. *Spectral selectivity of different types from Optics5 from LBNL*

	SHGC	Direct Solar Transmition	Light Tranmission	U - value (W/m2 K)
Single Blue 6mm	0.62	0.48	0.57	5.778
Single Low E Clear 3mm	0.768	0.741	0.821	3.835
Single Reflective 6mm	0.321	0.16	0.201	4.975
Single Low E Clear 6mm	0.72	0.68	0.811	3.779
Double Glazing with Air 6mm/13mm	0.497	0.373	0.505	2,665
Double Glazing with Argon 6mm/13mm	0.494	0.373	0.505	2,511
Triple Glazing with Air 3mm/13mm	0.684	0.595	0.738	1.757
Triple Glazing with Argon 3mm/13mm	0.685	0.595	0.738	1.620
Triple Low E Clear with Air 3mm/13mm	0.474	0.358	0.661	0.982
Triple Low E Clear with Air 6mm/13mm	0.31	0.21	0.455	1.202
Triple Low E Clear with Argon 3mm/13mm	0.474	0.358	0.661	0.780
Triple Low E Bronze with Air 6mm/13mm	0.154	0.07327	0.169	1.190
Triple Low E Clear with Air 3mm/6mm	0.569	0.478	0.711	1.833
Quadraple Low E Films with Krypton 3mm/8mm	0.466	0.338	0.624	0.781

Fig. 3.10. *Types and properties of various types of Glazing (Design Builder)*

All the above mentioned properties of glazing can be used as alternatives to shading systems. A variety of researchers compared various types of solar protective glazing with various types of shading devices. The comparison of switchable facades (electrochromic and gazochromic) to external shading devices showed that they have a similar potential for reducing cooling loads in both low and high latitudes. The former have the disadvantage of obstructing view to outside. This research refers to south climates (Rome) (Platzer, 2003). The potential energy savings due to different control strategies of electrochromic glazing has been analyzed. These systems proved to be insufficient for cooling dominated climates (Athens) (Assimakopoulos et al., 2007).

We have to note at this point that when comparing different types of shading devices, it is crucial that the same type of clear glazing is used.

More research is needed to assess the impact of shading devices on the window U-value with double, triple-pane and (low-e) coated windows. These effects need to be included in energy simulation programs (Dubois, 2001).

3.2. Parameters of Shading Design in relation to thermal gains

3.2.1. The effect of window size to thermal heat gains

The size of the window is a crucial factor for the energy balance of the building. (Bulow - Hube, 2001) argued that "*large windows may lead to thermal comfort problems and high energy costs during both winter and summer. Therefore, window size may be reduced in order to meet demands of energy efficiency*".

When increasing the window size thermal comfort problems might occur. When combining control glazing with a low emittance factor and low *g*-value and rather high visual transmittance, the *U*-value of the window walls will be higher than the *U* - value of the wall and won't achieve pleasant operative temperature. This can be achieved by decreasing the U-value of the window with the use of triple coated glazing, for example. In order to decrease U-value, without decreasing the window size, we can reduce the U-value of the glazing of the window (Bulow - Hube, 2001).

For small windows, overhangs were net energy "losers" because reductions in lighting levels were too high (Dubois, 1997).

However, when lighting was not automatically controlled, cooling and heating costs increased proportionally with window size (or Shading Coefficient, SC) and utility costs were minimum at window size= 0 m2 (or SC = 0). North proved to be the most beneficial exposure because the glass without a shading device offered greater illumination relative to solar gain than glass with shading device (no shading assumed on the north facade at all times) (Rundquist, 1991a) from (Dubois, 1997).

More specifically for south climates the type of glazing and the shading system is much more influencing the cooling energy loads of the office unit, than the window fraction on the façade. Especially for eastern and western windows cooling energy loads changes regardless the window fraction. Additionally shading contributes to the energy performance significantly, regardless of the window size and glazing technology used (Tsikaloudaki et al., 2012).

3.2.2. The relation between movable and fixed systems

The operational way of the shading system if it is movable or fixed is a crucial factor that affects their performance in terms of energy savings for heating, cooling and lighting the building. Various researchers have compared movable and fixed systems in terms of their energy efficiency.

It has been proven that the efficiency of the movable shading systems in north climates where the position of the sun is always low is higher and that fixed shading systems block the useful winter sun beam. It is also proven that fixed shading systems are more energy consuming than solar protective glazing but removable or dynamic shadings are performing better than all of them for north climates (Dubois,1997).

Furthermore Dubois (1997) studies of the impact of shading on annual energy use have demonstrated that shading devices reduce the cooling demand in buildings while increasing the heating loads due to loss of beneficial solar gains. Optimal shading strategies are thus climate dependent: in heat-dominated countries, fixed devices with medium to high solar transmittance and high thermal resistance or systems that can be removed in the winter are more energy efficient.

The assessment between movable and fixed louvers concerning the energy needs for heating, cooling and lighting for south climates has been done by (Carbonari et al. 2002). They conclude that movable shading systems are not by default more energy efficient, but that this depends on the climate where they are installed. This evaluation is focused in three different south climates (Venice, Rome, and Trapani). For the southern latitude (Trapani, 38 N) fixed louvers are more efficient than the seasonal ones in contrast with the more northern latitudes of Venice (45N) and Rome (41N).

The performance of the shading strategy of venetian blinds (manual or automatic movable, inclined and in different height positions) has been examined by Weinold (2007) according to energy savings and to view contact with the exterior. He concludes that the automatic cut – off system has proved to be the most convenient in terms of energy savings for heating, cooling, and lighting.

When including the energy needs for lighting, the total energy savings that a movable shading system can achieve, is significantly reduced. Tzempelikos & Athienitis (2007) analyzed the impact of exterior movable roller shades on building cooling and lighting energy demand. Substantial reduction of energy demand for cooling and lighting could be achieved in perimeter spaces, depending on climatic conditions, orientation, automatic or manual movable SD and automatic on/off or dimming lighting system. The percentage of the reduction of annual energy demands is high (50% for the city of Montreal) but is reduced (to 12%) if the energy for electric lighting is included.

We conclude that fixed shading devices have proved to be more energy consuming in north climates, in comparison to movable ones and to different glazing filters. For these latitudes, even when integrating PV systems it is proved that tracking louvers with integrated PV can generate up to 20% more energy than a fixed module (European Commission 5th FWP - ENERGY Programme, 2003). There is lack of data, for other types of SDs and for south climates. Additionally it is worthwhile mentioning here that due to high sun radiation angles, fixed shading devices for south climates do not necessarily obstruct view to outside, unlike solar protective glazing.

Moreover the efficiency of movable or adaptive shading systems has been questioned for public buildings due to the diversity and changeability of the users (Guillemin, 2003)

3.2.3. The relation of shading to the building envelope

Another decisive parameter for the energy performance of the Shading System is its position in relation to the envelope. Olgyay concludes that shading effectiveness varies according to its position in relation to the glass skin of a building: Exterior shading devices are more effective, interpane shading systems are less effective than exterior ones and worst performing are the interior shading systems. He explains that an interior shading protective device can intercept the solar energy that had passed the glazing and can control only that part of energy. Some of the enery falling upon an interior device is absorbed, and some convected and reradiated to the room (Olgyay, 1963, p. 70).

More specifically Olgyay (1963) took into account this definition of the shading coefficient (we define it in paragraph 3.3.1) in order to categorize various types of shading systems. He used a color with 50% of light transmittance for all types of shadings that he assessed. The categorization went as follows (starting with these of high shading coefficient): internal venetian blind system, internal roller shade system, tinted glass, outside shade screen, outside metal blind, coating on glass surface, trees, outside awning, outside fixed shading device, outside movable shading device. This was a first attempt to evaluate different shading systems that confirmed the superiority of the exterior shading system over the interior and inter-pane ones and the superiority of the movable to the fixed shading systems. Later on various researchers measured specific relations between different shading systems that incorporated energy needs and daylight comfort as a basic parameter for their evaluation.

Givoni (1969, pp. 216 - 218) examined the geometrical relation of the SDs to the envelope and concludes that in Israel, external devices are much more efficient than internal, and that the darker the colour of the external device the better its efficiency. Considering interior shading devices, he concluded that the lighter their colour, the better their efficiency (in these cases the windows are considered to be closed). He summarizes the conclusions of some studies done in several institutions in relation to the efficiency of various types of adjustable shading devices. In all studies the Shade Factor of the shading system was computed or measured. He concludes that external devices are much more efficient than internal and that the difference increases as the color of the internal shade is darker and the one of the external is lighter. This increase in efficiency of the external shading devices exists only when windows are closed. Moreover, he assessed internal and external shading devices, with different inclination and material reflectivity for Israel, for a south west facing window, according to the total heat gain using computer application (Givoni, 1969, pp. 215, Table 12II) (Fig 3. 11).

	a		q_{tsg}	1/3 q_{ag}	q_{ag}	q_{in}	q_{in} (%)	q_{in} (%) experiment al
Internal	30°	0.2	63.78	23.46	81.90	169.32	42.8	-
		0.4	50.16	21.90	151.86	223.92	56.6	54
		0.6	21.12	19.62	218.94	259.23	65.6	-
	45°	0.2	44.76	23.64	88.92	157.32	39.3	40
		0.4	30.90	22.20	150.18	203.28	51.4	51
		0.6	9.92	20.24	214.92	245.08	62.0	61
External	30°	0.2	63.78	1.38	5.04	70.20	17.8	-
		0.4	49.92	9.06	0.96	59.94	15.2	-
		0.6	21.12	0.36	13.38	34.86	8.9	-
	45°	0.2	44.76	5.16	0.84	50.76	12.9	-
		0.4	30.90	0.59	9.01	40.50	10.2	11
		0.6	9.924	0.038	21.59	31.89	8.1	-

Impinging radiation = 395 Kcal/h m^2

q_{tsg} = radiation transmitted through the glass - shading combination after reflection between the slats

q_{ag} = radiation absorbed in the glass, of about 1/3 is transferred to the interior

q_{in} = total solar heat gain

Fig.3.11. *Partitional heat gain (kcal/h m2) through different types of shading and the corresponding shade factors (%)* (Givoni, 1969, p. 215)

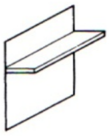
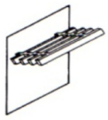
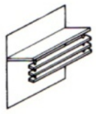
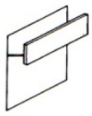
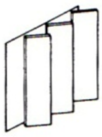
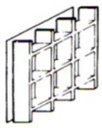
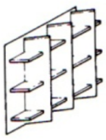
Bülow-Hübe et al. (Bülow-Hübe et al., 2003) compare external products (awnings, Italian awnings, venetian blinds, horizontal slatted baffle, fabric screens, solar control films), interpane (between panes) and internal products (pleated curtains, roller blinds, venetian blinds, solar control films) using the software tool ParaSol and conclude that external shading devices perform the best in terms of reducing cooling loads, internal products are the worst, while interpane products fall between these two.

More specifically for office buildings, the advantages of fixed shading systems in relation to movable ones are developed in paragraph 3.4.1.

3.2.3. Relation between shading and Orientation

Some important basic rules concerning the relation between orientation and geometrical configuration of the shading systems which further depend on the geometry of the sun's movement are being presented in this paragraph.

For south facing windows the horizontal overhangs are a very effective solution providing protection in the summer when the sun is higher. Although less effective there, the horizontal overhang is considered as the best solution also for east, southeast, southwest and west orientations. In hot climates, north shading is also needed and the vertical wings can work effectively due to the low altitude angle when sun moves to the north. For east and west orientation, the problem is bigger due to concurrent low altitude angle and vertical azimuth angle. The best solutions are achieved with geometries that combine horizontal and vertical fins facing south. The disadvantage of that solution is a restriction of the view from inside. The dimensions and the detailed geometry of these devices are defined according the specific latitude and the sun path diagram associated with it (Lechner, 2001, p. 210) (Fig.3.12.).

		Description name	Best Orientation	Comments
I		Overhang Horizontal Panel	South, East, West	Traps hot air, can be loaded by snow and wind
II		Overhang Horizontal louvers in horizontal Plane	South, East, West	Free Air movement. Snow or wind load is small. Small scale. Best Buy!
III		Overhang Horizontal louvers in vertical Plane	South, East, West	Reduces length of overhang. View restricted. Also availiable with miniature louvers
IV		Overhang vertical Plane	South, East, West	Free Air movement. No Snow load. View restricted.
V		Vertical Fin	East, West, North	Restricts view. For north facades in hot climates only
VI		Vertical Fin slanted	East, West	Slant toward north. Restricts view significantly
VII		Eggcrate	East, West	For very hot climates. View very restricted. Traps hot air
VIII		Eggcrate with slanted fins	East, West	Slant toward north. View very restricted. Traps hot air. For very hot climates.

From Architectural Graphic Standards, 8th ed., John R. Hoke, ed. Wiley, 1988

Fig.3.12. *Example of fixed shading devices* (Lechner, 2001)

Givoni & Hoffman (1964) have analyzed the efficiency of various types of shading devices in different orientations using various calculations. They calculated: a. the daily pattern of intensity of solar radiation falling upon an unprotected window in the case of Israel (latitude 32^{o}N). This can be calculated either by tabulated data providing the relation of radiation according to the angle of incidence of the sun or by using radiation calculators for a specific day of the year and in relation to the examined latitude as developed by Olgyay, A. & V. (1957, p. 63) (Fig.3.13), b. the percentage of the shade area, according to the type of shading system and according to the projection depth, c. the intensity of solar radiation on the unshaded part of the window.

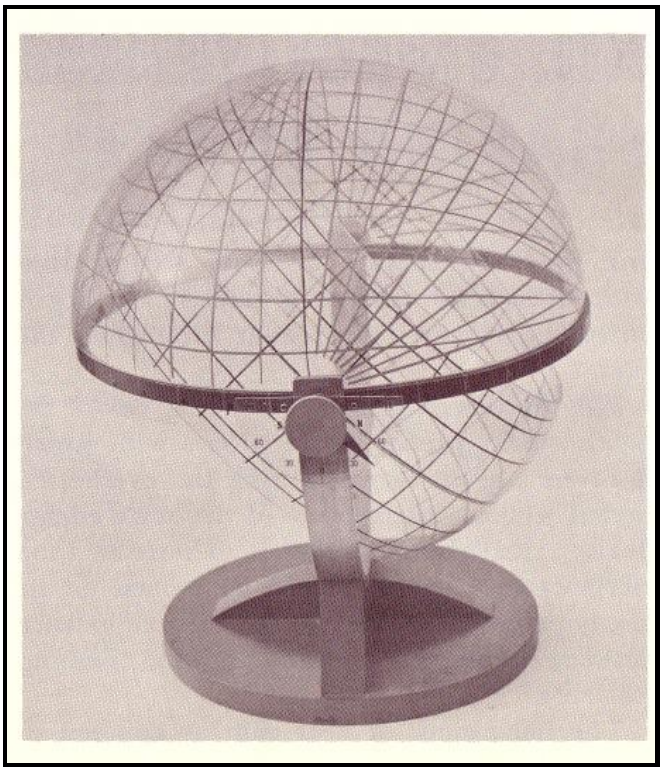


Fig.3.13. *Spherical radiation calculation in a position where the sun's angles can be measured at 40^{o} N latitude*
(Olgyay, A. & V., 1957, p. 63)

The summary of the above mentioned values produced a diagram describing the daily variation of the intensity of direct solar radiation falling upon a window. These researchers were the first to conclude specific geometrical characteristics for the shading systems of the examined windows in Israel (latitude 32^{o}N). For east and west orientation they concluded that the most efficient shading is the eggcrate type with the vertical members oblique at 45^{o} to south (or widely known Brise Soleil system). Horizontal shading are much more effective than vertical due to the fact that the latter obstruct winter sun and provide very poor shading in the summer. For south west and south east orientation they concluded that horizontal shading is more effective than vertical ones; specifically the eggcrated systems are considered to be the best.

Specifically, for south climates the influence of the orientation of the facade on the yearly energy consumption has been proven (Nikolaou, 2007). Horizontal overhangs for south oriented windows and vertical wing walls for east and west orientations in relation to the building's energy consumption for the weather of Athens have been analysed using the software tool TRNSYS 16 and real measurements. The average energy savings (heating, cooling, and lighting) are 8.7% larger when south overhangs are used. In the case of east - west facing window with vertical wing wall the energy savings are modest (1.4%).

3.3. Measuring the thermal behavior of shading devices: influencing factors and methods used

3.3.1. Solar Radiation in relation to the examined area

Traditionally, there are two methods to calculate solar radiation: the tabulated (or statistical) method and the diagrammatic (or graphical) method. Both methods are described by Olgyay (Olgyay, A. & V., 1957, p. 58)

The tabulated (statistical) method is based on the amount of solar energy received at normal incidence in relation to solar altitude (on dates that are given in the tables) and on the incident angle to the examined surface, in order to reduce the energy to its cosine function. The tabulated data are unique for each latitude and day of the year and Olgyays (1957) refers to Ephemeris of the Sun and to Hydrographic Office Bulletin (Table of Computed Altitude and Azimuth. Washington,D.C., 1940; The American Nautical Almanac, D.C., 1957).

The diagrammatic (or graphical) method is based on the use of a radiation calculator in relation to the latitude and the sun path diagram. The method was developed by Friedrich Tonne (Tonne, 1951). Olgyay's (1957) developed calculator charts are based on the assumption that the magnitude of the direct and diffuse radiation is a function of the solar altitude and the angle of incidence of the sun. The sums of direct and diffuse radiation for each point are projected on a sphere as isolines and correspond to vertical and horizontal surfaces. The direct radiation data corresponds to Moons's (1940) standards and the diffuse values to (Parmelee & Aubele, 1950) ASHVE recommendations.

Solar radiance measurements consist of global and/or direct radiation measurements taken periodically throughout the day. The measurements can be taken using either a pyranometer (measuring global radiation) and/or a pyrheliometer (measuring direct radiation). In well established locations, this data are collected for more than twenty years. An alternative method of measuring solar radiation, which is less accurate but also less expensive, is using a sunshine recorder. These sunshine recorders (also known as Campbell-Stokes recorders), measure the number of hours in the day during which the sunshine is above a certain level (typically 200 mW/cm2). Data collected in this way can be used to determine the solar insolation by comparing the measured number of sunshine hours to those based on calculations and including several correction factors. A final method to estimate solar insolation is cloud cover data taken from existing satellite images. Fig.3.14 shows equipment for solar irradiance measurements. (Photograph from David Pearsons) via NREL information exchange (http://pveducation.org).

Fig.3.14. *Instrument for solar irradiance measurements) via NREL information exchange (http://pveducation.org/pvcdrom/properties-of-sunlight/measurement-of-solar-radiation)*

Nowdays, these types of data are implemented in computer simulation software and are specific for each location. We will describe them in detail in the next paragraph (3.3.2.).

3.3.2. Factors and methods of Shading Systems' thermal behavior

The efficiency of a shading device should be judged on its yearly performance and on its relative balance between its shading performance and its heating efficiency. According to (Olgyay, A. & V., 1957, p. 64) shading at overheated times is twice as important as heat gain during the underheated season. He calculates the shading performance using the following equations:

For the summer shading performance:

$S_p = S_0/R_0 \cdot 100\%$, where:

S_p is the summer shading performance,

S_0 is the energy in Btu absorbed during overheated times and

R_0 is the energy in Btu which falls the surface during the overheated period.

The yearly effect is expressed in heat efficiency (H_e) by deducting the Btu losses during the shaded cold season (S_u) from (S_0) values and writing the result in percentage:

$H_e = S_0 - S_u / R_0 \cdot 100\%$.

The average value of the above mentioned calculated results, (the summer shading performance and the yearly energy balance) is called the Shading effect ratio (S_e) and it is expressed by the following equation:

$S_e = (S_p + H_e) / 2 = (S_0 – S_u/2) / R_0 \cdot 100\%$.

In that way Shading Devices can be evaluated for different orientations and localities. The effect of different materials, their color, reflection and heat transfer are not being considered in this evaluation. A "Regional Shading Chart" can then be created. It is a chart that shows the effective profile angle that shading should form for all orientations and for a specific location.

Another attempt to evaluate SDs according to energy transfer has been done by Givoni (Givoni, 1969). He introduced the "**shading factor**", which is the ratio of the heat entering the shaded window to the heat entering an unshaded window. He also introduced the comparison of actual indoor temperatures of different SDs with those obtained without shading. He divides the solar heat gain in three components: the part transmitted through the glass – shading combination, the part absorbed in the glass and the part absorbed in the shading material. In cases where the direct sun rays enter the window, a fourth component is used that incorporates the sun penetrating the shading. Moreover, he measures the efficiency of the adjustable shading devices that depends on their position in relation to the glass, on their color and ventilation conditions. Besides the "shading Factor" he uses the measurement of the thermal effect of the shading in order to evaluate the shading systems. In this second approach the calculation of the thermal effect of the shading is achieved by comparing the actual indoor temperatures obtained with different types of shading devices with those obtained without any shading (Aghemo et al., 2008).

More analytically Solar Factor (SF) is the Ratio of total solar energy flux entering through the glass to the incident solar energy. It is the total heat transmission of direct solar transmission and that proportion of absorbed radiation that is re-radiated into the building from the action of heat absorbing glass. It is also known as Solar Heat Gain Coefficient (SHGC).

Another characteristic factor for evaluating the energy performance of a fenestration system is "**shading coefficient**". Shading coefficient (SC) is a factor that can describe the efficiency of a shading system and it has been introduced by Olgyay in his book (1963). This is the ratio of the total heat gain from the transmitted, absorbed and reradiated energy by the shade and glass combination that enters the examined window to the total solar heat gain due to transmission, absorption and re- radiation by a single unshaded common window glass. "*It is a dimensionless number ranging from zero to one. Zero indicates that no solar radiation is passing through*". The shading coefficient is calculated by dividing the solar factor by 0.87, which is the solar factor of a 3 mm clear float glass. The position of the sun changes and therefore the relation of the sunbeam vector to the glazing changes constantly, so the absorption and reflection relations change. For the calculation of the shading coefficient these changes are not taken into account.

For a more complex SD a new coefficient is introduced: The new solar heat-gain coefficient (SHGC). It incorporates thermal properties of glazing and framing (Lechner, 2001).

According to ISO 13790 (2004) **Shading factor** (SF), is defined as:

$SF = F_{ib} \cdot I_b + F_{ad} \cdot I_d + I_{an} / I + I_d + I_{an}$ where:

$F_{a,b}$ = sunlight fraction of the window in presence of direct radiation (–).

$F_{a,d}$ = skylight fraction of the window in presence of direct radiation (–) and

I_b, I_d, I_a =direct irradiance, diffuse irradiance and irradiance reflected from the albedo incident onto the glazed surface in (W/m^2).

The solar heat gain is divided in three parts: the part transmitted through the glass – shading combination after reflection between the slats, the part absorbed within the glass and then transferred to the interior and the part absorbed by the shading material which in the case of internal shading is distributed to the interior and in cases of external shading is almost fully dissipated outdoors. When direct solar beam heats the window, a fourth part is added that is the part penetrating between the blinds.

Moreover various algorithmic relations and computer applications have been developed to calculate the thermal performance of shading systems. Furthermore Shaviv (1980) presented a computer method for determining the optimum "**shading coefficient**" for different shading systems, based on Olgyay's definition of the term.

Additionally, dynamic (hour by hour) computer programs were developed for the assessment of solar radiation entering a building. Some of them take into account the **solar angle dependent properties** of solar radiation. This is a parameter that the shading coefficient does not take into account. Mc Cluney (1991) and Prassard et al. (1992) observed this downside of the shading coefficient method, and Dubois (1997) refers to them as few of the most praiseworthy researchers on the subject.

However Papamichael & Winkelmann (1986), Furler (1991) and Pfrommer, (1995) developed algorithms that can determine solar angle dependent optical properties of glazing and can be used by computer models for more accurate results in the assessment of shading devices. These algorithms are appropriate for the specific shading systems that they are studied for. Further on Cho et al. (1995) developed a calculation module to connect with TRNSYS for the assessment of interior venetian blinds and Pfrommer et al., 1996) developed a computer software that calculates radiation flows through venetian blinds located outside and inside windows, taking into account both the diffuse and direct part of solar radiation and varying solar angles.

Advanced algorithms for windows and shading devices of arbitrary shape have been developed at Lund University and implemented in the dynamic, whole building energy simulation program *Derob-LTH,* for the simulation of heating and cooling demands and indoor temperatures*,* (see Källblad, 1998) (Dubois, 2001) . A Steady-state program for the estimation of heating demands on a monthly basis, the BKL-method, has been developed at the same University (Bulow - Hube, 2001).

The Advanced Window Information System **(WIS)** is a European software tool for calculating optical and thermal properties of commercial and innovative window systems, a big part of which are venetian blinds. One of the unique elements in this software is the combination of glazing and shading devices. This tool is particularly suited to calculate the thermal and solar performance of complex windows and active facades (Van Dijk & Oversloot, 2003). The way in which WIS treats the solar optical properties of a 'layer-type' shading device has been the basis of ISO 15099,(2003): Thermal performance of windows, doors and shading devices Detailed calculations (Tzempelikos, 2008).

Recently, computer applications were developed that can calculate in detail the total solar radiation of exterior surface. One of them is the EnergyPlus software, which incorporates features and capabilities of BLAST and DOE -2 software (Crawley, 2004). EnergyPlus can additionally take into account the reflected solar radiation from exterior surfaces and calculate the radiance from heating and cooling systems. This can be the reflected radiation from the surfaces of a shading device, from the surrounding buildings or from the surrounding ground. It can also take into account the sky condition that is represented as a superposition of four standard CIE skies using the approach described by Perez et al. (1990). Further it can calculate the shortwave radiation of an interior space. As we can read in the Engineering

Reference of EnergyPlus (2012, p. 185) "*The program determines the amount of this radiation that is (1) absorbed on the inside face of opaque surfaces, (2) absorbed in the glass and shading device layers of the zone's exterior and interior windows, (3) transmitted through the zone's interior windows to adjacent zones, and (4) transmitted back out of the exterior windows. The effects of movable shading devices positioned on the exterior windows are taken into account. Most of this calculation is done in subroutine CalcInteriorSolarDistribution in the Solar Shading module*". Details about the equations used can be read in the Engineering Reference of EnergyPlus.

A user friendly Software that can evaluate thoroughly the performance of shading systems is Ecotect. This computer application was developed at Cardiff University in 2000. It is a computer tool that can be easily used by architects and designers in the early design stage but its accuracy in terms of solar heat gains has been challenged. Due to the fact that in early design stages comparative and not absolute values are needed, it is an appropriate computer application for preliminary design ideas.

At the same time with the development of computer applications researchers develop applications for more detailed approaches. In particular (Alexander et al., 2005) developed modifications of the HTB2 software that was originally developed by (Alexander, 1997) to simulate venetian blinds systems. These modifications are concentrated in the Cavity Resistance algorithm and on the surface connective heat transfer for more accurate prediction of solar transmittance of inter-pane venetian blind systems.

Other more recently developed methods are the use of Complex Fenestration Systems (CFS) of EnergyPlus and the three face method of Radiance (Ward et al., 2011).

It is important to mention that the energy needs for heating and cooling not only depends on the effectiveness of the shading system but also hinges on the whole building layout, orientation, size and distribution of openings.

3.4. The issue of energy savings through shading systems: the case of office buildings

At this point, it is important to connect the performance of shading systems with the operation of office buildings.

"Almost half of the energy consumed in Europe is used to run building...
The relation of outside and inside has increased in importance for our living habits, as new materials and technologies have made it easier and less of an effort to actualize those functions of the buildings that provide protection from nature. The psychological gain that a transparent envelope offers, the seeing and the experiencing of day and night, wind and weather, summer and winter, become important components of open and exciting architecture in the twenty first century. Thus it has become one of the responsibilities of our time not only to channel natural daylight from an energy aspect, but also to integrate its influences on the physical constitution and on the psyche into architectonic concepts." (Hascher et al., 2002, p. 50).

Hence the issue of shading of office buildings becomes extremely important due to two reasons: firstly because we spend half of our life indoors in office buildings and the relation with the outside becomes very important and secondly because only through proper shading design can we simultaneously realise view contact with the outside world and low energy consumption for heating cooling, lighting.

When we observe a group of people busy with their ipads sipping latte sitting together at a coffee table we can assume that they are working. The office is one place where we work but there are other places to do this as well. Most of the people need a working environment where they have a sense of security, a fixed location where they continue where they left off the previous day and where they can have a word with colleagues. (Stanier B. & C., 2011). The office work can be done anywhere but the office conditions cannot be anyplace. The appropriate visual and thermal conditions can be achieved passively by the appropriate design of the facade and especially of the shading system.

In previous chapters the parameters, factors and methods used for assessing shading systems are presented. This research is focused particularly to office buildings facades in terms of the required interior comfort conditions. We examine the case of the single office cell with three working spaces as proposed by (Van Dijk, 2001) , (Fig.3.14) that belongs to a cluster of offices expanded in rows and columns. In the next few paragraphs we will describe the evolution of office buildings facades that influence the shading systems and explain the choice of the specific shadings for the purpose of this research.

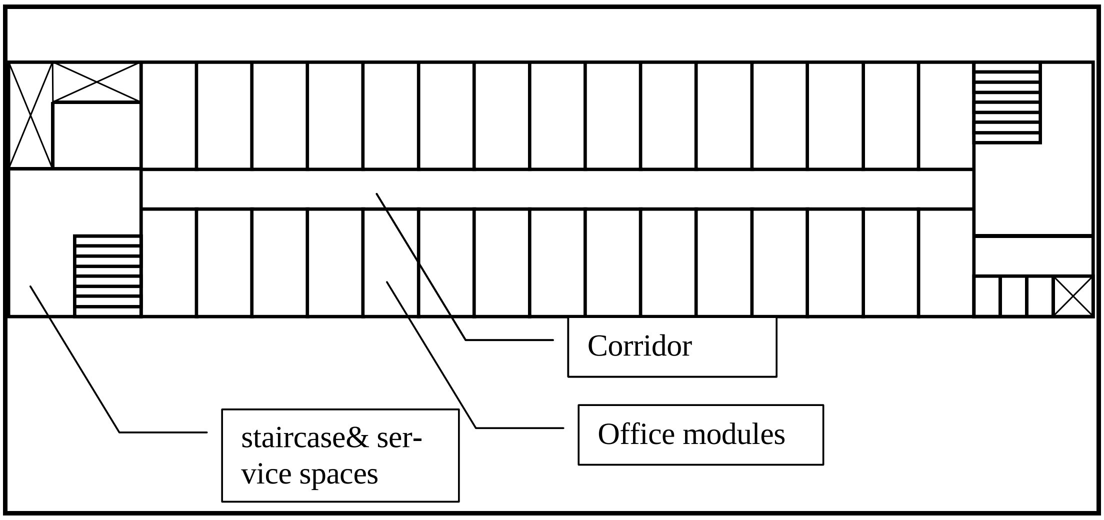


Fig.3.14. *Floor plan of the cluster of office units* (Van Dijk, 2001)

3.4.1. Evolution of office building's façade through time in Europe and Greece in particular

In this chapter we will develop the evolution of office typologies, since the beginning of office work within an organized space and the parallel evolution of office façade and shading.

The history of office building started the 13th century with the development of government's buildings. In fact the typology of office buildings started to be separated from other functions in the industrialization period due to the fact that bureaucratic procedures were developed. Most of the office buildings were following the traditional building typology and the offices were cellular offices around an external or internal corridor (Fig. 3.15).

The single office cell is the primary form of construction and the most common type in the public sector. It actually consists of a row of offices with one or two occupants, developed along the façade. All office desks are placed parallel to the façade. For this reason the use of specific façade systems that can exclude direct solar beams and at the same time achieve a comfortable visual and thermal interior environment are required (Fig. 3.15).

In the beginning of the 19th century new construction materials started to be used in buildings – like steel and Iron – but the typology of the façade has not changed drastically till the end of the 2nd World War. Basic requirement of light and ventilation were obtained through openings in the façade. That lead to the development of the first comfort regulation on 1924 (Roetzel & Tsangrassoulis, 2010).

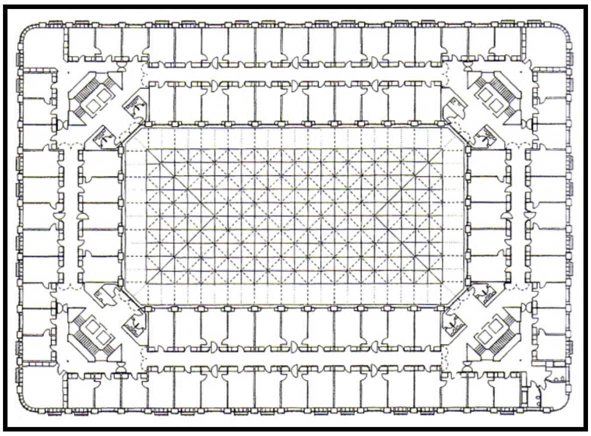


Fig. 3.15. *Diagrammatic plan of office units*
(Hascher et al. 2002, p. 103)

The period after 1945 is characterized by the use of nuclear power in the building environment. Air conditioning for heating and cooling as well as artificial lighting were introduced in the building sector and this resulted to the transformation of the façade envelope to a sealed structure that isolates the interior from its physical environment. The open plan office building was developed as a new internal configuration and the curtain wall façade was promoted due to newly developed construction methods. On 1938 a new comfort code was developed that incorporated air conditioning systems (op. cit).

The period after 70s is characterized by the development of new technologies in the computer science and communication and these changes have an impact in the office space requirements. The office work is based on the computer screen and the comfort requirements are taking on account these facts. A new work flow was developed that lead to the generation of other types of office spaces, more flexible, that foster collaboration. A new type of office configuration that emerged is the "Landscape office". It is based on the idea of a flowing space that can accommodated different types of working processes for individuals and team work. The "curtain wall" system and the separation of the supporting structure to the envelope could collaborate very well to the above mentioned internal configuration (Hascher et al., 2002) (Fig.3.16).

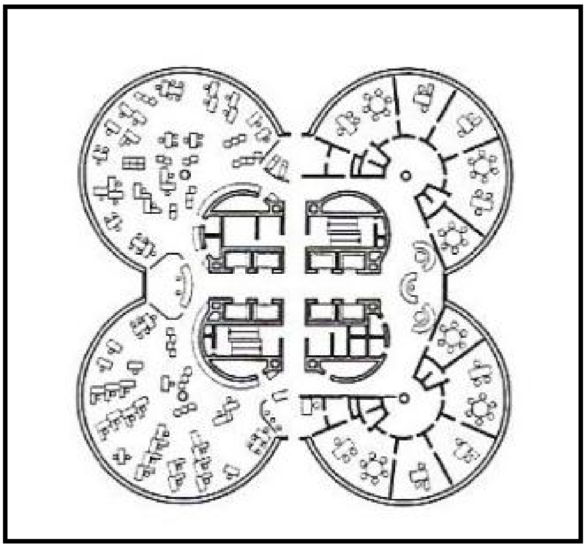


Fig. 3.16. *Diagrammatic plan of open - plan offices*
(Stanier, B & C., 2011)

A typical open- plan office can be seen in (Fig. 3.16). It has its origin in the US large factory type working spaces. It was introduced in Germany in the 1960s coinciding with the economic boom. The free layout of these offices requires specific arrangements on their façade in order to achieve uniform comfort conditions. A great effort is put in order for thermal and comfort conditions to be the same in offices near the façade and those further from it (30 to 40 m). This means that specific geometrical configurations, such as light-shelves for example, of semi-transparent elements, are used in the façade for distributing the light into the depth of the space, in order to avoid problems with glare and to gain thermal radiation

After the energy crisis in 1973 and the Chernobyl disaster in 1986, the sustainable development of the buildings and the environmental impact of them, became an extremely important issue. New buildings technologies started to be used in the façade that could better control the interior environment without additional energy usage. The parallel development of glass industry leads to the use of coated glazing that could control better solar gains but could lead to the increase of artificial lighting usage.

A combination of the above types is the group office, where space is actually divided in larger and bigger groups than the unit cell. This allows for smaller spatial dimensions and room depth that can provide natural light and sun through the façade. This means greater façade area in relation to function area. The group area can be subdivided in smaller areas with half-height furnishing or partitions (Stanier, B. & C., 2011) (Fig.3.17). A continues "curtain wall" façade system could accommodate all internal configurations.

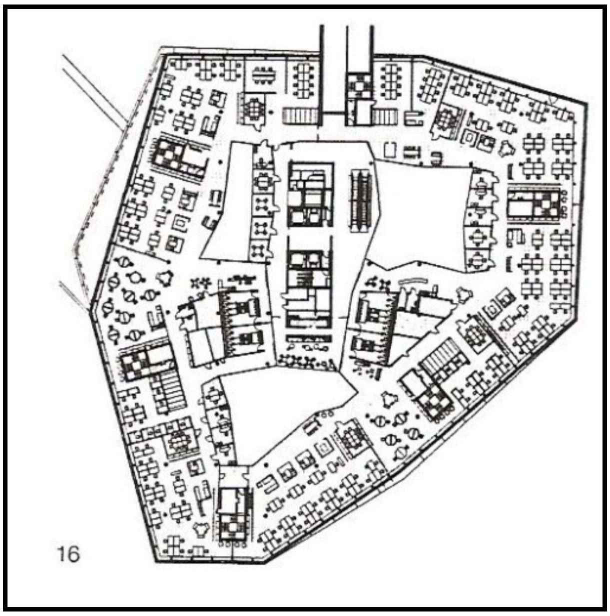


Fig. 3.17. *Credit Suisse Bank Zurich, 2011*
(Stanier, B. & C., 2011)

Before the end of 90s the idea of the complete sealed façade started to be questioned due to the recognition of the "Sick building Syndrome" by the World Health Organization. This ascertainment leads to the rejection of the isolation of internal environment through the façade and to the return of natural ventilated and daylighted office buildings. New types of facades are emerging that are combining environmental control and natural ventilation and lighting. Amongst them the automatic and mechanically controlled double skin high tech facades are the most common. In 1992 the new ASHRAE Standards were developed.

A more developed type of office is the combined type. It is the spatial combination of the unit cell and the open plan office. The standard unit cells are lined up along one façade, while an open plan distribution of office desks is developed along the other façade. The requirements are not completely different for the two facades. In both cases a minimum of 7 m of naturally lit and ventilated spaces is needed through the façade. More detailed analysis is needed mostly concerning specific daylight requirements for the specific subject units (Fig.3.18).

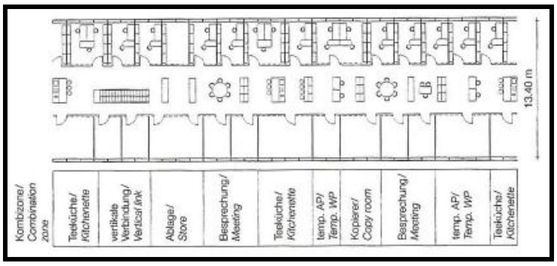


Fig. 3.18. *Diagrammatic plan of combination offices*
(Stanier, B. & C., 2011)

Nowadays the most popular office configuration is the "business club" that the space does not belong to an individual but can be shared by different occupants according to their needs. The reversible office is a common need that can be flexible in plan and in the façade. This lead to the use of lightweight materials in the interior and the decrease of thermal mass of the building that lead to much more energy needs of cooling the offices (Roetzel & Tsangrassoulis, 2010).

Additionally an important change in the new ASHRAE regulation is made in 2004: the differentiation of the natural ventilated buildings and the full air conditioned building are governed by different standards (op.cit.). New façade typologies are emerging that are taking into account the possibility of natural ventilation and the mechanically heating and cooling systems.

In Greece the first office buildings are built after 1928 and are based on the office cell organizational diagram. This organization is projected on the façade by a repetitive window of a fixed size that assures basic natural ventilation and daylight in each office unit. The glazing of the window was positioned at the inner side of the wall so that the width of the upper part of the opening could work as shading.

Later on, architectural style in Greece followed the European nomenclatures of the modern movement and the new modern office buildings possess a façade liberated from the skeleton. The curtain wall was established in Greek architecture ignoring the specific characteristics of the climate. High tech daylight distributing systems were used without any extra external shading protection devices – crucial for the Mediterranean climate due to high thermal gains for almost six months per year (Fig. 3.19). The first examples of the use of fixed external louvers and the Brise – Soleil system as a shading protection from the summer sun were introduced in Greece by the end of 60s. This feature can be seen in the multifunctional building of T. and D. Biris in Galatsi (E. Venizelou), Athens and the Bank of Crete of K. Dekavalas at Voukourestiou and Valaoritou Street in Athens (Philippidis, 1984).

Fig. 3.19. *Agriculture Bank of Greece, Athens with the light –self. The dark colour of the ceiling cancels the daylight distribution*
(Baker & Steemers, 2001, p. 154)

A lot of buildings had been constructed till then with either fixed shading systems or coated glazing. During 80s' and almost till the end of 90s' most of the office buildings in Greece were actually following European aesthetical and environmental standards. Large glazed coated single facades, that allow basic natural ventilated and daylighting, are the common form of office building in large cities. These façade systems could not achieve thermal comfort and the offices required high amount of energy in order to air condition the building, especially the long summer periods.

One of the first office buildings in Greece that followed the European Aesthetical standards that were connected to the economic development and reconstruction, that came to Greece some years later than Europe, was the Athens Tower build between 1968 and 1971. The offices are distributed in the four facades and in the center are the corridors and the elevators. All facades are having the same amount of coated glazing regarding the orientation without any additional shading (Fig. 3.20). After this high rise office building similar, with lees floor levels, started to come up in the most urban centers, all over Greece.

Fig.3.20. Athens Tower by I.Vikelas, 1968 – 1971, (http://en.wikipedia.org/wiki/File:Athens_Tower.jpg)

Greece has a Mediterranean climate. According to the relevant climatic data, the annual cycle can be divided into a cold and rainy season (October to March) and a warm and dry season (April to September). Temperatures on the Greek mainland present intense contrasts mainly due to geographic factors. Greece is between the average annual isothermal of 14.5 and 19.5°C. The extreme temperatures are close to -25 °C (during winter in the mountainous and northern regions) and +45 °C (during heat waves on the mainland). The climatic data above relate mainly to the countryside. In urban environments, in which the majority of buildings are situated, these data change as a result of the influence of the factors which make up the urban climate (Landsberg, 1981).

The factors influencing energy performance of buildings in Greece, under the particular climatic conditions, are more or less specific, similar throughout the country and outlined (Papamanolis, 2006). It is indicative that the regulatory framework of environmental design principles remains essentially the same since 1979. Unsuccessful efforts for its improvement have been done in the past. It is only since October of 2010, that the application of a set of measures for the improvement of the energy performance of buildings in Greece started, in order to apply the EU Directive 2002/91/EC (Papamanolis, Mandalaki, 2011).

Only after the EU directive office buildings in Greece started to adapt to the specific urban climatic conditions of the region and taking into account shading requirements (Fig.3.21, Fig.3.22). The implementation of the low that followed this directive came to the force officially on 2010. Till then almost all office building were following curtain wall glass facades that prevent heat gains through coated glazing and obtaining thermal comfort through air conditioning.

Fig. 3.21. Folli – Follie Building in Athens, Ag. Stefanos, 2003, M. Kokkinou – A. Kourkoulas (Hindrichs, 2009)

Fig. 3.22. Dikastiko Megaro Trikalon, 2006, Kizis, I. (Hindrichs, 2009)

Further non, movable Shading Systems were implemented in the Greek office building as well - some of them with integrated PV systems. Examples of buildings with movable shading louvers are AVAX offices of A. Tombazis in Athens and ABB offices of N. Ktenas in Thessaloniki (Philippidis, 1984) (Fig.3.23 and Fig.3.24).

Fig.3.23. AVAX office building. A. Tombazis, Athens
http://www.tombazis.com/main_gr.html/ accessed 12/2012

Fig.3.24. ABB office building. N Ktenas, Thessaloniki
DOMES, 11/2007, New office building in Greece II

Even if these systems have been extensively applied in Europe, they have not met the same support in Greece. Givoni (1969) has argued in favor of the improved performance of the movable shading systems for the climate of , that is very similar to that of the south of Greece. The application of these types of systems has not been expanded as one would expect. This is mainly due to three reasons:

1. Higher construction costs in relation to fixed shading systems, the requirement of precise construction details as well as maintenance costs. Both are not easy to obtain within the Greek construction market.

2. Lack of specialized designers that would promote these types of movable structures and

3. Lower user acceptance preference of automated movable systems especially in buildings like offices where there is a high users' turnover. On the other hand the non automated systems would not be operated by all the users because for this to happen technically, construction and installation costs would probably be higher than the savings. The predominance of fixed to movable systems in architectural applications is not the main subject of this research, but it is a fact that we took into account when focusing the main objectives of this research upon fixed shading systems.

We believe that office building cell is suitable for our study due to the fact that it allows for controllable conditions. Our research is based on the comparative analysis and not on the values themselves. In order to achieve the same fixed parameters for comparing the performance of different SDs we took the office cell as a basic unit. The performance of the SD is evaluated for this environment but the results are generalized according to relations between different geometrical configurations. The office unit examined with different SD has the same constant properties in relation to interior surface, color and materials used. We will describe the details in paragraph 3.5.1.

3.4.2. Energy savings through shading systems

The design of sun shades for windows is very important in Mediterranean countries. The role of window is to permit natural illumination and allow view to outside. The main issue in the design of the openings is to prevent as much penetration of direct solar radiation as possible.

Shading systems can help reduce energy loads in many ways; first of all by reducing the cooling loads during the summer period. Shading systems reduce direct solar radiation entering the building therefore the energy needs for supplying air conditioning systems are reduced.

In winter they can allow direct solar radiation. Depending on the orientation and the latitude, a well designed shading system can allow solar gains during winter.

Especially in the case of Mediterranean climate, characterized by a high position of the sun in the summer period and low in the winter period, the design of south facing shading systems can be effective, even for fixed shading systems. The balance between solar gains in the winter and solar exclusion in the summer in relation to reduction of daylight determines the efficiency of the shading system.

Shading systems can reduce daylight availability but at the same time depending on their design, they can increase the distribution of daylight in the room (light shelves or other daylighting systems). This fact is crucial in order to increase savings in the use of electric light. In chapter 4 more details will be presented. Daylighting systems are strictly not the subject of this research.

The reduction of the interior temperature that shading systems can achieve is very important for thermal comfort. Thermal comfort conditions are crucial for the health, the productivity and the sense of well-being of the users, especially in office buildings.

3.4.3. Thermal Comfort conditions

It is important at this point to define thermal comfort conditions as we will incorporate those in our research. Thermal comfort can be defined in two ways: connected to measured and non measured parameters.

Firstly thermal comfort can be defined as a specific combination of air temperature, relative humidity, air motion and mean radiant temperature (Lechner 2001). "Thermal comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the body's effort of regulation is minimized (after ASHRAE 1997). Certain combinations of air temperature, relative humidity (RH), air motion, and mean radiant temperature (MRT) will result in what most people consider thermal comfort. When these combinations of air temperature and RH are plotted on a psychrometric chart, they define an area known as the comfort zone. Since the psychrometric chart relates only temperature and humidity, the other two factors (air motion and MRT) are held fixed. The MRT is assumed to be near the air temperature, and the air motion is assumed to be modest."

A basic tool to define these parameters is the psychrometric chart. The area defined in the chart as shown in fig.3.25 is the combination of all the above parameters and defines the ideal thermal environment for the human body.

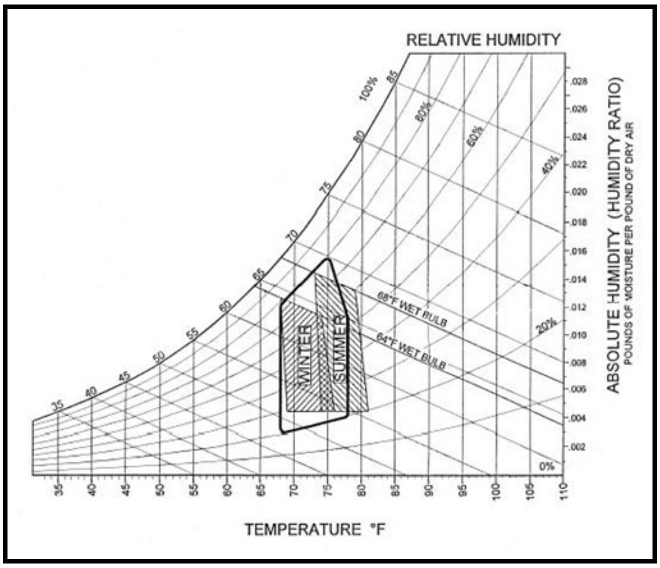


Fig. 3.25. *Psychrometric chart* (Lechner, 2001)

There is another definition for thermal comfort that includes non measured parameters and is according to ASHRAE: the condition of mind which expresses satisfaction with the thermal environment (ASHRAE n.d.). The condition of mind is a completely non predictable condition and it depends on non measured parameters dealing with the type of user, his level of education, the relation with his colleagues and superiors, time of pressure etc.

A basic "rule of thumb" can be found in basic diagrams proposing limit temperatures of comfort according to the activity within the space. In Greece, after the implementation of Energy Efficiency Building Regulation Low that followed the EU Directive 2002/91/EC on the Energy Performance of Buildings, these values have been recorded as in Fig.3.26.

Type of Building	Temperature °C		Relative Humidity	
	Winter period	**Summer period**	**Winter period**	**Summer period**
Single Family House - Multy story housing	20	26	40	45
Hotel all seasons	20	26	35	45
only summer period	20	26	35	45
only winter period	20	26	35	45
Hostel all seasons				
only summer period	20	26	35	45
only winter period	20	26	35	45
Boarding house	20	26	40	45
Hotel or Boarding Bedroom	20	26	35	50
Resaurant	20	26	35	50
Patisserie - café	20	26	35	50
Bank	20	26	35	45
School	20	26	35	45
RetailCenter	19	25	35	45
Office	20	26	35	45
Library	20	26	35	50
Garage	19	25	35	45

Fig. 3.26. *Optimum temperatures for different activities* (Energy Efficiency Building Regulation Low, 2010)

For the purpose of this research we will focus on the first definition of thermal comfort in order to assure some invariant parameters that can lead to comparative results. We consider the energy needs of an air conditioning system to provide for temperatures between 18 - 26 ^{o}C and we assume that relative humidity is kept between 20 to 80%, air velocity (20 fpm to 60 fpm) and mean radiant temperature near air temperature, following the psychrometric chart.

3.5. Experimental work with shading systems – Simulation of energy needs for heating and cooling

In order to evaluate the performance in energy savings of different shading geometries for the Mediterranean climate, we did experimental and simulation work. The experimental work is divided in three areas (as we can see in the Methodological diagram in Fig.1.1 in chapter 1). The first area concerns the determination of best performing systems in terms of energy needs for heating and cooling the shaded space. We examine both the energy needs for heating the space and the energy needs for cooling the space in order to achieve temperatures between 18 and 26^{o} C, for office hours of 9:00 to 17:00 for five days per week.

The other two areas will be presented in the next chapters and concern the visual performance of the shading system examined and the potential energy production through the integrated PVs on them. A balance between the reduction of daylighting levels and the replacement by electric light and the electricity produced by the PV is being achieved.

In the present chapter we focus only on thermal and cooling loads.

3.5.1. Properties of the reference office unit

The bibliography research conducted concerns shading systems that can be used for south orientation (Neufert et al., 2002) and then these systems were geometrically adapted to the latitude of Chania, Crete. The basic steps that Olgyays (1957) proposed are followed for their design. The determination of 100% shading for the overheated season (between June and August) and then the determination the times of the day that the 100% of the shading is needed are the two basic steps. We summarized that between 11:30 to 13:30 solar time we need full exclusion of the direct solar radiation. These where determined using the weather data of Chania, Souda that were implemented in the software Ecotect and EnergyPlus, in order to conduct the simulations.

Then the use of sun path diagrams (see Appendix) helped us to determine the specific geometry of the fourteen shading systems that we examined. These geometries have been designed in Ecotect and were tested in the beginning in the shadow display mode in order to confirm the exclusion of direct solar radiation between 1st of June till the 24rth of August from 11:30 to 13:30 solar time.

Due to the symmetrical movement of the sun (as we can see in the sun charts), and because exclusion of direct solar radiation is very important during August, the shaded period was expanded to the 18th of April. One of the main problems of fixed shading systems is the exclusion of direct solar radiation in periods when it might be useful.

We used the parameters proposed by the SWIFT project, Switchable Facade Technology, in the Reference office for thermal, solar and lighting calculations for the examined office unit. The reference office building is a middle-size office building with office units aligned on two facades, separated by a central corridor, with staircase/service spaces at both ends of the building (Van Dijk, 2001) (Fig.3.9).

The office unit is repeated horizontally to form one floor level and vertically to from all storey levels. We did not take into account the seven storey levels and the fifteen repeated units per storey because this would confuse the results of the performance of shading device. When calculating the energy production we did not take into account the overshadowing between the repeated shading systems, in order to avoid using dissimilar examined parameters. The longitudinal axis of the building is oriented east – west so that one series of office units is facing south and the other north. We examine shading systems with south facing devices.

The building is located on a flat terrain with no shading from adjacent hills, buildings or trees. We assumed a ground reflection for incident solar radiation of 0.20.

The office unit has net dimensions of 5.4 m to 3.5m with the short edge facing south as proposed by Van Dijk (2001). The height of the office unit is 2.9 m, and not 2.7m as proposed by Van Dijk, in order to be adapted to the typical floor height of Greek office buildings (Fig.3.27).

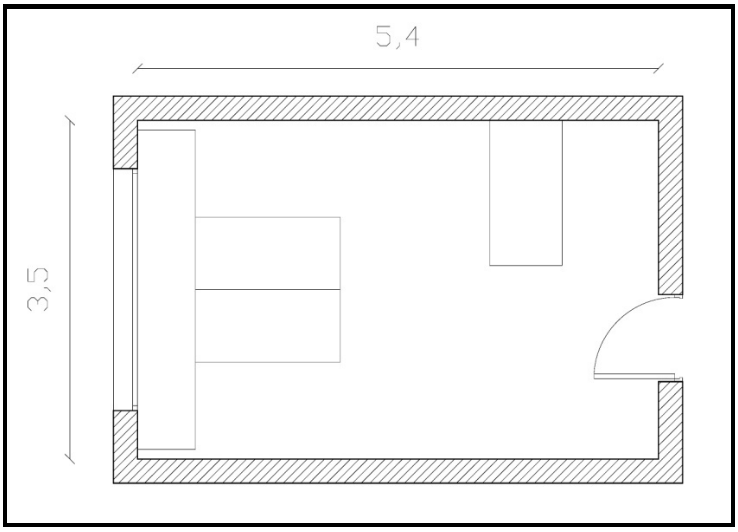


Fig. 3.27. *Floor Plan of the examined office unit*

The proposed window examined is taking into account the properties of the window proposed by Van Dijk, but has different geometrical proportions. It is a single window with net dimensions of 2.4m x 1.9m (width x height). In order to improve the validity and reliability of the results, another window is examined in parallel, its dimensions being 3.3 x 1.9m (width x height). The ratio of the window's surface to the floor area is either 24% (Van Dijk, 2001) or 33%. The ratio of window to facade area is 44.92% in the first case and 61.77% in the second one (Fig. 3.28).

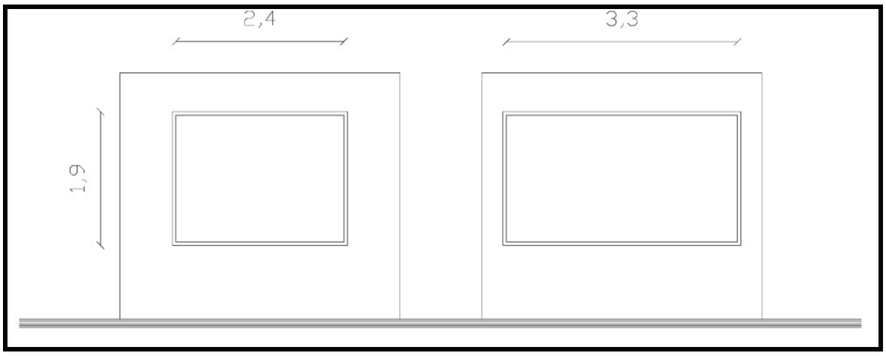


Fig. 3.28. *Two window sizes examined (44.92% and 61.77% WWA)*

The two types of window openings are examined for two latitude points, for Greece: Athens (37.58^{o} N) and Chania, Crete (35.30^{o} N). Both are coastal areas, typical examples of Mediterranean climate. This climate is characterized by mild winters with high solar radiation long daytime and by hot summers. The extreme positions of the sun are about 77^{o} high in the summer and about 30^{o} high in the winter at 12:00 solar time for a south facing plane. Both latitude points lie between the middle parallels of Mediterranean Sea. Demands for cooling, increase during summer due to high temperatures and the significant seasonal rise of population because of tourism.

The examined Shading systems are compared to a single, double glazed window type without shading (Ismail & Herniquez, 2003). The characteristics of the glass used for all shading systems examined, are similar to a typical double glazed **aluminum** frame window with thickness 0.042 m (glass, void, glass) and visible transmittance 0.898, total solar energy transmittance 0.837 and U-value 2.7 W/m2k.

Regarding the quality of the interior materials, all five surfaces of the reference room are considered to be adiabatic. Only the wall on the facade that incorporates the window is thermally conductive and through this wall, there is heat exchange with the outside. The materials used are the following: a concrete floor with carpet and external insulation, a suspended concrete ceiling and interior framed plasterboard partitions (considered as adiabatic), external double brick wall with insulation and U-value = 2.700 W/m2k, density 1030.42 kg/m3, and a double glazing as described above. The reflectance of the material used is 0.85 for the ceiling, 0.65 for the walls and 0.20 for the floor – these parameters are used for the lighting analysis. Internal gains from lights, appliances and people have been excluded from this research.

More details concerning the proposed positions of the occupants, the position of the luminance and interior furnishing that we took into account are going to be presented in the next few chapters because they mainly influence the daylight evaluation parameters.

For the evaluation of the shading systems and the comparison of their performance in relation to an un-shaded double glazed window we used the validated software EnergyPlus. The weather data for the city of Athens are imported from the website of EnergyPlus software. The input in the computer application of the weather data for the city of Chania is a work that has been done at, at the Renewable and Sustainable Energy Laboratory of the department of Environmental Engineering, Technical University of Crete (see Appendix).

3.5.2. Thermal behavior of the examined space

In this paragraph we focus to the thermal behavior of the examined space. In the case of the office unit that we examine heat transfer occurs through the external wall and through the glazing and frame combination. The rest of the walls, roof and floor are considered to be adiabatic.

We will further on briefly describe the way that Energy Plus measures heat transfer from a shaded window. EnergyPlus calculates the solar radiation incident on the outside of the window from the sun, sky and ground. Direct solar from the sun is determined from measured direct normal irradiance from the weather file and calculated incidence angle. Ground diffuse solar is determined from total solar incident on the ground, ground solar reflectance and view factor from window to ground. In general the EnergyPlus calculates solar radiation incident on window, total horizontal solar radiation, outside air temperature, inside temperature. Glass is considered to be opaque to long wave radiation and the glass layers are extremely thin so that heat storage can be neglected. Additionally glass face are isothermal and the short wave radiation that is absorbed in the layers can be equally distributed in the two layers of the glass pane. Shadows from shading devices and other obstruction are taken into account: For each window EnergyPlus calculates the shadowing of solar radiation caused by setback, overhangs, neighbouring buildings and other obstructions (Winkelmann, 2001).

Furthermore the fluctuation of the solar-optical properties (T, A) of the conventional glass used in construction, without coating is used in the calculations taking into account the angle of incidence and the thickness of glass. Finally, the reflection coefficient is calculated from the equation:

$\rho=1-\tau-\alpha$ (ASHRAE, 1981)

3.5.3. Description of Shading Systems Examined

We designed thirteen basic types of shading systems according to geometrical specifications for the latitude of Crete so as to exclude direct solar radiation till the 30th of August at least between 11:30 to 13:30 solar time for a south facing window. For some systems the exclusion of direct solar radiation covers a wider period of the year. This does not mean that these systems can be considered to work better than others because the reduction of cooling loads means at the same time increase of heating loads for the cold season.

The specific geometrical configuration of the systems is presented in the following figures. The examined systems are basically divided in two main groups: The façade systems are obstructing view to outside and the non façade systems allow the transparency of the façade. They are the following:

Shading systems that allow transparency:

1. **Canopy horizontal**: is a 1m width canopy in order to provide 100% shade till 13:30 solar time in August (Fig.3.29).

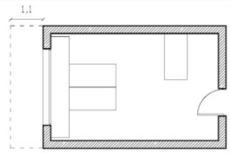
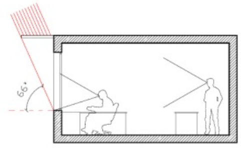
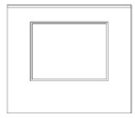
Shading System	Plan	Section	Front View
Canopy Horizontal			

Fig. 3.29. *Plan, section and Front view of canopy horizontal shading System*

2. **Canopy horizontal double:** is composed of two canopies of 0.63m width, placed in the upper part of the window in order to provide 100% shade till 13:30 solar time in August (Fig.3.30).

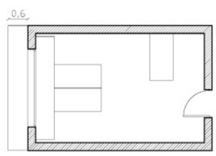
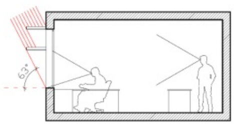
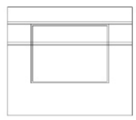
Shading System	Plan	Section	Front View
Canopy Horizontal Double			

Fig. 3.30. *Plan, section and Front view of canopy horizontal double shading System*

3. **Brise Soleil full façade:** is composed of four elements around the window, two horizontal and two vertical with 1.00m width in order to afford 100% shade all day long till the end of September (Fig.3.31).

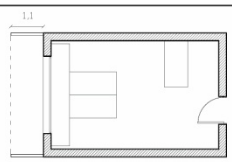
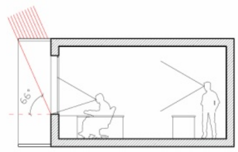
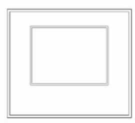
Shading System	Plan	Section	Front View
Brise Soleil Full Facade			

Fig.3.31. *Plan, section and Front view of Brise Soleil Full Facade shading System*

4. **Brise Soleil Semi façade:** is almost the same as the previous one with two basic differences in the position of the horizontal element which are placed near the edges of the window and their width is 0.87m in order to provide 100% shade all day long till the end of September (Fig.3.32).

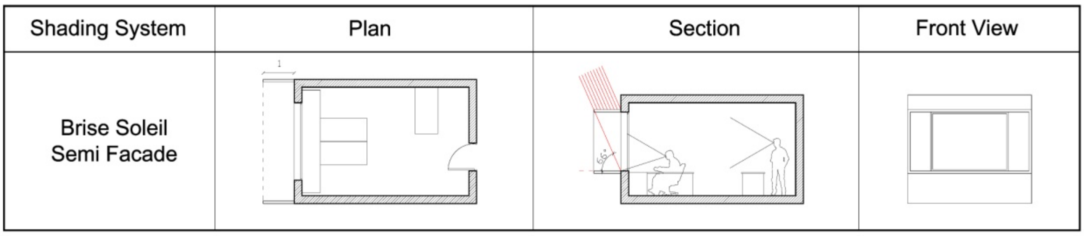


Fig.3.32. *Plan, section and Front view of Brise Soleil Semi Facade shading System*

5. **Surrounding Shade:** is composed of a horizontal and two vertical triangular elements. The horizontal element has 1.78m width in order to afford 100% shade all day long till the end of September (Fig.3.33).

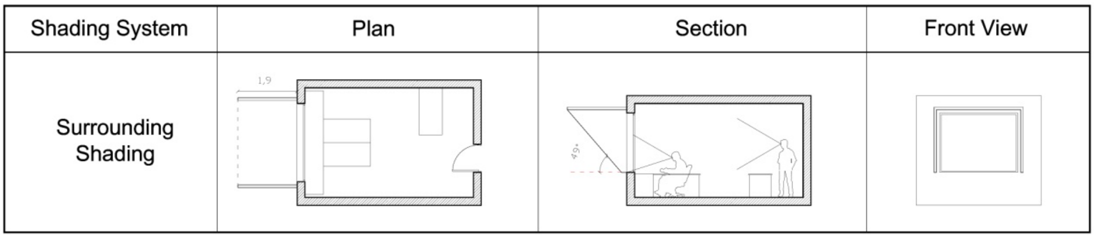


Fig.3.33. *Plan, section and Front view of Surrounding shading System*

6. **Canopy Louvers:** is composed of a canopy of 1m width with inclined louvers of 16° in order to provide 100% shade till 13:30 solar time in August (Fig.3.34).

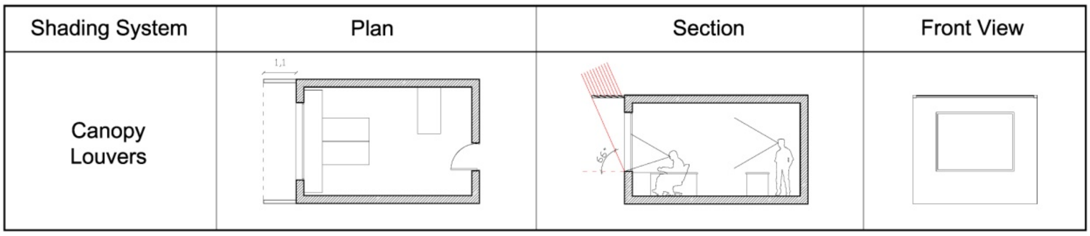


Fig.3.34. *Plan, section and Front view of Canopy Louvers shading System*

7. **Canopy Inclined Single:** is composed of an inclined canopy with inclination of 24° and 0.89m width in order to ensure 100% shade till 13:30 solar time in August (Fig.3.35).

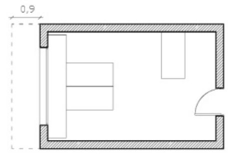
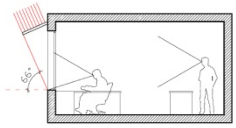
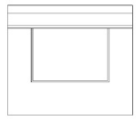
Shading System	Plan	Section	Front View
Canopy Inclined Single			

Fig.3.35. *Plan, section and Front view of Canopy Inclined Single shading System*

Façade Shading Systems that obstruct view to outside:

8. **Canopy Inclined double:** is composed of two inclined canopies with inclination of 30 ^{o} and 0.62m width in order to ensure that there is 100% shade till 13:30 solar time in August (Fig.3.36).

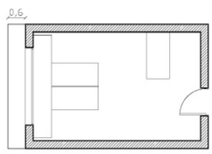
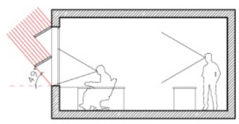
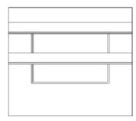
Shading System	Plan	Section	Front View
Canopy Inclined Double			

Fig.3.36. *Plan, section and Front view of Canopy Inclined Double shading System*

9. **Brise Soleil Semi Façade with Louvers:** Is the same as the Brise Soleil Semi facade system with additional louvers of 0.30m width on its façade in order to ensure 100% shade all day long until the end of September (Fig.3.37).

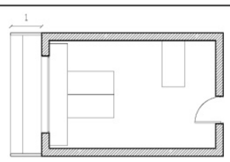
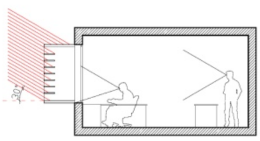
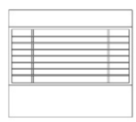
Shading System	Plan	Section	Front View
Brise Soleil Semi Facade Louvers			

Fig.3.37. *Plan, section and Front view of Brise Soleil Louvers shading System*

10. **Louvers Vertical:** is composed of vertical louvers of 0.20m width and 0.15m axial net distance between them in order to provide 100% shade till 13:30 solar time in August (except at 12.00 solar time) (Fig.3.38).

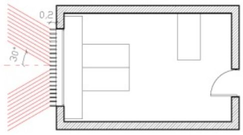
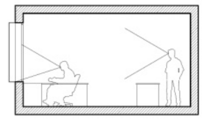
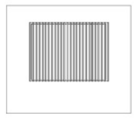
Shading System	Plan	Section	Front View
Louvers Vertical			

Fig.3.38. *Plan, section and Front view of Louvers Vertical shading System*

11. **Louvers Horizontal:** composed of horizontal louvers of 0.10m and net axial distance 0.08m in order to afford 100% shade all daylong till the end of October (Fig.3.39).

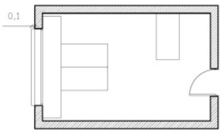
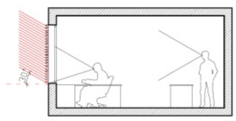
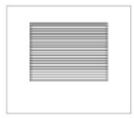
Shading System	Plan	Section	Front View
Louvers Horizontal			

Fig.3.39. *Plan, section and Front view of Louvers Horizontal shading System*

12. **Louvers Horizontal inwards inclined**: composed of louvers inclined at 46^{o} and width 0.20m in order to ensure that there is 100% shade all daylong till the end of October (Fig.3.40).

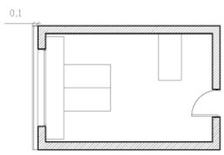
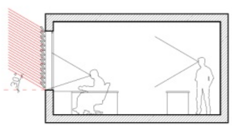
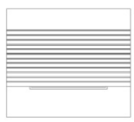
Shading System	Plan	Section	Front View
Louvers Horizontal Inwards Inclined			

Fig.3.40. *Plan, section and Front view of Louvers Horizontal inwards inclined shading System*

13. **Louvers Horizontal Outwards Inclined:** composed of louvers inclined at 57^{o} and width 0.20m in order to provide100% shade all daylong till the end of October (Fig.3.41).

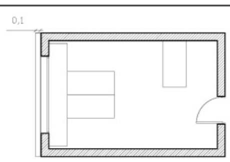
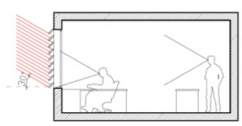
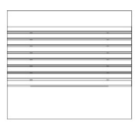
Shading System	Plan	Section	Front View
Louvers Horizontal Outwards Inclined			

Fig.3.41. *Plan, section and Front view of Louvers Horizontal outwards inclined shading System*

Additionally in order to incorporate the holistic parameter of the integration of PV systems to the design systems we assumed a width of 3cm for the cases of louvers, as a worst case scenario. In the case of the rest of the shading systems we assume a skeleton of 8cm that supports the PV modules.

3.6. Conclusions – The balance between reduction of cooling and increase of heating loads

As expected, according to thermal simulation concerning cooling and heating loads, there are some differences between the two latitudes examined, due to different sun position. There are even some differences between the same latitude point and different window sizes due to new geometry that is actually needed for different window sizes. This geometrical adjustment was not made in this research because it would have confused the results.

The SDs that seem to be the most efficient in terms of energy savings for both latitudes and both window sizes are **Surrounding shading**, some of the systems with **Louvers** depending on the relation of the inclination to the examined latitude and the **Brise–Soleil full façade** or **semi facade** depending on the latitude and the window size. Some of these systems do not block reflected sun beams entirely and at the same time they allow communication with the outside. The systems of **Louvers horizontal inclined or not** and the **Brise–Soleil semi facade louvers** have proved to consume energy mostly for heating purposes. These, are systems that block direct and reflected sun radiation and it is obvious that they can be efficient enough in terms of cooling loads, needed most of the year, but at the same time they block beneficial solar radiation for the winter. We will discuss their performance in relation to daylighting in the next chapter.

Additionally, it is important to mention that despite having SDs there is still energy needed to cool the office unit for all the cases of the examined shading systems (Fig. 3.42).

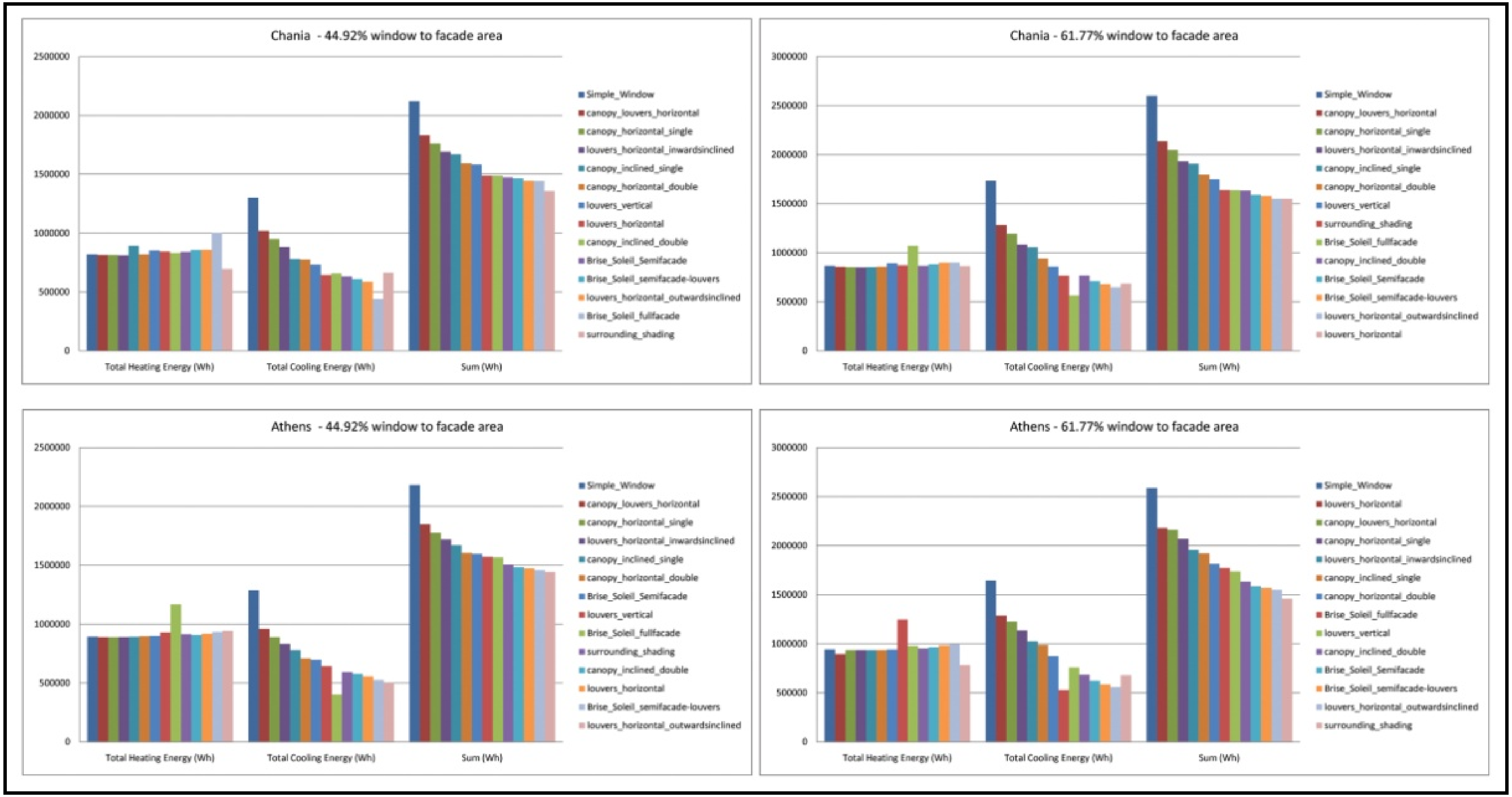


Fig.3.42. *Energy consumption for heating and cooling the office unit*

The energy used for cooling is approximately the same with the energy used for heating for all shading systems except for the case of Brise – Soleil Full Façade. This system even if it is among the most energy saving system, it consumes the most for heating the space, probably due to exclusion of direct sun light during the winter period. Further research needs to be done for this type of shading system in order to decrease the energy needs for heating the space that it shades, maybe by changing its wings inclination or by increasing its permeability to sun radiation according to different material properties (Fig. 3.43 – 3.44).

If we look in a more detailed way the energy needs of each space shaded by a different SD we can see that that for both Chania and Athens when the energy needs are high this is due to cooling loads, meaning that the shading system does not perform well: when the shading system is not appropriate designed the energy needs of the space are changing drastically.

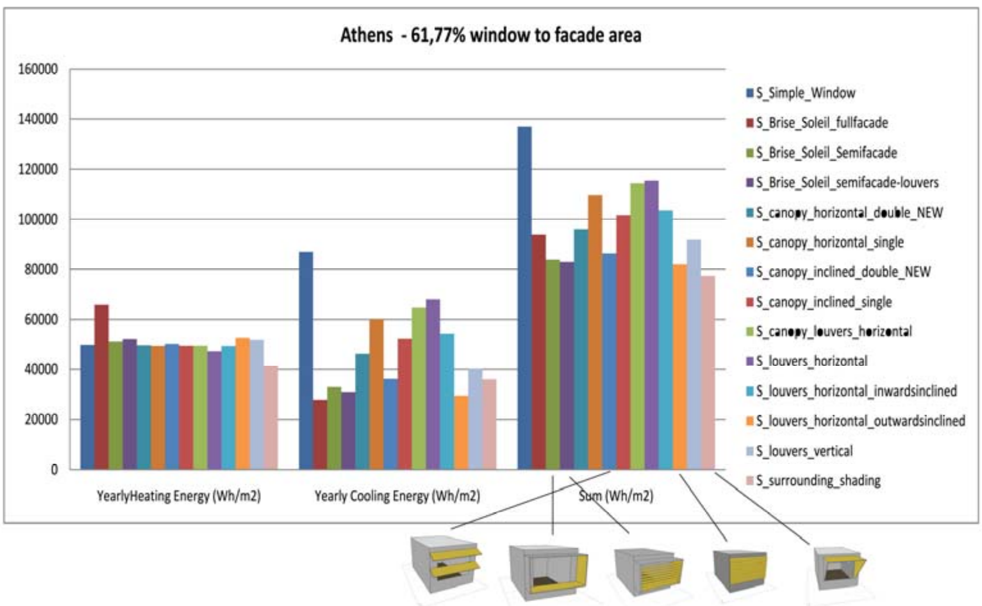


Fig. 3.43.*Yearly Energy needs per m2 for office units with different shading systems in Athens*

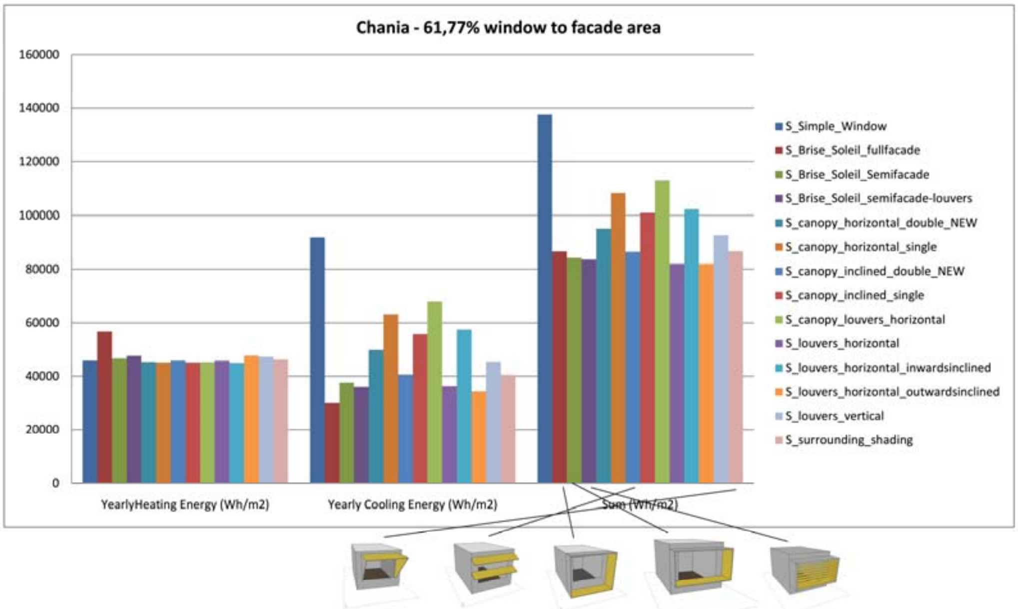


Fig. 3.44.*Yearly Energy needs per m2 for office units with different shading systems in Chania*

It is remarkable to see that the same systems are amongst the best performing for both latitudes points but their exact order is changing slightly according to the latitude (Fig. 3.45).

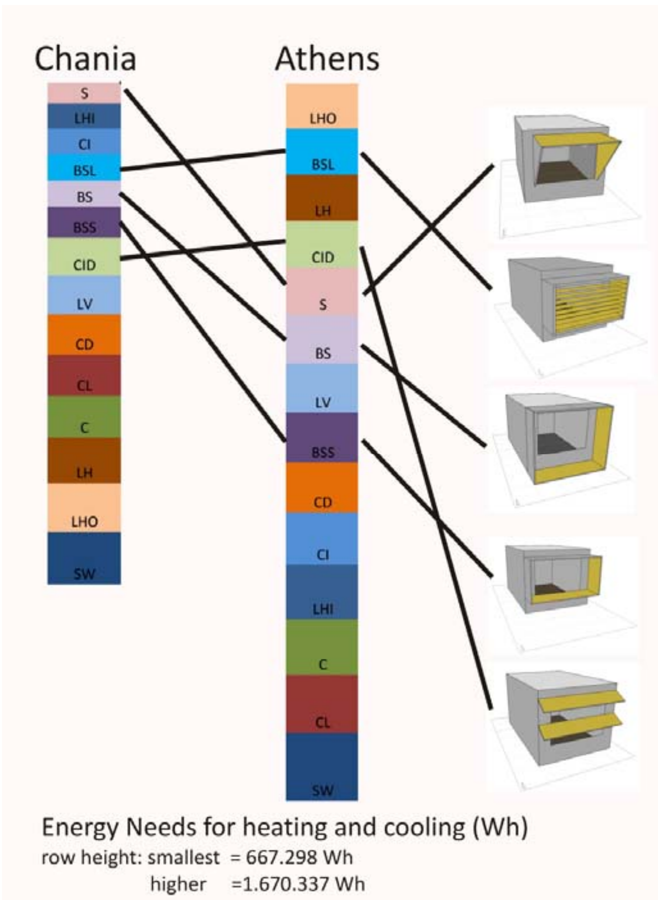


Fig. 3.45. *Yearly energy needs of the office unit according to different latitude (Athens and Chania)*

4. Shading Systems: relation to daylighting

When examining ways to utilise solar radiation we should do this in parallel with studying the availability of daylight. Nowadays we use shading systems to decrease the incoming solar radiation. At other times the interior daylight levels decrease and the use of electric lighting consequently increases which results in demand for extra energy and increasing thermal loads indoors (Koster, 2004).

There is a quantitative difference between the energy loads released from the electric lighting (depending on the type of light-bulb used) and the energy from the sun used to illuminate the interior space. Sun radiation provides about 100 lumen per W while an electric light-bulb gives us only 50 lumen per W. So in order to achieve the same levels of illumination, more energy loads are released when we use electric lighting. This is one of the main reasons why the controlled use of daylight can lead to additional energy savings: because apart from electricity savings from reduced use of artificial lighting we save energy due to less need of energy for cooling (op.cit.).

For buildings predominantly used during daytime, (e.g. offices) using large amounts of energy to provide artificial illumination makes little sense financially. For this reason the implementation of a shading system is crucial in order to reduce the energy needs for electric lighting, and as we showed in chapter 3 to reduce the total energy needs.

In the previous chapter we showed that some shading systems are better in reducing the energy loads for heating and cooling. In this chapter we will examine the behaviour of 13 shading systems and their relation to daylight in terms of its quantity and quality. With reference to daylight quantity we will further on estimate the energy savings from the reduction in the use of electric lighting. In terms of daylight quality we will evaluate the systems in terms of the visual comfort they afford. Daylight quality is valuable in the office space as it indirectly contributes to energy savings (see 4.2.1).

4.1. Fundamentals of daylight: illumination, luminance, behaviour of light

Before we talk about the relation of shading systems with daylight, it is necessary to clarify some basic terms of light and daylight.

Light is defined as that portion of the electromagnetic spectrum to which our eyes are visually sensitive. An illustration of the rate at which a light source emits light energy could be the rate at which water is sprayed out of a garden hose. The quantity of light a light bulb emits in all directions is represented by the lumen value (Lechner, 2001).

The lumens from a light source will illuminate a surface. A meaningful comparison of various illumination schemes is possible only when we compare the light falling on the same areas. Illuminance is, therefore, equal to the number of lumens falling on each square foot of a surface. The unit of illumination is the foot-candle. For example, when a light of 80 lumens falls uniformly on a 4-square-foot table, the illumination of that table is 20 lumens per square foot, or 20 foot-candles. Illumination is measured with **foot-candle meters**, also known as **illuminance meters** or **photometers** (op.cit).

The terms brightness and luminance are closely related. The brightness of an object refers to the perception of a human observer, while the object's luminance refers to the objective measurement by a light meter. The perception of brightness is a result of the object's actual luminance, the adaptation of the eye, and the brightness of adjacent objects. Although the words are interchangeable most of the time, under certain conditions there is a significant discrepancy between what we see (brightness) and what a light meter reads (luminance). Luminance is the amount of light that is reflected off an object's surface and reaches the eye. The luminance of an object is a result of the following: the illumination, the geometry of the viewer in relation to the light source, the specularity, (also referred to as mirror-like reflection), of the object and the colour, (or reflectance), of the object. Light emitted from glowing or translucent object is also called luminance. Thus, we can talk about the luminance of a table, an electric light bulb, or a translucent window (op.cit).

The behaviour of light after its emission from a light source and its incidence within a space can be described as follows: some of it is transmitted, some of it is absorbed by the surfaces of the space and transformed to heat and some of it is reflected and diffused.

The reflectance factor (RF) indicates how much of the light falling on a surface is reflected. To determine the RF of a surface, we divide the reflected light by the incident light. Since the reflected light (brightness) is always less than the incident light (illumination), the RF is always less than one, and since some light is always reflected, the RF is never zero. A white surface has an RF of about 0.85, while a black surface has an RF of only 0.05. The RF does not predict how the light will be reflected, only how much of it. Very smooth polished surfaces, such as mirrors, produce specular reflections where the angle of incidence is equal to the angle of reflection. Very flat or matte surfaces scatter the light to produce diffuse reflections. Most materials reflect light in both a specular and a diffuse manner. The diffusion does not affect the quantity of light transmitted (both clear and frosted glass transmit about 85 percent of the incident light) but it affects the quality of daylight distribution in the room (op.cit).

Another basic characteristic of the reflection of light is the spectral selection (colour) of it. This is not a subject of this research, and we shall not describe it here. In paragraph 3.1.2 we described the relation of colour to the behaviour of solar radiation in relation to thermal gains.

4.2. Visual comfort Aspects

In the next few paragraphs we shall describe the relation of the resulting daylight to the perception of space in order to describe the fundamental function of the shading system to affect visual conditions and consequently energy savings.

4.2.1. Relation of light to visual perception

Vision is the ability to gain information through light entering the eyes. Our eyes convert light into electrical signals subsequently processed by the brain. The brain's interpretation of what the eyes see is called perception.

To accommodate the large range of brightness levels in our environment, the eye adapts by varying the size of the pupil with a muscle called iris, as well as by changing in the sensitivity of the retina. However, it takes about an hour for the eye to make a full adaptation, and, in the meantime, vision is not at its best. Rapid and extreme changes in brightness cause stress and fatigue. However, the eye is very well accustomed to the gradual changes of brightness which are associated with daylighting. A gradual change in environmental brightness is not a liability and might even be considered as an asset because changes are more stimulating than static conditions.

In a previous paragraph we defined luminance as the absolute value of brightness as measured by a photometer (light meter). A human being, however, judges the brightness of an object by comparing it with the brightness of the immediate surroundings (Lechner, 2001).

4.2.2. Daylight quantity and quality - Glare

The subject of the quality of the illuminated environment is a rather complicated subject related to various parameters, e.g. relation of horizontal to vertical illuminance, changeability of the brightening environment, task of the user, etc. We shall present some of these parameters in the following paragraphs. Moreover, we shall use some of these parameters to access different shading systems.

One of the most important factors when assessing daylight quality is glare. Glare is ''visual noise" interfering with visual performance (Lechner, 2001). It incorporates a variety of other parameters and depends on them. Glare is dependent on the length of time the glare source is present, the luminance ratio between glare source and its surroundings and the requirements of the visual task to be performed.

According to CIE glare is “the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance or extreme contrast” (Baker et al., 1993). According to the light source two kinds of glare exist, direct and indirect, and each can have very detrimental effects on the ability to see. Direct glare is caused by a light source sufficiently bright to cause annoyance, discomfort, or loss in visual performance. The closer an offending light source is to the centre of vision, the worse the glare. For this reason, windows are often a serious source of glare. Indirect glare can be either reflected or caused by veiling reflections. Reflected glare is caused by shiny or glossy surfaces reflecting images of light sources to the eyes. Veiling reflections occur when small areas within visual range reflect light form a bright source; this process/reflection reduces contrast between the focus of vision and its surroundings (op. cit).

It is important to mention that according to the effect upon human perception there are also two types of glare: disability glare and discomfort glare. Disability glare is the glare that lessens the ability to see details and it does not necessarily cause visual discomfort. Discomfort glare occurs when the presence of an excessively bright source in the visual field causes a state of discomfort. The source may appear bright in relation to darker surroundings (op. cit).

Shading systems which can reduce glare and increase the diffuse light distribution are preferable, especially for working spaces. The best performing systems are those that block or redirect direct solar beams (preferably towards the ceiling) and distribute the diffuse light, (e.g. special section venetian blind systems). When using screens as shading systems, their transmittance should be carefully selected. That transmittance depends on the window to wall ratio, on window to floor ratio and the required set of tasks to be performed in the interior. When high transmittance screen is used (transmittance more than 25%) the lighting levels could be too high to allow work on computer screens and when low transmittance screens are used (transmittance lower than 10%) the lighting levels could be too low to allow comfortable office work on paper or on screens (Dubois, 2001).

According to a research conducted by Collins (1976), when individual subjects were examined, 50% accepted a minimum of 25% of glazing-to-wall area ratio (GWAR) and 85% accepted 35% of GWAR. That research also showed that the acceptable window size in relation to room dimensions was affected by several parameters such as view of content, distance from window, window height and visual angle. Keighley (Bulow - Hube, 2001) postulate that window size less than 10% is unsatisfactory and that satisfaction increases for WWR of 20% and above. According to a Danish research (Christoffersen, 1995) the optimum acceptable window size is the 30% of GWAR.

We should mention here that glare mainly appears in overlit spaces. When an external fixed shading system is used, extensively widely used system able to control glare is the interior movable roller shades. These systems reduce daylight levels evenly within the whole of the room and consequently they significantly contribute to the increase of the energy loads due to increased need to use electric lighting.

In order to evaluate different shading systems it is essential to assess them in relation to glare. A quantitative assessment of glare discomfort is the Daylight Glare Index (DGI) (see more in 4.3.3).

4.2.3. Light, health and psychology

Apart from energy savings and daylight quality in the working environment, daylight is an important parameter affecting our health and well being. Humans rely on exposure to daylight to activate a wide range of physiological functions. These depend on the intensity of daylight exposure and more specifically to the ultraviolet (UV) component of daylight. Large amounts of strong light are needed each morning to prompt the pineal gland to switch off production of melatonin (the "sleep" hormone) (Baker & Steemers, 2001).

The major parameters affecting daylight in a room are the size, shape and position of windows and the room depth. Other important parameters are the transmittance of the glazing and any external obstructions such as shading devices, opposing buildings or vegetation. Generally, tall windows compared to wide windows of the same size admit the light deeper into the room. Dividing the window area into several surfaces, preferably on opposing walls, is often considered preferable since it gives a more even and pleasant result (better illumination) (Bulow - Hube, 2001)**.**

Light also has an effect on behaviour and emotions as indicated by the work of Küller et al. (1999) and (Küller & Lindsten, 1992). A research by Boyce & Kennaway (1987) showed that illuminance levels as high as 2500 lx did not suppress melatonin to daytime levels, which contradicted Lewy et al. (1980) who concluded that bright artificial light of 2500 lx was able to suppress melatonin to daytime levels and that 500 lx was insufficient to do so while 1500 lx provided an intermediate amount of inhibition of melatonin secretion (Dubois, 1997). On the other hand this large amount of light proved to cause uncomfortable visual conditions and glare.

This is the main reason why we believe, shading systems enabling morning daylight penetration and allowing some degree of user initiative are more preferable in office buildings. These are mainly external fixed shading systems with movable interior blinds or roller shades. The external fixed shading system protects from direct sunlight during peak hours in the overheated period while the interior movable system allows the control of discomfort glare during the underheated period when the sun is low and during the hot season during hours that fixed shadings do not protect from direct solar radiation. Due to the above mentioned facts all shading systems examined are fixed external shading systems (described in par 3.5.3).

4.3. Evaluation of visual comfort

4.3.1. Task of the user

In order to evaluate different shading systems according to their effect on visual conditions, the basic requirements in relation to daylight and the function of office buildings should be clarified. A basic parameter considered when comparing different daylight environments is the task of the user.

Many factors affect the performance of a visual task (i.e. a task where visibility is important). Some of these factors are inherent in the task, some describe the lighting conditions, and the remainder reflects the condition of the person performing the task. An increase in brightness during the task initially results in a significant improvement in visual performance, but additional increases yield increasingly smaller benefits. The "law of diminishing returns" explains the nonlinear relationship between brightness and visual performance. Increasing the illumination from 0 to 50 foot-candles, will result to an increase of brightness and the visual performance will improve by about 85 percent; a further increase of 50 foot-candles will improve the visual performance only by 5 percent (Lechner, 2001).

The most complete work in relation to SDs and their visual performance has been done by Dubois (2001) and (1997), who compares different types of SD geometries. This research incorporates the colour of the SD and the task of the user (traditional visual task or computer related one) as additional parameters. Results showed that for south orientation, the overhang, white awning and horizontal venetian blinds generated work space illuminance levels more suitable for offices where traditional visual tasks are carried out. The 45° venetian blind, white screen and blue awning provided work space illuminance levels suitable for offices where a combination of paper and computer work is carried out. The study incorporates a variety of SDs. However systems such as Brise-Soleil or double awnings or venetian blinds with different inclinations were not studied.

Bülow - Hübe (2008) also examined the importance of the user task (visual or computer) when evaluating the performance of shading systems. They proved that

Venetian blinds systems are applicable in both visual and computer based tasks. They proposed an exterior shading system for south and west orientation (positioned in the upper part of the opening) with slats; this can only work well between mid-April and the end of August if it is in a fixed position and during both winter and summer if it is movable (Bülow - Hübe, 2008).

Consequently, the user task is one of the most important parameters that greatly influence the evaluation of visual comfort conditions, especially concerning the detailed design stage of a building. Various factors and methods exist that can be chosen according to the evaluated environment.

4.3.2. Methods and Factors/Variables of assessment of daylight levels

Another parameter influencing the result is the method and the variables used to measure daylight levels; there might be discrepancies between results when using different methods or different variables.

The daylight component can be measured in lux. But this is not a comparable number because it depends on the outdoor illuminance from the diffuse sky that varies according to the period of the year and the sky condition in a specific place. Additionally, due to the adaptive properties of human vision, the absolute values are less important than comparative values.

Another more relative value used to describe daylight levels is the ratio of the illuminance inside the room over the illuminance outside. This ratio, usually expressed as a percentage is called daylight factor (DF). Daylight factor is the ratio of the illuminance at a specific point in the room, over the illuminance measured simultaneously outside, under overcast sky. The disadvantage of this variable is that it can only be measured under overcast sky conditions. Rooms or interiors of offices with a DF in the range of 1% to 5% can be considered to be sufficiently illuminated by day light (Baker & Steemers, 2001).

When considering the daylight performance of an examined room over a year a new variable/factor called the Daylight autonomy (DA) can be used to predict daylight levels. A basic difference in relation to daylight factor is that DA is not based upon a specific sky condition but is dependent on all possible sky illuminance levels throughout the year according to the weather data of the area. Daylight autonomy describes the percentage of hours that the illuminance of the space is over a prescribed value (for example 500 lux for offices where both computer and paper task is carried out). Daylight autonomy has two basic disadvantages: it disregards the illuminance levels lower than the given prescribed values; these low levels can be useful for some other types of work (e.g. for computer work) or for some types of users. The second disadvantage is that DA does not give any information on daylight quality, because it does not take into account instances when the daylight levels are over the comfort range (very high) (Meresi, 2010).

In the previous paragraph we described the different factors used when measuring daylight levels. In the next paragraph (4.3.3) we will describe some additional basic factors that can be used to assess daylight quality. These factors can be calculated using either physical scale models or simulation applications and in some cases mock – up scaled down models.

We examined the methods used to assess both daylight quantity and quality due to the fact that they are interdependent; Earlier on we presented an example: we showed that DF shows the levels of daylight in relation to the outside illuminance.; due to the fact that it is a ratio value it relates to the outside illuminance; DF is a value of visual comfort similar to contrast of background to the task object.

Another example concerns DA. DA also expresses daylight levels and daylight distribution in the average period of the year. Daylight distribution, is more a quality value of daylight due to the fact that it describes daylight levels in the whole of the space and section of the examined unit and it describes the relation of daylight between the front and the back of the room and between desk and eye (we are interested in these different daylight levels in office buildings). There are no specific values that these differences between daylight levels should adhere to, but they can express the quality of the day lit environment (e.g. an evenly day lit space creates a calmer temper for its users than a space with sharp daylight variations, but the latter creates a stimulating and maybe more interesting environment).

4.3.3. Methods and Factors/Variables during assessment of daylight quality

In paragraph 4.3.2 as well in paragraph 2.4 we showed that there are some basic factors/variables when we assess the performance of a shading system in relation to interior daylight conditions. Factors that we described in this chapter are based on basic geometrical rules that can be used by architects – practitioners. Further on, regarding the detailed analysis of the resulting daylight quality various factors have been developed which attempt to quantify daylight quality. Most of them require special knowledge of computer applications or advanced mathematical skills elusive to most practitioners. Nevertheless this specialized knowledge is a well known practice for experts and researchers who analyse daylighting in space. These factors are presented in this paragraph as well as the methods that can be used to measure the quantity as well as other quality factors. An important examined factor used for calculating daylight performance it the daylight coefficient. It is defined (Tregenza & Waters, 1983) as the ratio between the luminance of a patch of sky and the illuminance within the building due to light from that patch. The use of daylight coefficient has been proposed by other researchers as an accurate method to predict daylight levels in relation to the luminance distribution of the sky (Reinhart & Herkel, 2000). The accuracy of the daylight coefficient depends on the division of the sky dome (Tsangrassoulis et al., 1996).

A new method has been developed using a simplified algorithm to assess the indoor natural illuminance on a prefixed point with external fixed shading devices (overhangs and vertical fins). The method is based on the split of the internal illuminance into two components, linked to direct diffuse solar radiation respectively. A reflected component is also incorporated into the calculations, according to a ground reflectance component. The occurring simplifications depend on the detailed use of the equations developed to measure the luminous efficacy of the sun for each shading system examined (Gugliermetti & Bisegna, 2006).

In order to quantify discomfort glare a new factor is introduced by Baker et al. (1993): the Daylight glare Index (DGI). First the “glare constant” G has been introduced.

It is $G = K P (L_s^{1.6} \omega^{0.8}) / L_b$, where:

K is a constant depending on the units employed
P is a position factor depending on the position of the source in relation to the line of sight
L_s is the luminance of the source
L_b is the field luminance
ω is the solid angle subtended by the source

For artificially lit rooms, the IES (Illuminating Engineering Society) has defined Glare Index (GI) as:
$GI = 10 \log_{10} G$

The IES suggests limiting values of GI for different environments according to the function of the building (Baker et al., 1993, p. 2.17). More specifically we introduce a new variable: the Daylight glare Index (DGI) is related to daylit environments. The DGI is related to the IES Glare Index for artificial Lighting (GI) and is given in the equation:

$DGI = 2/3 (GI + 14)$ for values up to 28

The above equation expresses the fact that there is greater tolerance to glare from the sky than to glare form artificial light, for the observer. (Baker et al., 1993, p. 2.18) (Fig.2.1) presented a table describing acceptable and unacceptable DGI values. Three broad categories were introduced: environments where no glare at all is permissible and the acceptable glare index has a limit of up to 16, environments where glare is kept to the minimum acceptable, with a glare index maximum of 24 and environments where different degrees of glare are uncomfortable, and glare index limits are above 24 (Baker & Steemers, 2001, p. 178).

Glare Citerion	DGI	DGPS
Imperceptible	Below 16	0
Perceptible	16 - 20	0 - 2
Acceptable	20 - 24	2 - 4
Uncomfortable	24 - 28	4 - 6
Intolerable	Above 28	Above 6

Fig. 4.1. *Limits of acceptable DGI and DGPS*
(Baker et al., 1993, p. 2.18)

Nazzal (2005) defined a new method to evaluate discomfort from unwanted glare. Previously developed methods only assess horizontal illuminance when assessing users' levels of comfort: this is unsatisfactory. The use of CCD (Charge-Couple Device) cameras to measure discomfort from glare is not accurate enough due to the fact that the resulting luminance value changes with shutter speed, and there is a substantial difference between the spectral sensitivity curve of the CCD camera and that of the human eye. In real environments many different lighting stimuli appear simultaneously, something that unfortunately cannot be replicated in the laboratory as yet (Dec 2012).

Discomfort from glare represented by the daylight glare index (**DGI**) can be measured mathematically and accurately with the proposed method. DGI takes into account the source luminance, the window luminance, the background luminance and the adaptation illuminance used; the latter is defined as the illuminance of the surroundings including reflections from internal surfaces. DGI can also be used when direct sunlight heats the window. The method can be applied to different shading systems. However, further studies with a large number of daylighting systems are recommended to generalize the conclusions (op. Cit.).

Daylight glare probability (DGP) is a recently proposed discomfort glare index. This was proposed by Wienold and Christoffersen from laboratory studies in day lit spaces using 72 test subjects in Denmark and Germany (Weinold & Christoffersen, 2006) (for detail see Appendix).

For visual comfort conditions Weinold (2007) introduced a simplified glare measure, the **"Daylight Glare Probability simplified (DGPs)**". He validated DGP for situations when the sunlight does not fall directly on the eye. DGP is the simulation of vertical illuminance at eye level. When evaluating the contrast of the computer screen only the veiling luminance is taken into account, due to the fact that Daysim cannot take into account self-luminant surfaces (Weinold, 2007).

As we showed in a previous paragraph glare is caused by a significant ratio of luminance between the object (which is looked at) and the glare source. Factors such as the angle between the object and the glare source and eye adaptation have a significant impact on the experience of glare.

The Adaptation luminance (L_{adapt}) introduces a new method to assess glare. It cannot usually be measured directly with simple and inexpensive instruments, but can be measured by dividing the illuminance at the focal plane of the eye of an observer (E_{eye}) with π ($L_{adapt} = E_{eye} / \pi$) (Cuttle, 2003).

A novel parameter which can describe daylight levels and daylight quality is the Useful Daylight Illuminance (UDI). UDI enables us to detect areas that fall in the range of visual comfort (100 – 2000 lx). Hence UDI can be used at a 'point by point' basis instead of being used to evaluate the whole space. This detailed measure, allows us to spot the problematic areas which can subsequently be improved by altering some of the parameters involved in the shading design (Ajmat et al., 2005), (Nabil & Mardaljevic, 2005).

When evaluating daylight conditions in the interior of a room, if we use e.g. only daylight levels values such as DF or lux, we might arrive to misleading conclusions (e.g. when evaluating different shading devices the one that allows the highest levels of daylight could appear to be better). However when we incorporate UDI in the equation we can see that these devices providing the highest percentage of UDI perform better than the ones affording higher daylight levels (Nabil & Mardaljevic, 2005). This fact supports the argument that we should evaluate the examined shading systems in relation to both daylight autonomy (DA) and to Useful daylight Illuminance (UDI) values.

Johnsen et al. (2006) proposed the use of well known parameters when assessing daylight quality, such as the relation of the glazing area to the frame of the window, the horizontal illuminance and daylight factor in combination with additional novel variables used to assess daylight quality: Cylindrical illuminance (sunny sky conditions), Illuminance on cube, vertical-to-horizontal illuminance, Luminance distribution, Luminance in the field of view, Daylight Glare Index, Luminance Difference Index (a measure of light variation in space) and Scale of Shadows (the latter was developed by Frandsen it is a systematic description of the relation between the light source and the object.

An overview of different factors used to evaluate different daylight qualities can be seen in Fig.4.2.

Daylight Metrics	Daylight Parameter
DF	illuminanace
UDI	
DGI	Glare
DGP	
luminance ratio in the field of view	distribution
altitude of illuminance vector	directionality of light
ratio of vector to scalar illuminance (Ev/Es)	
	colour rendering and colour appearance of light
	flicker

Fig. 4.2. Basic factor and metrics of daylight quality
(Cantine & Dubois, 2011)

The use of genetic algorithms is a rather complex way to design of SDs. These algorithms can incorporate more parameters than simply the geometry; they have been developed for the design of slat-type blinds. These algorithms are actually the evolution of the nomograms. The method incorporates three types of parameters: the dimensions of blinds, their material and the **2D light intensity distribution (LID)**; the latter is the value of luminous intensity in a section perpendicular to the plane of blinds. Different ways of designing SDs can be experimented with by the method of trial and error according to the required distribution of light intensity (Tsangrassoulis et al., 2006).

An important factor, when we assess daylight levels and quality afforded by different shading types, is the measuring tool used. Daylight levels can be measured by various computer simulation tools and applications, and they can be measured in physical scale models in real sky or artificial skies, in mock - up models or finally we can measure daylight levels in the real researched building. The accuracy of the results varies according to the method used.

Finally, it should be noted that the aforementioned methodologies do not concern the evaluation of thermal comfort conditions. Due to the fact that this research is mainly focus on daylight levels we will only describe different methods used to evaluate thermal comfort in combination with daylight.

4.3.4. Combined methods to assess thermal and visual comfort

In this chapter we shall examine the thermal behaviour of lighting in relation to daylight levels. The methods presented attempt to relate outdoor daylight levels with thermal gains.

A European software tool (named WIS) was developed to enable us to measure the lighting and thermal transmittance of transparent elements for direct and diffuse light (Van Dijk & Oversloot, 2003). The tool uses an algorithm informed by the International Standard 15099 (2003) for windows, doors and shading devices. This tool/algorithm is suitable for use with a variety of multi layer glazing and shading devices.

An existing simplified thermal simulation tool called Building Calc and a daylight simulation tool called Light Calc (Nielsen, 2005a) formed the starting point for the work on combined methods. A new simulation method to predict thermal performance of buildings with shading devices using a hybrid dynamic lighting/thermal model has been developed by Ajmat et al. (2005). In this method the irradiance predictions coming from ray tracing calculations on virtual photocells provide input to a simplified model which estimates thermal response and calculates the energy loads (cooling, heating, electric lighting) as well as the carbon dioxide emissions. For south oriented openings in Guangzhou the system with vertical blinds inclined at 45 degrees proved to be the most energy efficient.

An integrated evaluation of SDs according to both their visual and thermal performance has been proposed. This is called “Decision making framework” and it sets the parameters used by an algorithm in a computer simulation tool to help select the most appropriate SD. The method is mostly appropriate for blinds systems

(Olbina, 2005). It incorporates a variety of factors: heat transfer, HVAC conditions, facade type, and position of SD relative to the façade and thermal, visual, acoustic and aesthetic performance of SD, cost and control strategy of SD. The research also incorporates all standards and codes used for façade: standards for window size, for daylighting, for electric/artificial lighting, for shading, for controls. A new SD with blinds is proposed.

Hviid (2008) presented a simple building simulation tool based on algorithms, used for combined daylight and thermal analysis; this is the Adeline computer simulation software that can perform in both directions but it disregards the interactivity between daylight, lighting, solar shading and the thermal performance of the building. Another approach is the software Radiance in combination with a thermal simulation program and implemented in ESP-r.

All of the above mentioned methods are considered to be accurate enough. A basic criterion that we use in order to find the most appropriate one is the type of the examined systems (if facade of transparent systems is evaluated) and the stage of the design. Due to the high degree of information these methods are basically appropriate for the final design stage.

4.3.5. Comparison between simulations, measurements in physical models and measurements in real buildings in relation to daylight inside the building

Each method has its advantages and its limitations.

Regarding simulation methods there are two approaches which can be used for an accurate estimation of the luminous environment in the interior of a building: the ray-tracing and the radiosity method.

There are several differences between the two. When using the ray – tracing method rays are emitted from a light source towards the surface points and towards the opposite direction. Radiance is one well known computer application that is based on ray- tracing rendering. Regarding the visualization of the results, ray-tracing is a view-dependent process. This means that when the viewer's position changes, we have to repeat most of the process. In the radiosity method the space is considered as a mesh with lambertian reflectors, which reflect light to all directions regardless of the viewer's position. Each patch receives and reflects back light. This method cannot simulate specular reflections and this is one of its main disadvantages. Some computer applications have been developed using the radiosity method e.g. Superlight. Radiosity is the exact opposite of the ray-tracing method. Calculations are based only on the geometry of the environment. Additionally we should mention that ray-tracing in a more accurate technique than radiosity (Tsangrassoulis et al., 1996).

A theoretical and experimental analysis of daylight performance for various shading systems has been carried out by the aforementioned researchers using the daylight coefficient, in order to calculate the illuminance in the interior of a room under various sky luminance variations. The analysis compares three methods: the existing radiosity method, the ray-tracing method and the PASSYS test-cell (Passive Solar Systems and Component Testing: a European project (Hahne & Pfluger, 1996)). "PASSYS test-cell of the University of Athens, located at the National Observatory of Athens (NOA) was used. This test-cell is 5 m long, 2.7 m wide and 3 m high from floor to ceiling and is installed with the narrow side facing south". Two types of shading systems were examined in vertical and horizontal position: the perforated metal sheet and the sand blasted glass. The proposed method can be used for more complex shading systems (complicated geometry and materials). The error of the proposed method depends on the prediction of horizontal illuminance and the number of sky divisions. This error of the horizontal illuminance prediction is smaller at high sun angles and larger at low ones (op.cit.).

Bourgeois and Reinhart (Bourgeois & Reinhart, 2006) presented the results of a Radiance-based comparison between the validated Daysim daylight coefficient model and a proposed standard model for dynamic daylighting simulations (DDS). The results showed that DDS outperforms Daysim, especially in cases where sensors are subjected to sudden changes of exposure to solar radiation.

Rubin et al. (2007) compared the ray-tracing and radiosity technique when measuring daylight quality. Directional-hemispherical transmittance and reflectance are in excellent agreement when they studied slat shadings in all conditions.

Tzempelikos (2008) presented a review of developed computer methods of assessing the optical properties of SDs. He examines the ability of the ASHRAE, the ISO 15099 method and the Energy Plus software to assess Venetian blinds, Roller Shades and Draperies. In all methods certain simplifications are made. Direct to diffuse transmittance may not be modelled accurately with EnergyPlus. On the contrary Ray-tracing techniques can provide more accurate results.

Regarding physical model methods (Cannon - Brookes, 1997) have experimented with small scale models to estimate lighting levels. Physical scale models are a reliable tool to simulate natural daylight. The lighting models overestimate the illuminance levels in comparison to the actual illuminace levels in real buildings. Mardaljevic (2001) concluded that scale models generally over-estimate illuminance by a significant margin in overcast sky conditions. For non overcast skies the difference between the estimated illuminace of the model and the measured illuminance in the real building performance is still significant.

Hence, the illuminance estimated by the physical model is about 60% greater than the illuminance measured in a real building. Under real clear sky the estimated illuminance by the physical model is 100% to 250% greater compared with the measured illuminace of the building. "This is due to the way the model is constructed and the positioning of the sensors in areas where illuminance changes rapidly and due to the uncertainty of the illuminance of the real sky characterised by rapid changes with dark or small light clouds or changes due to snow falling; these changes in illuminance cannot be imprinted in the sky scanner. The differences of illuminance at the back of the room are due to intereflections which are too complex to be simulated; it is much harder to simulate interreflections than the direct illuminance".

For these reasons, the International Daylight Measurement Program (IDMP) was introduced, as a new benchmark for the validation of illuminance prediction techniques. Fifteen standard skies were established for daylight researchers and were described in ISO 15469:2004. These standardised types of sky can represent all possible weather conditions (CIE *standard general sky*, 2003). They include CIE standard overcast sky - CIE clear sky as previously adapted (CIE *standard overcast and clear sky*, 1996), (Meresi, 2010) (Fig.4.3).

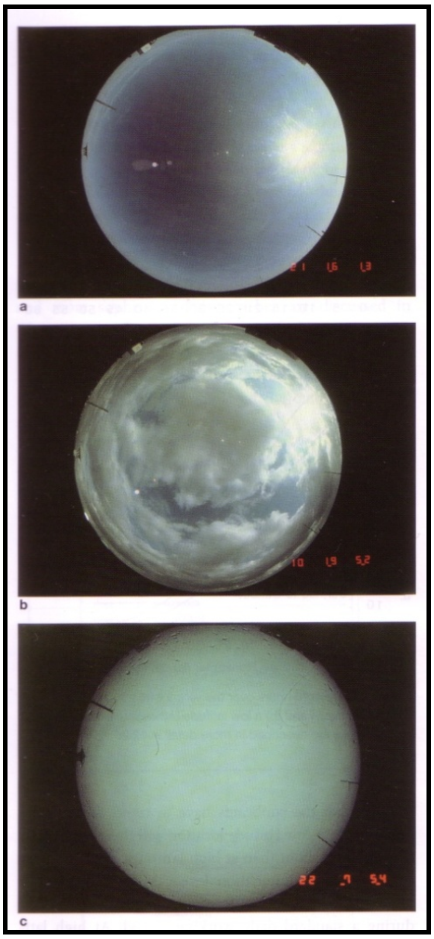


Fig. 4.3. *Sky vault photos illustrating the brightness distribution for (a) clear sky, (b) partly overcast sky, (c) fully overcast sky,*
(Baker & Steemers, 2001)

In 2004 it was concluded that the differences in illuminance levels between models and simulation are due to the difficulty to simulate the overcast sky accurately (Mardaljevic, 2004).

Additionally, when the physical models are tested in real sky conditions, it is very difficult to distinguish the sky from CIE skies, especially in the cases of overcast and intermediate sky. For this reason a sky scanner should be used to monitor sky luminance so that specific sky conditions can be identified in relation to the fifteen standard skies (op.cit.). Even in these cases of monitoring accurate sky there are observed inaccuracies due to imprecision in the sky's representation by the model when using the operational mode of the lighting simulation program. Mardaljevic (2001) reported that the accuracy in predictions for lighting when we use simulations under real sky conditions is far greater than that reported by Cannon-Brookes (1997), when sky scanners are used.

It is very helpful to test the physical model in both overcast and clear sky. As waiting for the specific types of skies would cause delays, experiments in artificial skies could be done. The electric light bulbs of artificial skies can be controlled by a computer in order to simulate the CIE standard skies. The dominant weather type in Northern Europe is the overcast or partially overcast days. Clear sunny days are rare, (see measured solar radiation data for Lund). Therefore, the diffuse sky is the main source for lighting a room; there is not really much direct sunlight. In order to perform accurate calculations of daylight, the luminance distribution of the sky must be known. Since measurements of sky distributions are not yet commonly available in more than a few sites worldwide, we usually resort to using standardized sky distributions (Bulow - Hube, 2001, p. 83).

Accuracy can be achieved in the physical models if the sky and the surroundings can be replicated in detail. Errors committed in the replication of real sky conditions are a source of inaccuracy of the results when using physical models (Fig.4.4).

REAL BUILDING	PHYSICAL MODEL REAL SKY	PHYSICAL MODEL ARTIFICIAL SKY	SIMULATION	PAPER
Low	High	High		Cannon-Brookes (1997)
Low	High	Middle		Mardaljevic, 2001
	High	Middle	Low	Mardaljevic, 2004

Fig.4.4. *Comparison of visual assessment methods' value - in terms of prediction of Daylight levels*

4.3.6. Subjective factors

In previous paragraphs we described different factors and methods that can be used by researchers and to some extent by practicing architects to assess the daylight environment. In order to apply these types of research to real buildings and to build architecture it is necessary to study the connection of the buildings to the user's behaviour. This connection will reduce the possible errors of the results.

An important problem and source of error is the absence of subjective parameters within the calculations. The coexistence of measured and behavioural studies to confirm the conclusions about visual comfort for different SDs is supported by (Veitch, J.A. and Newsham, G.R., 1995). The luminance within the field of view plays a major role and should weight more in the overall assessment of daylight quality than the horizontal illuminance or the illuminance uniformity. Researchers have pointed out that one of the difficulties when assessing visual comfort – and in particular discomfort glare – is the large variation of responses usually found when interviewing buildings' users (Osterhaus, 1996 & 2001). Velds (2000) used two methods to evaluate daylighting systems: Visual Comfort Evaluation method and the User Acceptance Studies in order to overcome confounding factors in measures and subjective parameters. She concluded that older subjects (›50 years) preferred more contrast level (5000lx) than younger ones (2000lx).

The introduction of a series of important unmeasurable ("soft") parameters used to evaluate lighting quality, in sunny skies when there are more problems with glare , was proposed by (Schuster, 2006). SDs were assessed according to different levels of acceptance in terms of space perception, feeling of brightness, the "visual" protection function, the role of individual control and the feeling of enclosure of the user. The feeling of openness can be achieved in brighter spaces and effective light directing systems can supply this feeling, (e.g. venetian blinds placed in the upper part of the window plane).

Moreover, Osterhaus (2009) outlines the need for a systematic study of discomfort glare that will connect previous research with the current research and will incorporate the perceptions of glare in different samples of representative populations.

Frontczak & Wargocki (2011) proved that thermal and visual comfort depends on different subjective parameters and they proposed that in order to evaluate the environmental conditions user acceptance studies should be done, using questionnaires. More specifically results of their studies showed that **thermal comfort** was influenced by the level of education, the relationship with superiors and colleagues and time pressure, but not by gender, age, body build, fitness, health, self-estimated environmental sensitivity, menstruation cycle, pattern of smoking and coffee drinking, job stress or hours worked per week. On the other hand **Visual comfort** was affected by occupants' age and type of job, but not by job satisfaction, relationship with superiors and colleagues or job stress.

Antoine Guillemin (2003) managed to use genetic algorithms to incorporate users' wishes to adaptive shading systems. He concluded that adaptive systems are inappropriate for public buildings due to the diversity of users with conflicting preferences.

We showed that in order to estimate visual comfort conditions both simulations and measured results are necessary, especially for complicated Shading systems. Regarding visual comfort conditions we concluded that: Glare is a complicated concept/variable due to the changeability and complexity of daylight and the way that illuminance between the subject, the background and the opening interact with each other. Consequently, a series of additional parameters related to vertical, horizontal and cylindrical illuminance should be measured.

The coexistence of measured and behavioural parameters is important in the evaluation of visual and thermal performance of SDs. The mathematical predictions (the algorithm to be used) for computer simulations have evolved in order to incorporate both measured and behavioural aspects of visual and thermal comfort. Due to the diversity and changeability of users of public buildings no selected SD would meet everyone's requirements.

4.4. The influence of daylight parameters in the design of SD

As we showed in paragraph 2.1, some of the basic objectives of a SD are to prevent sunlight from falling directly onto occupants or to surfaces that may be glare sources to the occupants (Baker & Steemers, 2001). These requirements are essential in office buildings and might lead us either to change the geometry of the device or use a different secondary system. Both solutions could be effective according to the desired aesthetics of the building.

The task of the shading systems we examine is to completely prevent direct summer sun between 11:30 to 13:30 and partly prevent the sun during most of summer working hours (9.00 to 17.00) in the case of Crete, Chania. We examine glare prevention in the underheated period using different interior furnishings and different occupants' places in the office room to those proposed by Van Dijk (2001). We will use this new interior configuration for our research (Fig.3.20).

In order to prevent glare during the overheated period we examined a different interior furnishing and occupants places of the office room than those proposed by Van Dijk (2001). We will further develop the specific SDs examined in relation to glare avoidance.

4.4.1. Control of daylight and shade using one or separate SDs

We have carried out a full research in relation to daylight quality and quantity that different types of SDs mainly define in offices and classrooms. **The system of externally used venetian blinds has proved to perform better in terms of visual comfort, especially when used in the upper part of the window, for north climates.** The performance of the system for overcast sky is very low, and this is the reason why movable systems are preferable. These results are location and climate specific. Further research in the area of interest needs to be done in order to arrive to specific conclusions regarding the best performing SD.

Dubois (2001) examined different shading systems in terms of daylight quality. She mostly examined systems that are at the same time daylight controllers and shading systems (black, brown, grey and white screens with different transparencies, white and blue awnings, horizontal or inclined Venetian blinds). The results generally indicated that the venetian blind may be the best daylight control device. Also, a screen with a transmittance of at least 15% may also be acceptable but the transmittance should not be higher than around 25% and not lower than 10 %, especially in offices where the work is mostly computer-based.

She argues that externally installed shading systems, like awnings and canopies, do not solve the daylight glare problem for office buildings, especially during winter when the sun is low. This problem exists especially in high latitudes where the sun is almost as low as merely above the horizon in winter. In these cases an additional shading is needed, one that can cover the window plane, and can be movable, like venetian blinds or screens. An optimum solution is the combination of an external shading device with low g-value (an awning), with an internal shading device with high g- value (venetian blind). This combination is advantageous because of the reduction in daylight glare of the awning during summer, when additional heating factors should be limited and because of the same effect of the interior shade during winter when the passive heating is desirable.

Velds (2000) proposed venetian blind system placed in the upper part of the window as an efficient system in terms of daylighting and shading, especially when it is movable. The system cannot work with overcast sky and this is the main reason why it is more efficient when movable.

We conclude from the above mentioned researches that two types of systems are preferred so as to achieve better visual and thermal comfort: the first one is a fixed external system in combination with an internal movable (retractable of adjustable according to the definition of (Baker & Steemers, 2001, p. 110) and the second one is a movable external shading system. Due to many reasons such as wear and tear and due to cost, fixed external shading systems are preferred from the users and the designers according to different researchers (see paragraph 3.4.2).

4.5. Energy savings through artificial (electric) lighting

An important aspect of daylight quality is the energy balance between daylight and electric light needs. In order to achieve substantial energy savings it is not enough to ensure that a large amount of daylight is admitted into the building. An appropriate lighting control system is essential.

There are various daylight control systems which increase daylight levels in the back of the room and at the same time afford satisfactory visual comfort levels, as described in previous paragraphs. These systems, even though they can ensure better distribution of daylight and consequently higher energy savings through the reduced need to use electric light, are not the subject of this research.

Ways to use shading devices and artificial lighting need to be studied by means of measurements in physical models and through computer simulations in order to achieve an optimum balance between energy used and quality of the interior environment (Dubois, 2001).

In this research we assess external fixed shading systems with integrated PV. The electricity needs are an important factor for this assessment because we will use the electricity produced from the PV, to satisfy these needs. Even though these systems are not designed to increase lighting levels they influence the day lit interior environment.

4.5.1. Relation of energy savings to the electric system adopted (dimming or on/off)

Case studies have shown that in conventional day lit buildings the choice of control can make 30-40% of difference to the resulting use of electric lighting. To make this happen the system should work effectively.

Lighting control systems can be either a manual on/off system or a centrally managed light responsive dimming system including scheduling and occupancy detection.

Human occupants are poor light control detectors due to the fact that they are able to recognize insufficient light, but they cannot recognize too much light or “more light than necessary”. Characteristic good example of this is the fact that when people enter their office in the morning and the lighting levels are low they switch on the lights and then they do not turn them off during the day when the daylight levels are generally higher. They may only switch them off when they leave the space. This occupancy behaviour proves the ineffectiveness of the on/off system as an energy saving lighting system (Baker & Steemers, 2001).

When using a continuous electric light dimming strategy whenever the daylight luminance falls below the required level during the lighting demand period, the shortfall must be provided by electric lighting. If only an on/off control were used, the electricity needs for lighting would be much higher (Vartiainen, 1998). The demand for electricity due to artificial lighting in each reference office is directly calculated as a function of different shading devices, using the daylighting simulation formula: $E_L = P_L - t_y A (1 \_ DAR)$ where the P_L is the installed light power (W/m2), t_y is the number of working hours in a year, A is the floor area in m2 and DAR is the daylight autonomy ratio defined as the fraction of working time in a year during which sufficient daylight (more than a pre-specified set point, for example 500 lx) is available on the work plane surface (Tzempelikos & Athienitis, 2007).

On the other hand fully automated systems completely removing control from the occupants are often unpopular.

4.6. Experimental work on daylight quality and quantity

We examine a single office unit with the characteristics described in paragraph 3.5.3 According to the study of Van Dijk (2001) the reflectance of the material used is 0.85 for the ceiling, 0.65 for the walls and 0.20 for the floor. The ground reflection for incident solar radiation is 0.20. The office unit is considered to be in the ground floor and no changeability in the reflections of the surroundings was considered (Mardaljevic, 2001).

More specifically, according to (Van Dijk, 2001) three occupants' positions are proposed. In order to avoid glare problems we examine a different plan configuration which allows positioning of the users further away from the facade. We examine the office unit for two possible positions of the users that can be seen in figures 4.13 and figure 4.15.

With reference to daylight levels, we focus on a reference window of 2.4 x 1.9 m (44.92%WWR) with a sill height of 0.80m in Chania latitude. We conducted simulations and measurements of daylight levels with physical models in real sky conditions. We measured daylight illuminance on the desk level according to USA standards.

We examined two basic geometrical groups of shading systems:

1. More transparent systems allowing unobstructed view to outside but having the potential to cause problems with high glare in the winter due to the fact that they do not block direct solar radiation (canopy, canopy inclined, canopy double, Brise soleil full facade, Brise soleil semi facade) and 2. louvers systems with different inclinations and geometrical configurations (canopy inclined double, louvers horizontal, louvers inwards inclined, louvers outwards inclined, Brise soleil louvers, louvers vertical) which exclude both summer and most of winter direct solar beam.

All Systems have been designed to completely exclude direct solar beam for the period of 1st of June till 24rth of August from 11:30 to 13:30 solar time.

The Stages of the Experimental procedure regarding daylight assessment of shading systems are described below:

1. Assessment of daylight levels of shading systems with simulations (Radiance) and physical Model (assessment of how values of daylight compare with each other and not of the values themselves). The Integration of 3cm and 1.5cm thickness of PV louver systems is examined in absolute figures. Conclusions in relation to the method used are presented.

2. Assessment of daylight levels in terms of Daylight Autonomy (DA) with two simulating tools, Ecotect and DaySim. Differences of the results according to the application used for a specific design stage are presented and analyzed according to the design stage.

3. Assessment of daylight quality using the combination of various factors, namely Useful Daylight Illuminance (UDI) and Daylight Autonomy (DA) with the simulation software DaySim.

4. Assessment of daylight quality in terms of glare, using the factor of Daylight Glare Index (DGI), calculated with the simulation software Radiance.

4.6.1. Construction of Daylight Physical model and experiment set up

In order to decide the scale of the physical model an extensive literature review was conducted. The scale of the physical model depends on the sky used, whether artificial or real. In the case of artificial sky, the models' dimensions depend on the dimensions and the geometry of the sky. The largest dimension of the model should be around 10% of the diameter of the artificial sky dome (www.daylightinglab.com and (Lechner, 2001)). Possible dimensions of scale models can be from 1/200 to 1/10 of the geometry of the sky (Baker & Steemers, 2001).

According to Bodart (2007) the scale of the examined model, if real sky is used, is not dependent to the sky dome diameter, as for the cases of artificial sky. In contrast to the thermal, acoustic and structural physical models, the models in the field of daylight research does are not affected by scale when tested under real sky (Baker et al., 1993). This is due to the fact that the wavelength of light is very small (lower than one millionth of a meter) and its behaviour is unaffected by scale (Meresi, 2010).

The scale of the physical model under real sky depends on the characteristic of the measurement device, the camera used and the size of the illuminance sensors. The International Energy Agency (2000) provides a table that related the scale of the daylight model to the daylighting design purposes (Fig.4.5). For the cases of integration critical industrial components, of assessing daylighting devices that cannot be reduced in scale and to precede to final evaluation of advanced daylighting systems through monitoring and user assessment scales of 1/10 to 1/1 are suitable. For making sky measurements in real sky we conclude that an appropriate scale for our model was 1/10 as we need to evaluate specific shading systems. Additionally facts that influenced our decision for the use of this specific scale is the size of our sensors for achieving desk level appropriate for our scale model and the available width of the dark blue Plexiglas material, that was going to imitate shading systems with integrated PV. The 3 cm width of framed PV installations assigns in scale 1/10 to 3mm of dark blue Plexiglas that we used. We followed detailed instructions from various studies on how to construct a physical model for daylight simulations (Fig. 4.6).

Scale	Objectives
1/200 to 1/500	For preliminary design and concept development
	To provide a gross sense of the massing of the project
	To study the shadows generated by the future building or from a neighboring building
1/200 to 1/50	To study direct sunlight penetration into a building
	To study diffuse daylight in a very big space
1/100 to 1/10	To consider detailed refinement of spacial components
	To have highly detailed inside views
	To study accurately diffuse and direct daylight penetration
1/10 to 1/1	To integrate critical industrial components
	To consider daylighting devices that cannot be reduced in scale
	To proceed to final evaluation of advanced daylighting systems through monitoring and user assessment

Fig.4.5. *Scale choice of testing models as a function of daylighting design purpose (International Energy Agency, 2000)* (Bodart et al., 2007)

Fig.4.6. *Photos of physical model of 1/10 scale.*

In order to arrive to as much accuracy as possible in the comparison of the physical model's illumination levels results to that achieved by simulations we carried out the simulation with modelled the sensors and their two sets of bases and without the sensors and their bases. The differences in the illuminance level values where small, but we decided to keep the results of the simulation models with the sensors and their bases. The differences in the simulated results with the measured results in the model with the sensors and without them are provided in the Appendix. In Fig. 4.5 the first set up of the experiment is presented. More detail pictures of all shading systems and the other type of sensors' bases used, are presented in the Appendix.

We carried out experimental work in real sky conditions around three characteristic days of the year: winter solstice, equinox and summer solstice in order to arrive to more robust conclusions. The days of measurements were randomly selected in order to cover a wide range of naturally occurring sky conditions, ranging from overcast to intermediate and clear.

The colours used for the model are Vivechrom brand codes: WP121 for the floor, BC350 for the walls and WP011 for the ceiling and their reflectance is measured with a Spectrophotometer Spectraflash SF 600+CV UV. That measurement was done with the help of Vivechrom Company in order to approximate the simulated reflectance values. For the glass of the window, a Plexiglas was used; this has a transparency value of 90% (see the manual of the product in the Appendix).

We used six interior lux sensors manufactured by Skye (dimensions: 34mmx38mm = HxW) and one external lux sensor that was placed horizontally outside in order to measure sky illuminance. All the sensors were connected to a data logger also manufactured by Skye (DataHog2). Specific characteristics of the instruments used can be seen in Appendix. We programmed the data logger to take measurements of illuminance every 5 minutes. The sensors were positioned as in (Fig.4.7) at 0.75m height. Similar positioning of sensors and methodology of measuring daylight conditions can be seen in www.daylightinglab.com and (Aghemo et al., 2008).

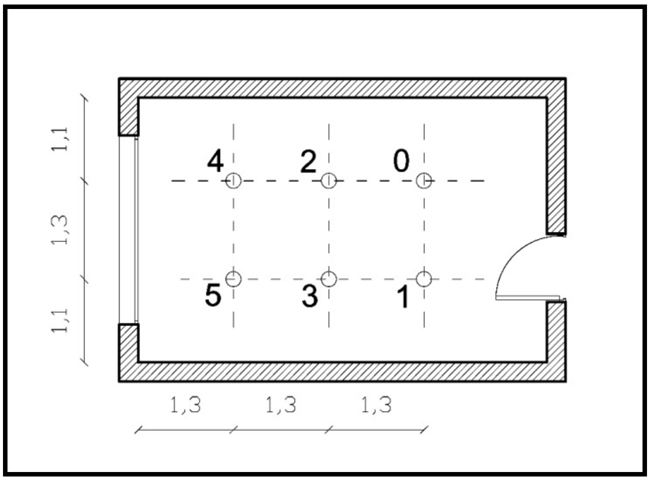


Fig. 4.7. *Plan showing the position of errors in the model*

Due to the fact that the results were to be used not as absolute values but in a comparative manner and for reasons of efficiency and economy one model of the office unit was constructed. A system was devised in which the façade that carries the shading device is changing. Fourteen different facades were constructed and tested in total (thirteen different shading systems and one facade as a simple window).

4.6.2. Simulations of the reference office unit

In order to arrive to more accurate results we additionally carried out a series of simulations of the same shading systems and we compared them to each other. As found in literature, physical models overestimate the illuminance levels in comparison with the illuminance levels of a real building.

These differences in estimating the illuminance levels become larger in the case of sunny sky when a sensor might be in a position where daylight changes rapidly. For all the reasons mentioned in previous paragraphs what interests our research is the comparison between measured and simulated data and not the values themselves. In the examined cases the differences between the physical model and the simulated data are attributed to difficulties in simulating real sky conditions accurately. Although all the basic rules mentioned in bibliography when constructing and measuring physical models for simulations of daylight were followed, the method is not validated and the results are only approximate.

In order to further investigate the influence of the integration of PVs on the interior illuminance levels we carried out another series of simulations with PV filters integrated in louvers systems. The basic difference compared with the integration of PV panels is the thickness of the panel, which in the case of panels was simulated as 3.5cm and in the case of the glass PV filters was simulated at about 1.5cm. Technical data of the glass PV filters made by the manufacturer Schuco were taken into account.

In order to conduct a complete research concerning the daylight levels throughout the year we conducted further research and we simulated daylight autonomy. Daylight factor and illuminance distributions are *static* daylighting metrics, i.e. they are based on a single sky condition. Dynamic or climate-based metrics are based on all different sky conditions that occur in a year at a given building site. With Dynamic analysis we can have an overall analysis of the daylight levels for the whole of the year.

Further on we investigated daylight levels in relation to daylight autonomy levels, in order to analyze energy savings through daylighting.

In order to arrive to more accurate conclusions we calculated daylight autonomy levels with both Ecotect and Daysim.

DAYSIM is validated daylighting analysis software; it calculates the annual daylight availability in arbitrary buildings based on RADIANCE backward ray tracer. It provides more accurate results than the split-flux method used by ECOTECT for daylight factor calculations.

Moreover, in order to evaluate the daylight quality of the examined shading systems we studied two more variables regarding daylight quality: the Useful Daylight illuminance (UDI) (Mardaljevic, 2001) and the Daylight Glare Index (DGI) (Baker & Steemers, 2001).

In relation to UDI, we assess three basic statistical values: UDI 100 -2000 (the mean value of the UDI), the UDI 100, (the percentage of the time of the year when the space has daylight under 100lux; this level is considered very low) and the UDI 2000, (the percentage of the time of the year that the space has daylight above 2000lux; these levels of daylight are considered to result in uncomfortable comfort conditions).

To evaluate DGI we used the basic table given by (Baker et al., 1993, p. 2.18). Values below 16 are considered to result in an imperceptible visual environment.

Originally we selected the "worst viewing position" for the simulations. In theory, the worst viewing position is the one that has the highest vertical viewing angle of the window that constitutes the main light source of the space in question, and the one with the widest viewing angle onto the surface of the window (Meresi, 2010). We selected this position in Ecotect model as it can be seen in figure 4.13.

It is well known that fixed shading systems which allow view to outside need additional interior movable solar shading (Dubois, 2001). We mostly compared the two groups of shading systems, the louvers systems and the systems that allow view to outside. We compared them according to daylight quality using the following two basic variables: the UDI and the DGI.

4.6.3. Comparison between physical models and simulations

As we saw in a previous paragraph the comparison between measurements on physical models and simulations can be a complicated task, especially in cases when the physical model has been tested in real sky conditions. For this reason, research has been carried out and we have arrived at some basic conclusions with reference to the measurements from the validated simulation tool used and the measurements from the constructed model. In general the physical model overestimates the values in comparison with the simulation tool (Mardaljevic, 2001). In some cases the overestimation is in the range of 100%.

When the divergence between the two models is in the range of 300% and over this is due to the rapid changeability of the daylight and to the small divergence of positioning the sensor in relation to the simulated model. In cases where the sun is higher in the sky (summer solstice) the divergence is higher. Moreover, in the complicated geometries of Venetian blind systems the divergences become even higher. It is important to mention that in contrast with the reported data by (Mardaljevic, 2001) the differences between measurements in a physical model and measurements in simulations are higher in positions near the window and not at the back of the room (Fig. 4.8).

Aghemo et al. (2008) examined scaled models of a classroom with different shading systems in sky simulators. The experiment considered to be in the town of Turin (45^o N, 7^o E). Among their examined systems was also the overhang. The WWR of their examined window is 44.44%, very close to ours (44.92%). Even though there are differences between the reflectance of the interior finishing and the examined latitude in relation to our experiment we can see the similarities in the results in the case of the canopy at noon of 29.06.2012 and 21.06 in their case. The illuminance (lux) in 1.26 m behind the window is about 3000 lux measured with our physical model and in the case of the research done by Aghemo et al. (2008) in a distance of 1.5m behind the window is a bit lower than the 3000lux, concerning Turin latitude with reference to standard CIE clear sky and with the use of a sky simulator. This fact proves the accuracy of our measuring method with the physical model.

Moreover, we carried out additional sets of simulations for the louver systems in order to assess the influence of the thickness of the material of the PV louvers. We shall present the results of this comparison in the next chapter.

Finally it should be noted that the daylight evaluation method with the use of physical models should be used in the detailed design stage of the facade, and not earlier, especially when physical sky is used for the measurements. This is due to two facts: firstly to the random changeability of real sky (it is time consuming to wait for the same sky conditions) and secondly to the fact that in order to achieve accuracy of the results a detailed model is necessary. On the contrary, in the early design stage, it’s possible to use simulation tools to evaluate daylight levels. The measurement conditions are 100% controllable in comparison to the measurement conditions on a real building. The only disadvantage is that designers are used to assess their design using physical models and are not familiar with the values used by the simulating tool. The image output of the simulation tool in this case, should be more frequently used.

Concluding we can summarize the results of the comparison using physical models and simulations for daylight levels assessment as follows:

- The comparison of simulations and physical models is a complicated task, especially when real sky conditions are used and there is no use of sky scaner. When absolute values of daylight levels is the goal the use of exactly the same sky illuminance should be achieved, something that is not possible due to rapid changeability of the sky, especially the winter period. When comparative analysis is the goal, the procedure is time consuming because it requires the same values of sky illuminance for all examined systems. We focused on the evaluation of the daylight levels separately for each system in order to arrive to a pattern of relation between simulations and physical model of 1/10 scale and the use of real sky conditions.
- In general physical model overestimate the daylight levels in comparison to simulations. Only for the case of Louvers Horizontal Outwards Inclined simulations are higher than measurements of the physical model. The percentage of overestimation depends on the position of the sun in the horizon and the point in the space examined in relation to the depth of the room (Fig. 4.9).
- For the cases of low sun position the differences between experimental measurers and simulations are higher in the case of the front of the room. For the case of the back of the room the differences are lower than 50% and for the case of the front of the room the differences are higher than 50% but less than 70%. For middle points of room the difference are in the range of 50%.
- For the case of higher sun positions the differences are becoming lower. Still thought the differences are higher than 45% for the cases of the front of the room but less than 70%. For the case of the back of the room the differences are lower than 45%. Additionally we can see that for most of the cases the differences are closer to the range of 45% and there are not high differences as in the case of low sun position.

Low sun Position

Back of the room

SD	Dif(%)
LV	5
LH	12
BSS	19
BSL	19
C	20
LHO	21
CI	35
CID	43
CD	45
LHI	54
SW	68
BS	83
CL	84
S	92
Aver. Dif(%)	43

Front of the room

SD	Dif(%)
LHO	22
LH	24
CI	27
C	32
LV	36
BSS	38
CD	50
S	52
CID	53
BSL	56
LHI	62
SW	71
CL	73
BS	77
Aver. Dif(%)	48

High sun Position

Back of the room

SD	Dif(%)
SW	-22
BSS	-14
CD	-14
CID	-8
CL	18
LHI	19
S	23
LH	25
BS	26
CI	30
C	32
LV	33
LHO	55
BSL	60
Aver. Dif(%)	27

Front of the room

SD	Dif(%)
BSS	-3
CD	13
CID	13
CL	25
CI	32
BS	35
SW	39
S	41
LV	42
C	47
LH	51
LHI	55
LHO	60
BSL	78
Aver. Dif(%)	38

Fig. 4.8. *Comparative diagram of measured differences in daylight levels between Physical Scale Model and Simulation*

- These types of scale models (1/10) can be used for measuring daylight levels of an interior space and they will be safe to expect daylight levels lower than 45% in real buildings than these measured for summer period, for the case of the back of the room that the direct sun ray is excluded, and over 45% for the case of positions near the light source,
- For the cases of complicated geometries the results are not accurate. The detailing of the model plays the major role and very small differences between the model and the simulation can drastically affect the results.
- For measuring daylight levels in positions at the front of the room – near the daylight source (opening) – daylight levels are closer to the overestimation of 50% for the case sun position near the equinox.
- In general the higher the sky illuminance the small the differences between the estimated values of the physical model and the simulation for the back of the room.
- The use of physical model for estimating daylight levels is accurate in the case of high sun position, clear sky and for points at the front of the room. The overestimation in these cases is near the range of 40%.

- For positions at the back of the room measurements with the physical model are not accurate due to the fact the differences are cluttered. This is probably due to over reflections of light beam that occur at the back room, which are not happening in the front, near the light source.

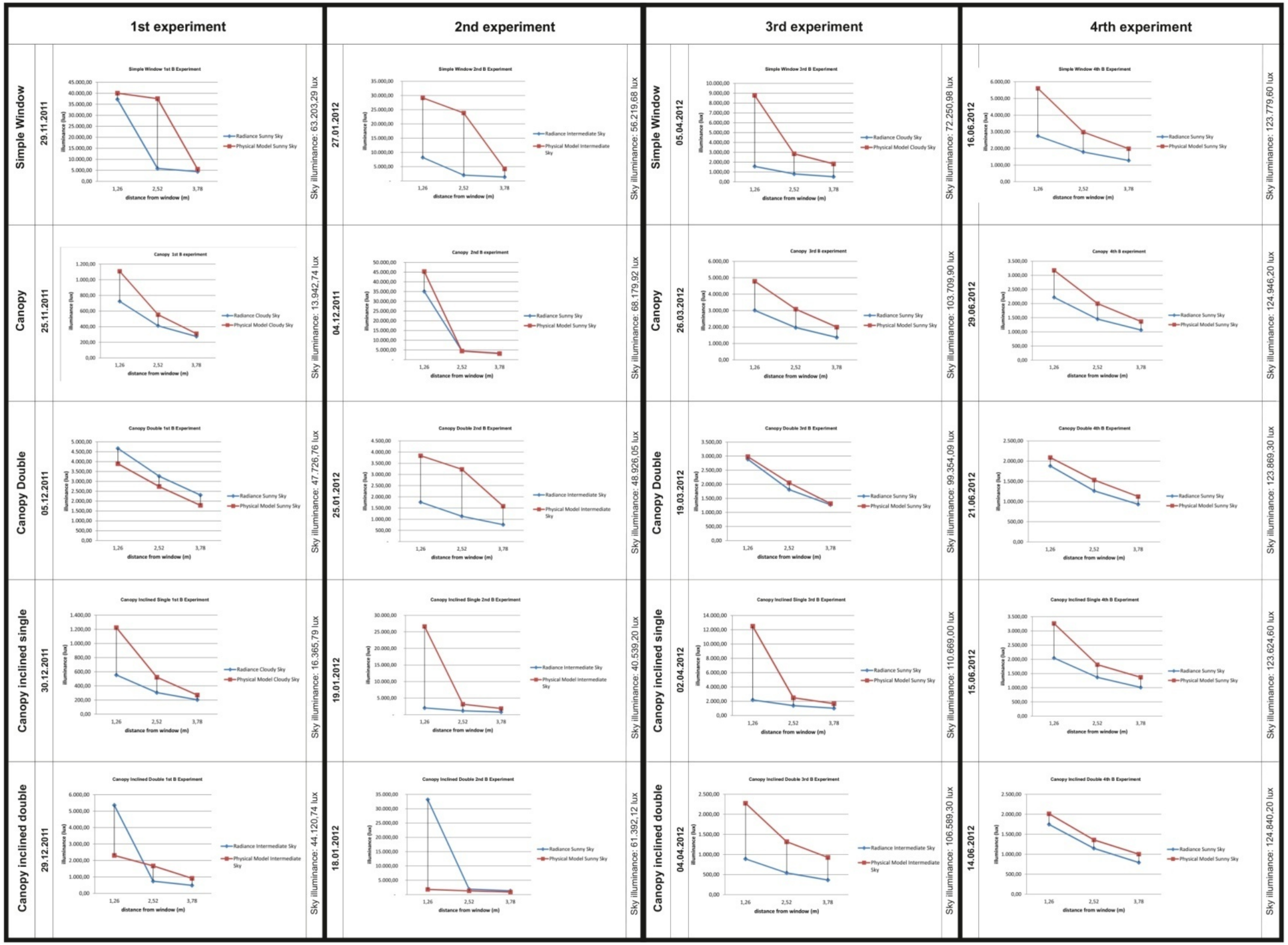


Fig. 4.9. *Comparison of results of simulations and measurements with physical models of 44.92% WWR for Chania Latitude*

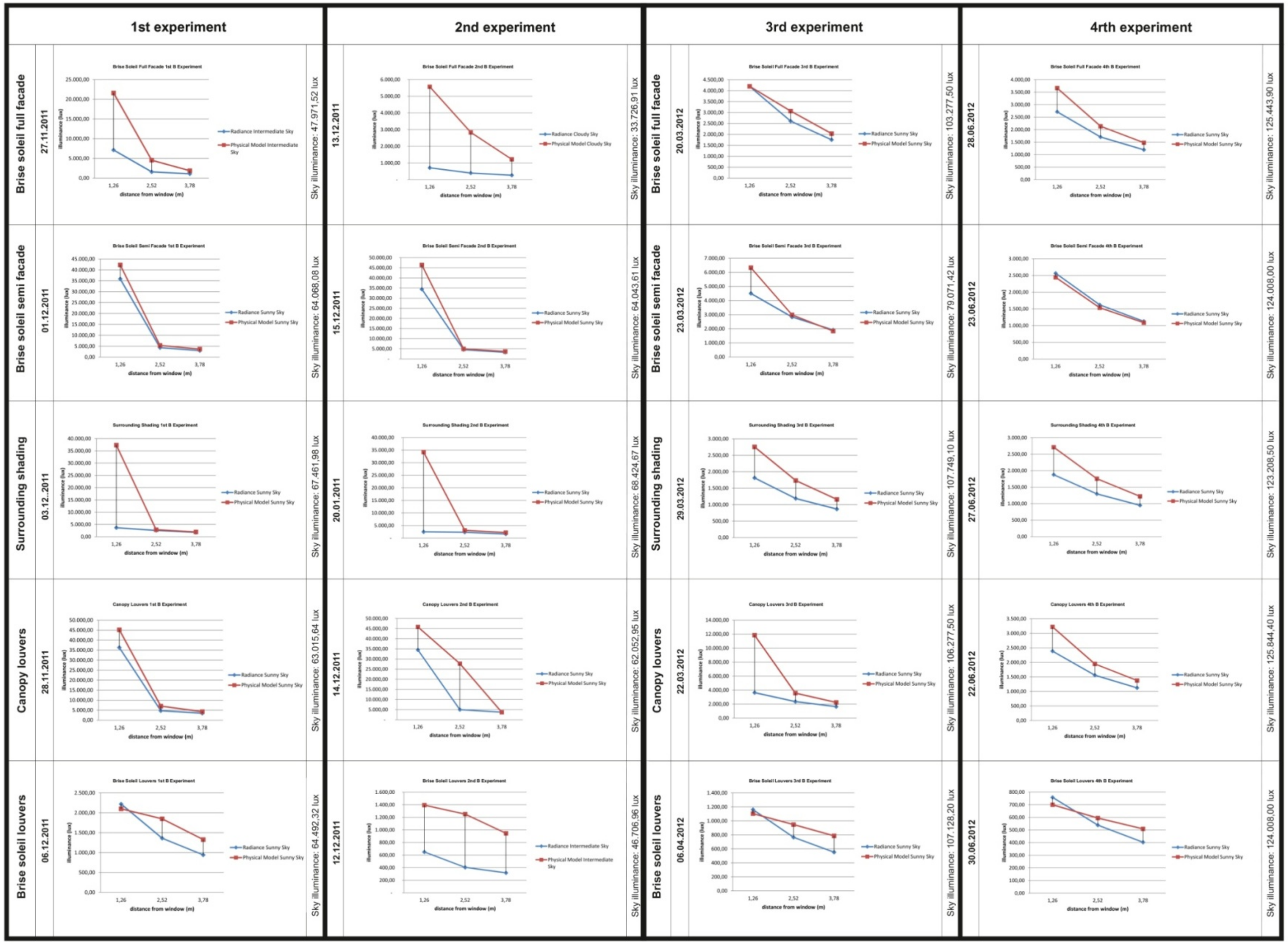


Fig. 4.9. *Comparison of results of simulations and measurements with physical models of 44.92% WWR for Chania Latitude for 11.35 solar time*

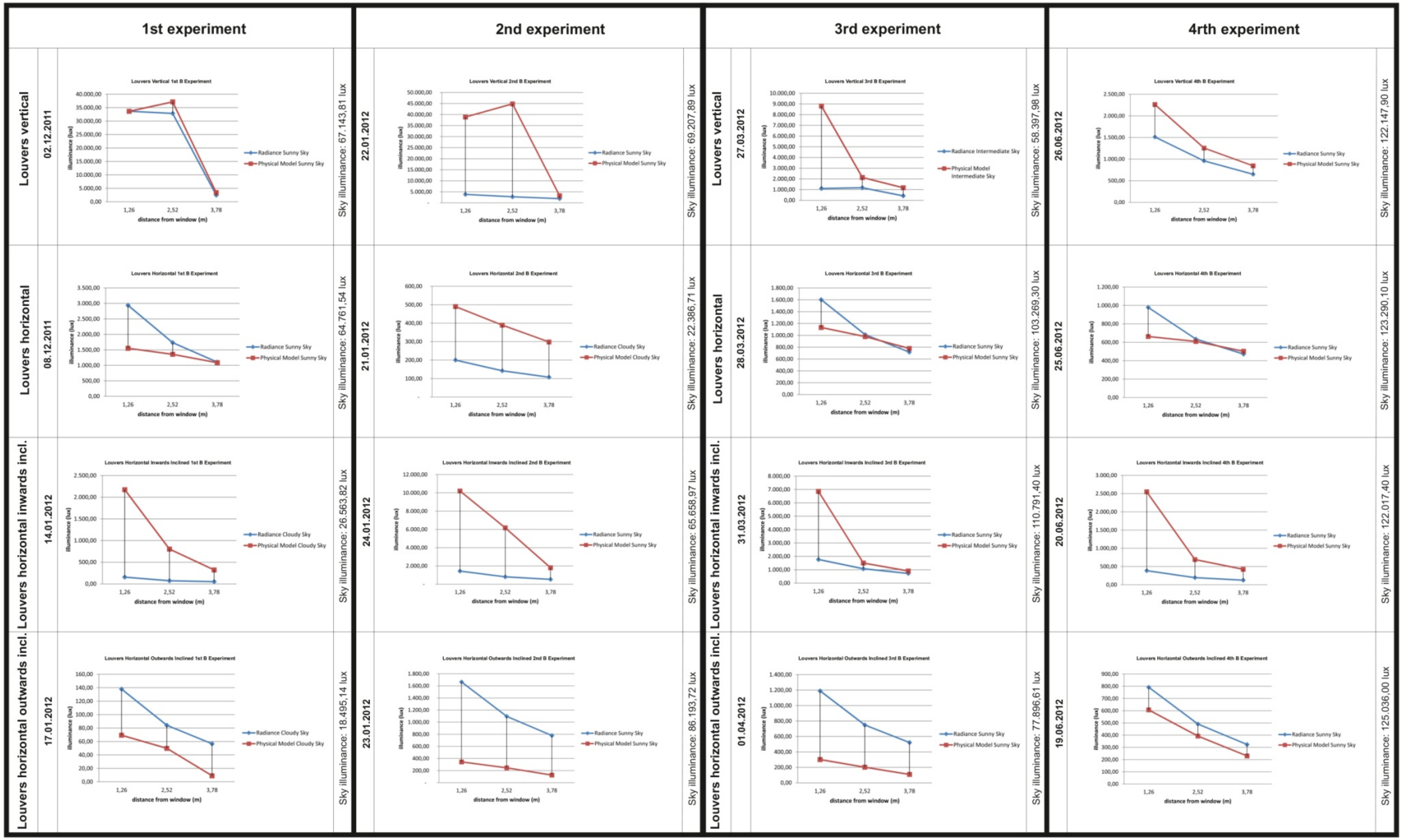


Fig. 4.9. *Comparison of results of simulations and measurements with physical models of 44.92% WWR for Chania Latitude for 11.35 solar time*

4.6.4. Comparison of the daylight levels in terms of Daylight Autonomy (DA)

Regarding Daylight Autonomy (DA) for daylight levels above 500lux, systems allowing outside view perform better than louvers systems. From the first group of shading systems (transparent systems) **Canopy louvers** and **Brise soleil** systems perform better while the **Surrounding shade** has the lowest value of DA. In the second group of shading systems **Louvers vertical** and **Louvers horizontal** perform better when compared with Louvers Horizontal Outwards Inclined (Fig.4.10).

Moreover we can relate the DA to the energy of electric light needed and we can arrive at the above mentioned conclusions in relation to the system saving energy the most in terms of lighting: the system of **Canopy louvers** and the **Brise Soleil system** are the most economical systems in relation to the electricity used for lighting. Amongst the façade systems that obstruct the view to outside the system of **Louvers horizontal** and the one of **Louvers vertical** perform well. As expected the DA levels are higher for all Shading Systems examined in the case of Chania latitude in comparison with the DA levels in the Athens latitude (Fig. 4.11).

We simulate DA using two computer simulation applications (Ecotect and Daysim: the former uses a split-flux method and the latter dynamic simulation software). Some differences have been observed between the two methods. In most cases the Daysim calculates higher levels of average daylight autonomy (DA) and the differences are in the range of 16%. This difference is probably enhanced by the fact that for Ecotect Illumination levels are calculated for 85% of the time between 9am and 5pm. So Autonomy results do not apply to 100% of the time for the entire year.

For more complicated systems of venetian blind the differences are higher and are in the range of 40%. For complicated systems and for detailed analysis only the dynamic software is accurate enough (Fig.4.11 and Fig.4.12).

Additional we can see that the same systems are performing well for both latitude points and that there are some small differences between them in relation to their exact distribution (Fig.4.13).

DA is not a value that can be examined by itself to evaluate daylight quality. It should be examined together with other daylight quality criteria. This is due to the fact that DA gives information about daylight levels over 500 lux, but does not give information about overlit areas which can be uncomfortable or areas with lighting lower than 500 lux where lighting levels must be increased in order to reach the desired light intensity. That is the reason why we evaluated DA in relation to two other factors (the UDI and the DGI) and we will analyze the combined results in the next paragraph.

Moreover, in the next chapter the electricity needs are presented in relation to the electricity production of the PV panel integrated in the shading system. We arrived at a general conclusion concerning the energy performance of the shading systems examined in relation to energy savings and comfort conditions.

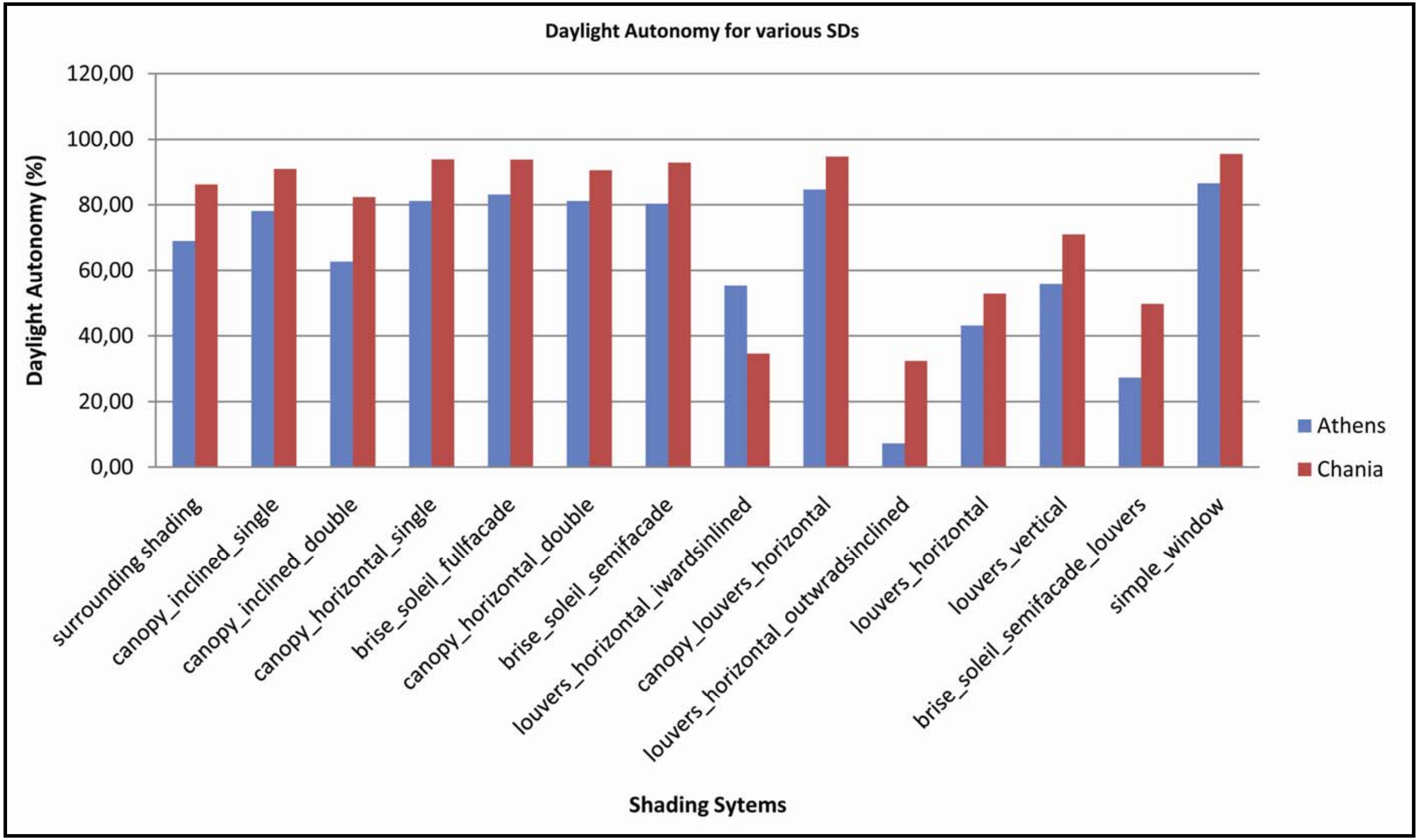


Fig.4.10. *Comparison of Daylight Autonomy for Athens and Chania*

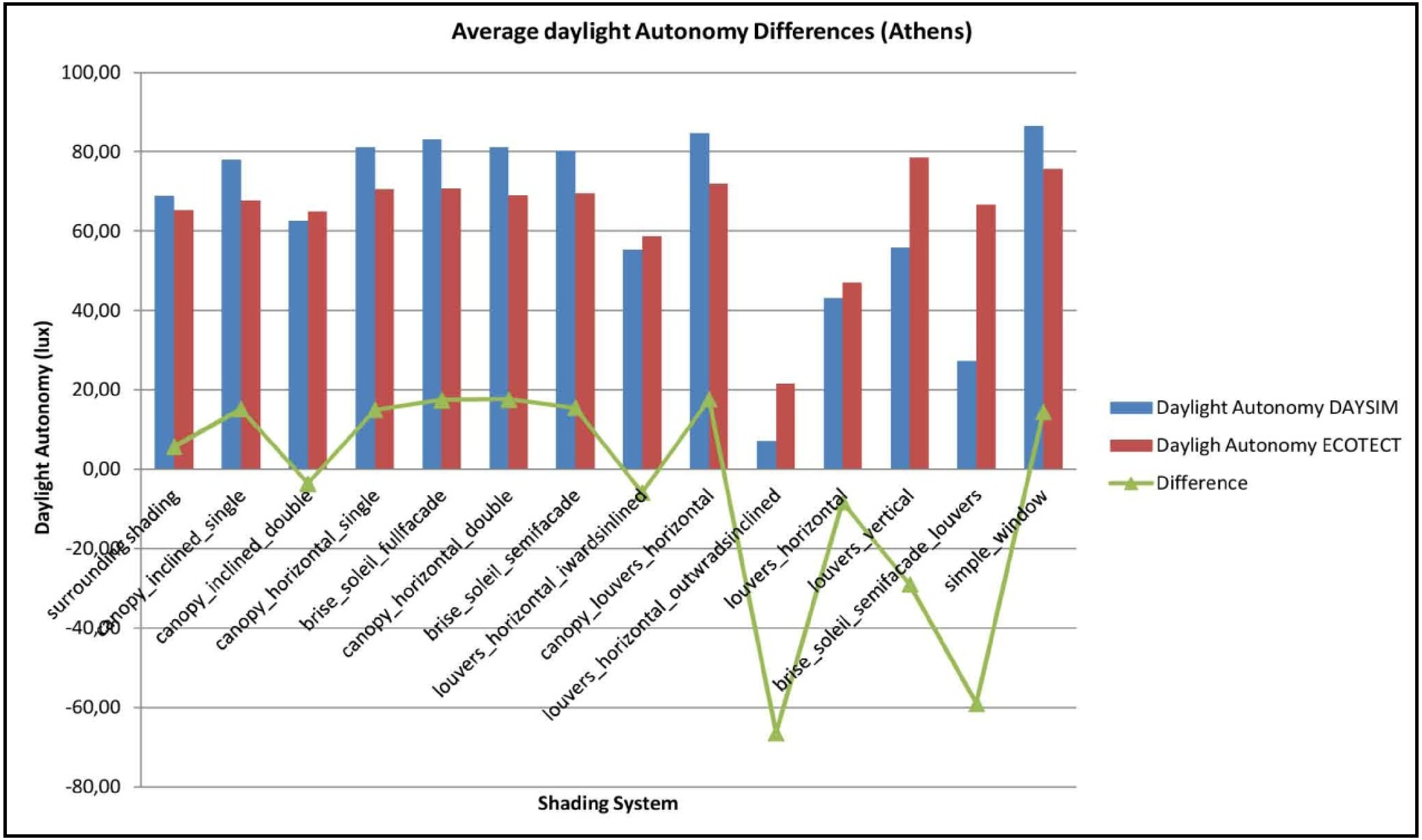


Fig. 4.11. *Difference of calculated DA for Athens Latitude between Daysim and Ecotect application software*

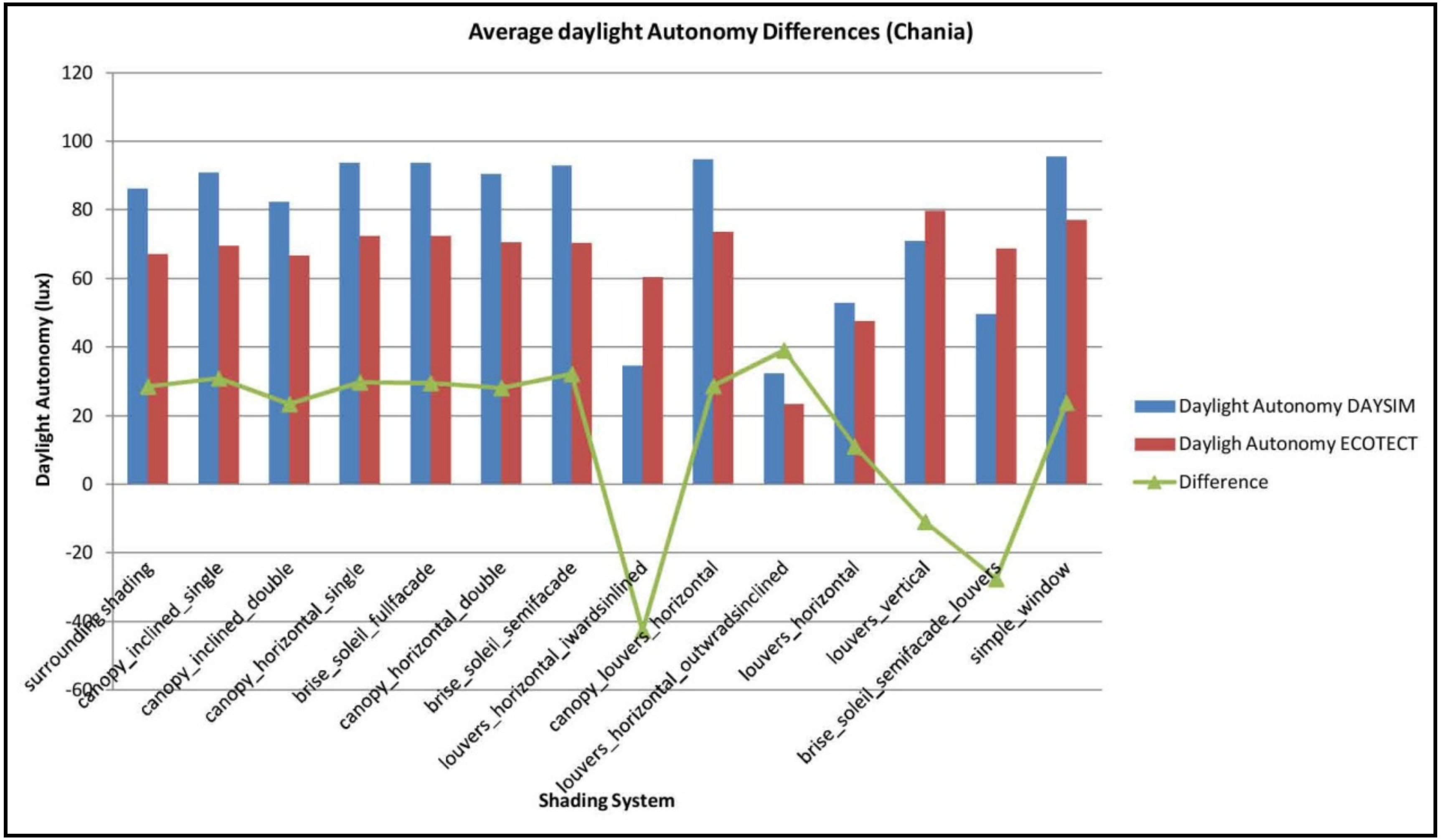


Fig. 4.12. *Difference of calculated DA for Athens Latitude between Daysim and Ecotect application software*

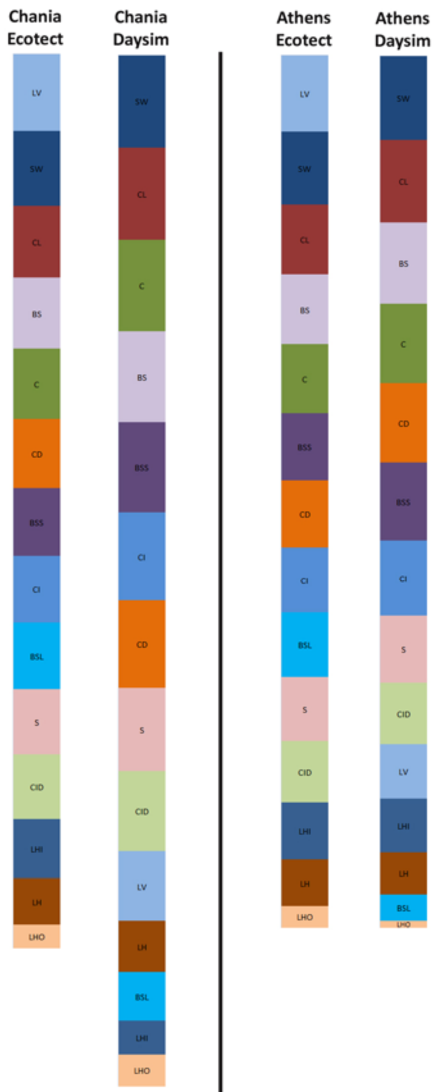


Fig. 4.13. *Comparison of simulated Daylight Autonomy by Ecotect and Daysim for two latitude points (Chania – Athens)*

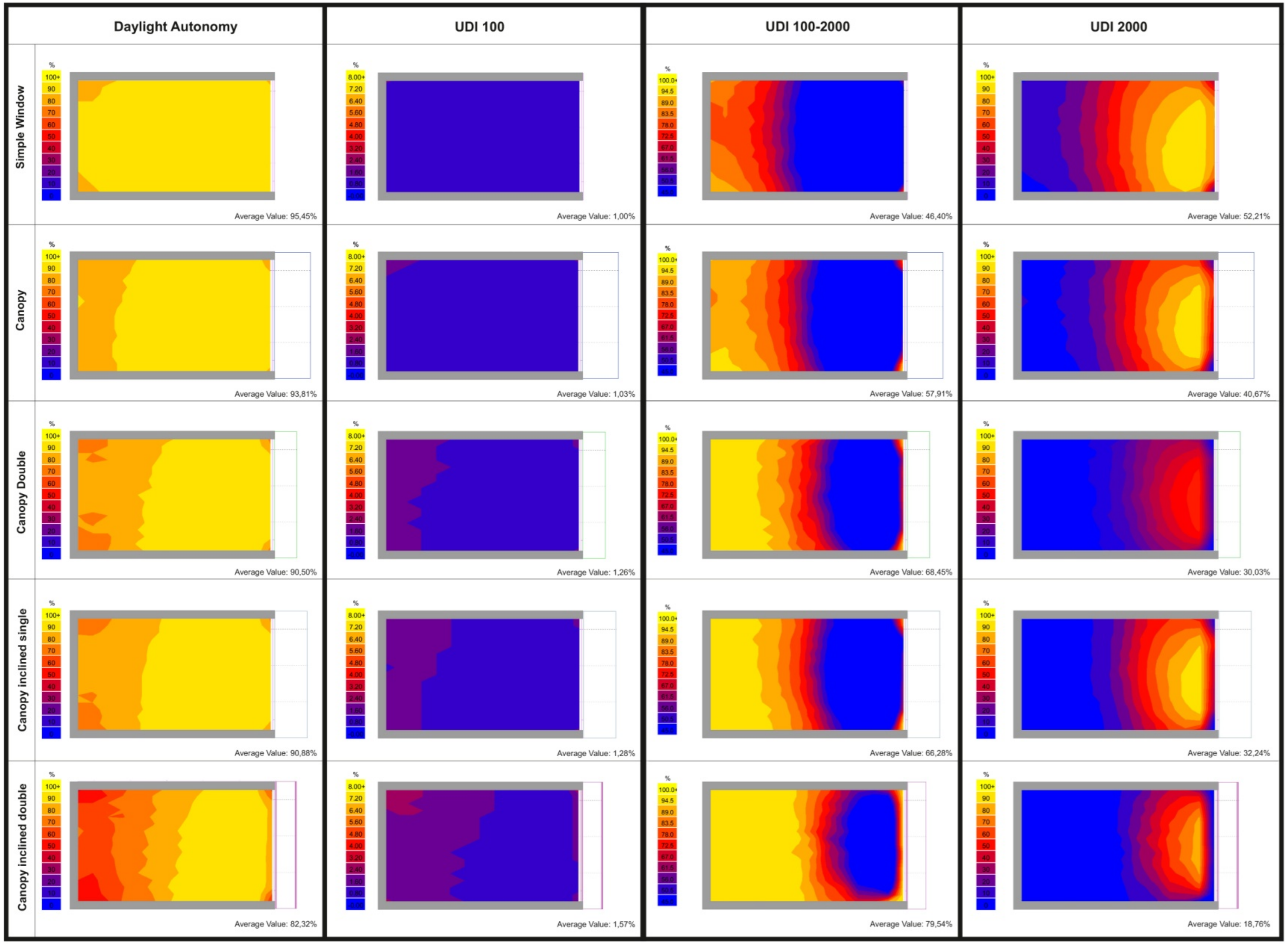
4.6.5. Comparison of Daylight quality in terms of Useful Daylight Illuminance (UDI)

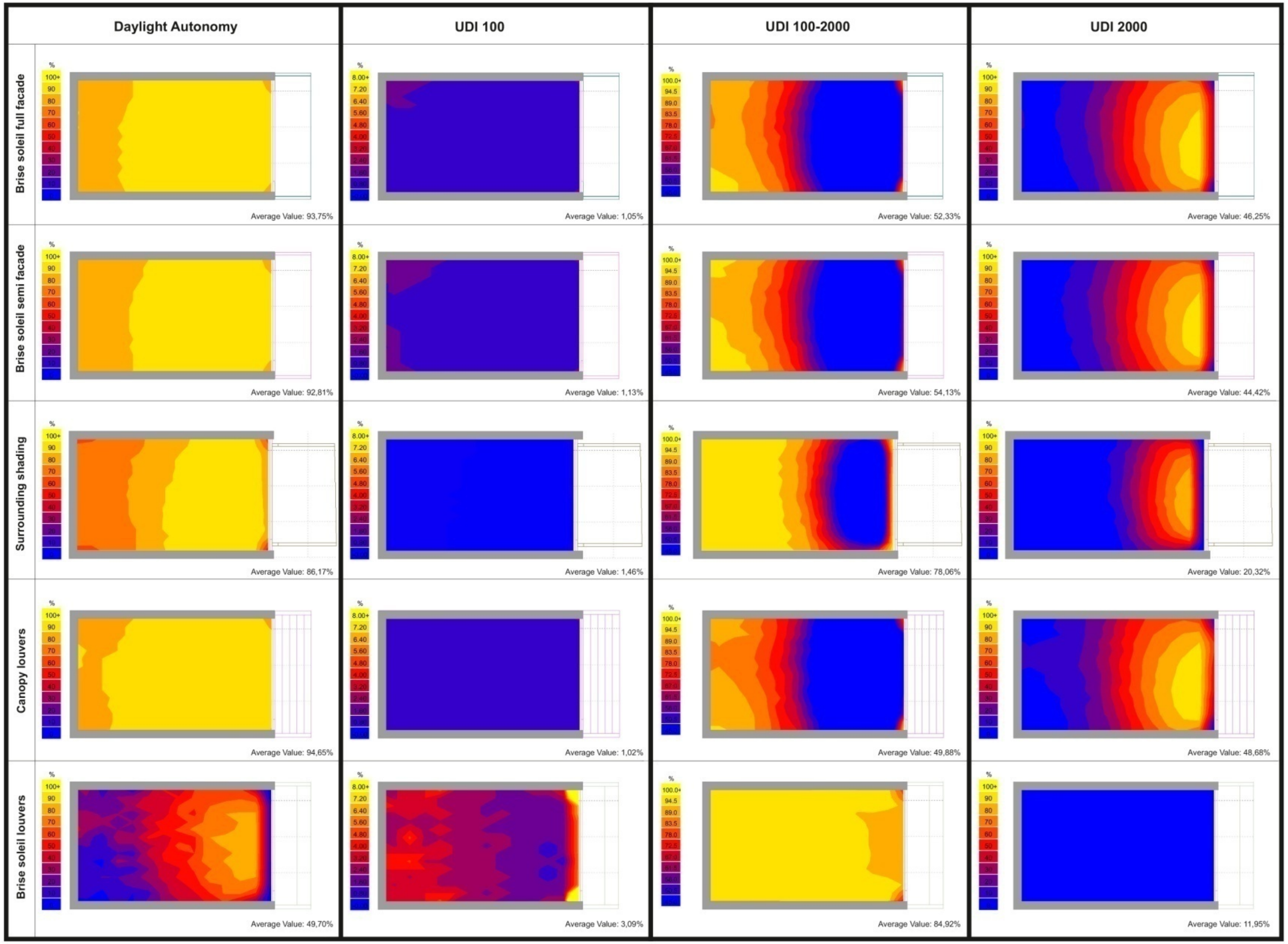
In the third experimental stage the daylight quality is assessed in relation to Useful Daylight illuminance (UDI). As it can be seen in Fig. 4.14 the **Canopy** systems (with louver or simple) have high daylight autonomy (DA) value (almost 94%) but at the same time they have low UDI 100 -2000 value (almost 50%), resulting in an uncomfortably daylit space. This UDI 100 -2000 value is the lowest in comparison to other systems. Similar results apply for **Brise Soleil** systems. Both systems perform very low in terms of daylight quality and almost the same as the Simple unshaded window.

Amongst transparent façade systems **Surrounding Shade** seems to perform well because it has high UDI 100 – 2000 values, low UDI 100 value and low UDI2000 value in comparison to other transparent shading systems. Additionally **Canopy Double** systems **Inclined or not** perform well in relation to the three examined UDI values, but lower than Surrounding Shade.

In general, façade shading systems and especially **louvers** systems perform better in terms of high percentage of UDI 100-2000. Amongst these systems, Louvers Horizontal has the highest UDI 100 -2000 and simultaneously the lowest UDI 100 (resulting in low daylight levels) but the highest UDI 2000, near the window that might produce glare. Systems such as **Brise Soleil Louvers and Louvers Horizontal** seem to produce a comfortable daylight environment due to their low value of UDI 100 and Low value of UDI 2000. Additionally the system of **Louvers horizontal outwards inclined** is the 3rd best performing system in relation to all examined UDI values (Fig. 4.14).

In conclusion, façade systems perform better in relation to Useful daylight illuminance (UDI), as expected and not according to DA. At the same time, of course due to low DA, they result in high energy consumption for daylighting. We will further on investigate their performance in relation to daylight quality in the next paragraph where glare will be evaluated.


Daylight Autonomy
UDI 100
UDI 100-2000
UDI 2000
Simple Window
Canopy
Canopy Double
Canopy inclined single
Canopy inclined double
Average Value: 95,45%
Average Value: 1,00%
Average Value: 46,40%
Average Value: 52,21%
Average Value: 93,81%
Average Value: 1,03%
Average Value: 57,91%
Average Value: 40,67%
Average Value: 90,50%
Average Value: 1,26%
Average Value: 68,45%
Average Value: 30,03%
Average Value: 90,88%
Average Value: 1,28%
Average Value: 66,28%
Average Value: 32,24%
Average Value: 82,32%
Average Value: 1,57%
Average Value: 79,54%
Average Value: 18,76%


Daylight Autonomy
UDI 100
UDI 100-2000
UDI 2000
Brise soleil full facade
Average Value: 93,75%
Average Value: 1,05%
Average Value: 52,33%
Average Value: 46,25%
Brise soleil semi facade
Average Value: 92,81%
Average Value: 1,13%
Average Value: 54,13%
Average Value: 44,42%
Surrounding shading
Average Value: 86,17%
Average Value: 1,46%
Average Value: 78,06%
Average Value: 20,32%
Canopy louvers
Average Value: 94,65%
Average Value: 1,02%
Average Value: 49,88%
Average Value: 48,68%
Brise soleil louvers
Average Value: 49,70%
Average Value: 3,09%
Average Value: 84,92%
Average Value: 11,95%

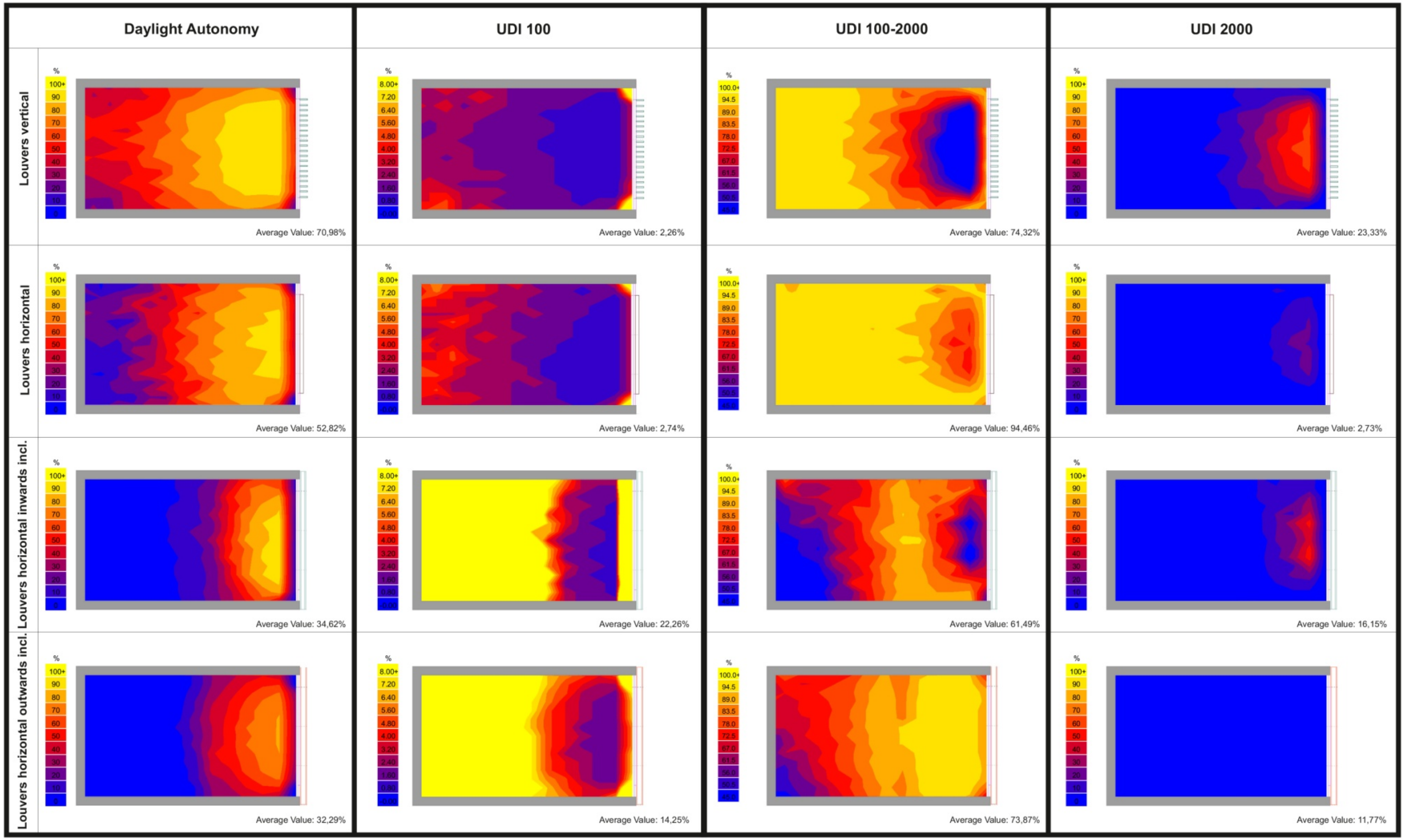


Fig. 4.14. *Comparison of UDI values in relation to DA values for all SDs examined for the case of Chania*

4.6.6. Comparison of Daylight quality in terms of Glare

As we can see in Fig. 4.15 most of the systems have DGI values of above 16 for most of the viewing angles. It is important to mention here that we have chosen to examine glare for the worst possible position in the room (the most remote point inside the room) (Fig. 4.16). This means that the results are appropriate for this position of occupants and not for cases of occupants near the window. We chose to examine this position in order to arrive to holistic conclusions concerning the daylight quality and not to specify them to determinate user's positions. Further research will be needed in order to evaluate glare probability in specific user's positions.

We calculated that only some systems can result in values below 16 and these are presented here in sequence starting from the best performing: **Canopy louvers, Louvers vertical, Brise Soleil Full Façade and Brise Soleil Semi Facade** These systems even though we showed in the previous paragraph that they do not perform very well in terms of UDI values, they perform very well in terms of low glare values and in terms of DA. They can further on result in low energy consuming systems in relation to electric light needs.

Some systems result in perceptible glare conditions (values between 16 -20). These are **Brise Soleil Semi Façade** and **Canopy Horizontal Double**. At the same time Canopy horizontal double results in an acceptable level of UDI values. The rest of the examined systems result in acceptable glare conditions (values between 20 to 24) presented in row from the worst to the best: **Brise soleil Louvers**, **Louvers Horizontal**, **Louvers Horizontal inwards inclined**, **Surrounding shade**, **Canopy inclined Single**, **Canopy Inclined Double**, **and Louvers Horizontal Outwards**. We can further see the resulting environment in Fig. 4.17.

We additionally examine the performance of SDs in relation to glare for camera positions near the window, in order to evaluate visual environment in these positions. In Fig. 4.18 the positioning of the new camera is presented.

We can see (Fig.4.19) that systems of **Brise – Soleil Semi facade and Full facade, Surrounding, Canopy Inclined Double** perform very well in terms of glare for positions near the window. From them only the **Brise Soleil System** performs well perform very well in relation to camera positions away from window. Additionally the system of **Surrounding Shade** and of **Canopy Inclined Double** even if they are not performing excellent for positions at the back of the room they can be considered as potentially well performing systems because they can assure acceptable glare conditions at the back and perceptible daylight comfort conditions at the front of the room, near the daylight source.

Generally we can see that all systems have almost the same changeability of the curve. The more cantered the angle view the more glare is created. The more the eye view is turning away from the window the better the visual comfort.

It is remarkable that in these areas the UDI values are higher for a lot of case near the walls, and this generated questions concerning the possible glare problems that might occur in these areas due to the over-reflection of the bright colour wall. According to DGI value these areas are not dreadful for glare problems.

Some systems result in zero (0) DGI value. This is due to inability of the software to calculate DGI values for these cases and we won't take into account their DGI performance.

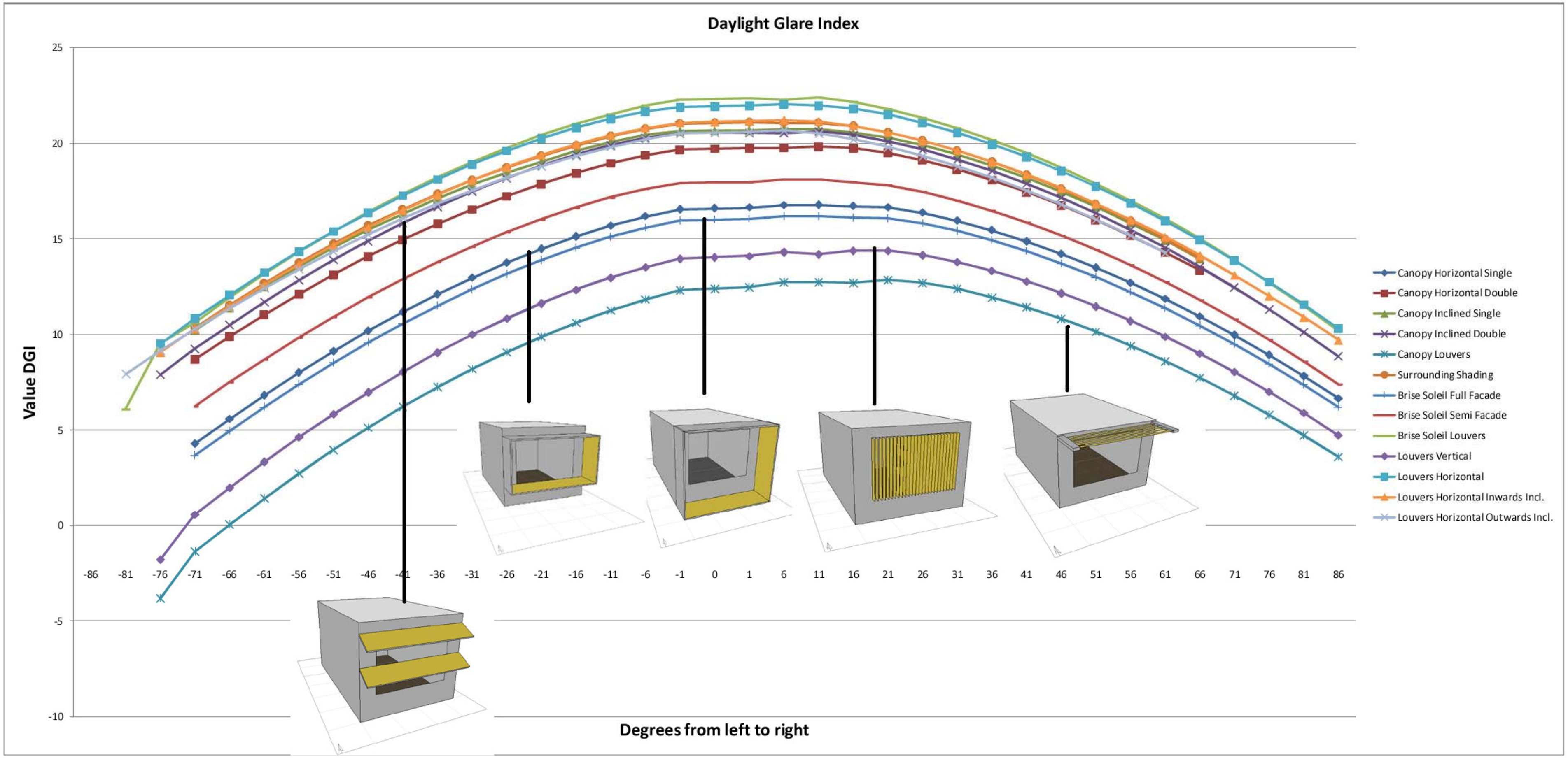


Fig. 4.15. *DGI values for the 21 December at 12:00 o'clock for all examined systems in relation to the angle of view for the camera away from window*

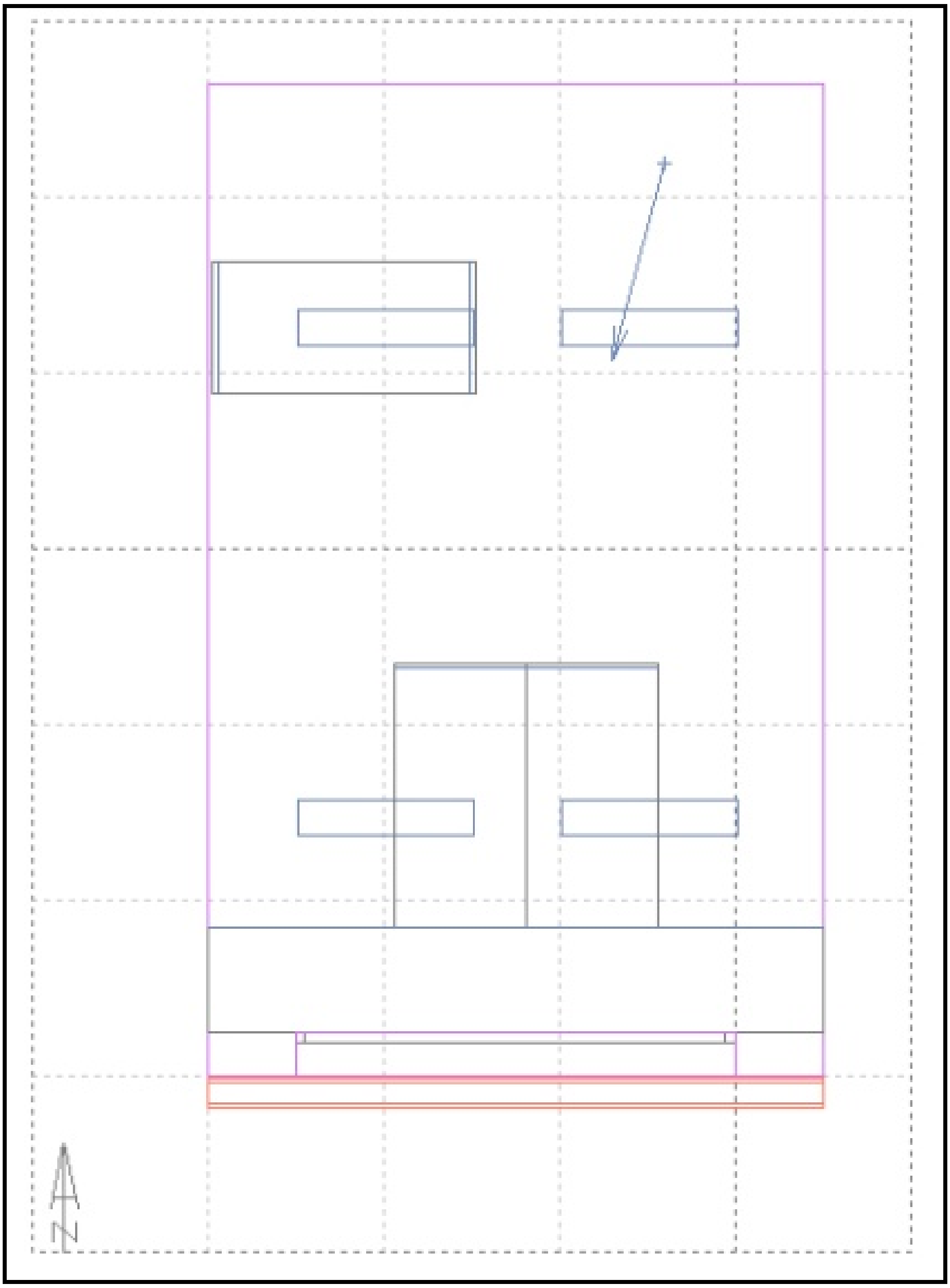


Fig.4.16. *Camera view for calculating DGI for South facing SDs for Chania Latitude*

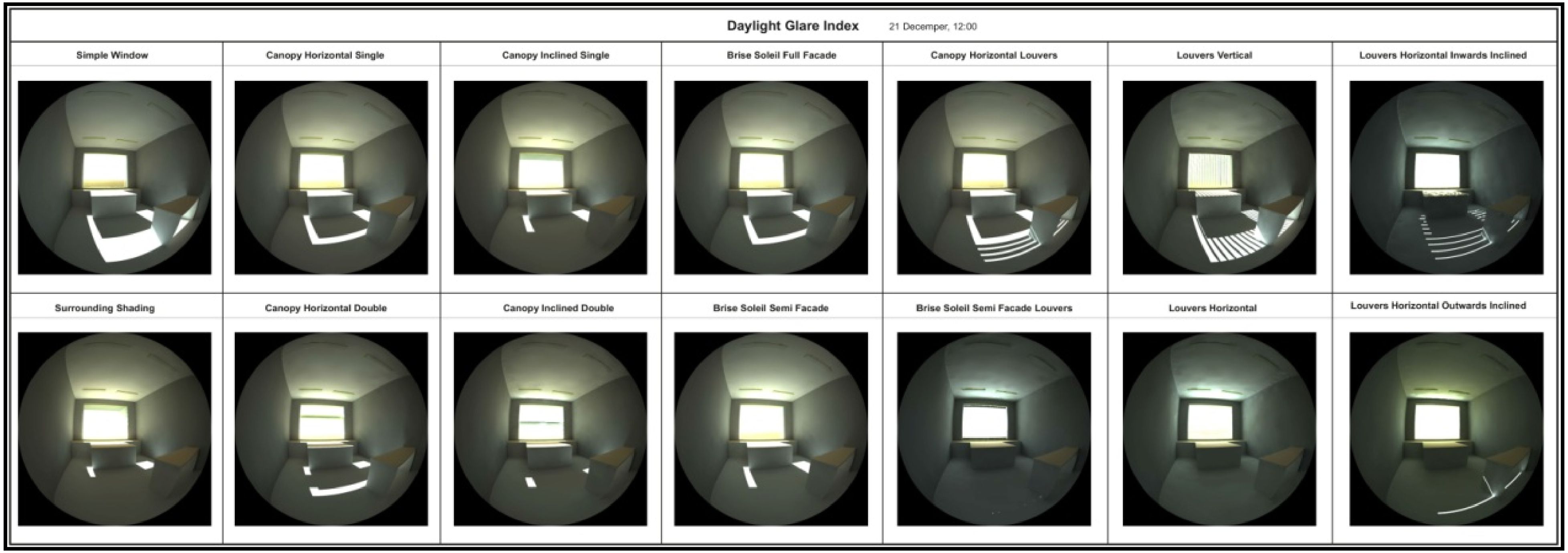


Fig. 4.17. *Fish eye camera for the 21 December at 12:00 o'clock for all examined systems in relation to the angle of view for the camera away from window*

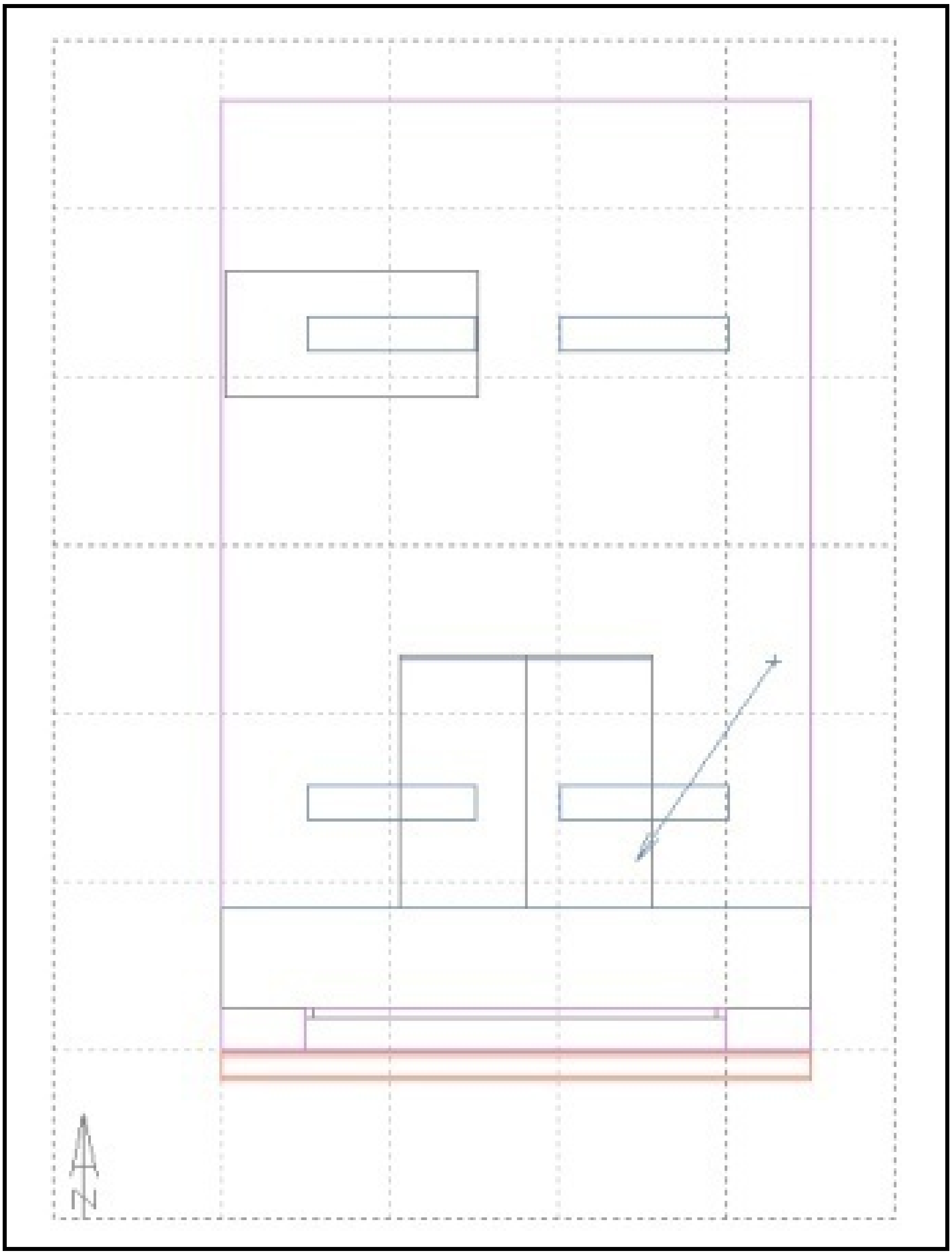


Fig.4.18. *Position of the new examined camera*

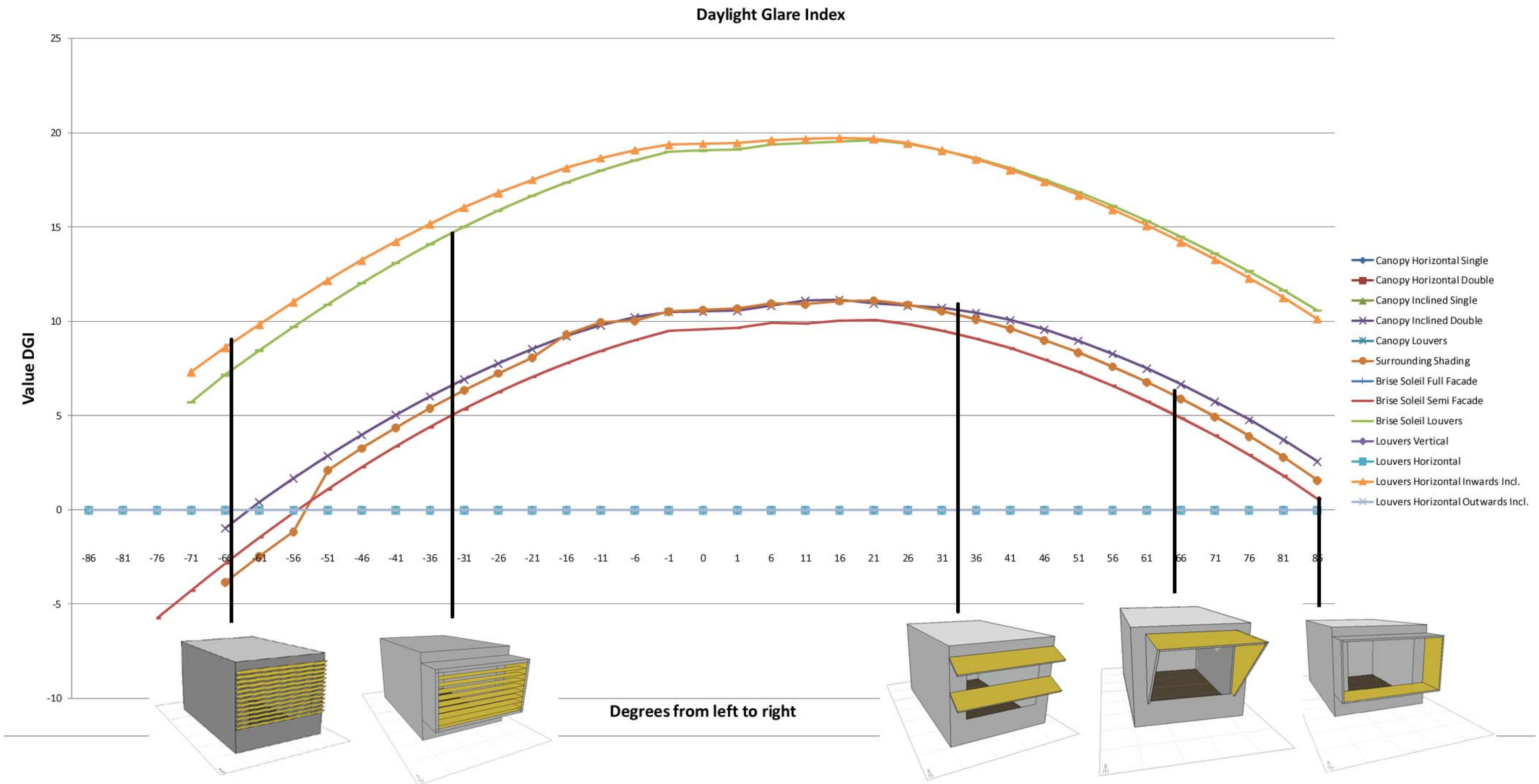


Fig.4.19. *DGI values for the 21 December at 12:00 o'clock for all examined systems in relation to the angle of view for camera near the window.*

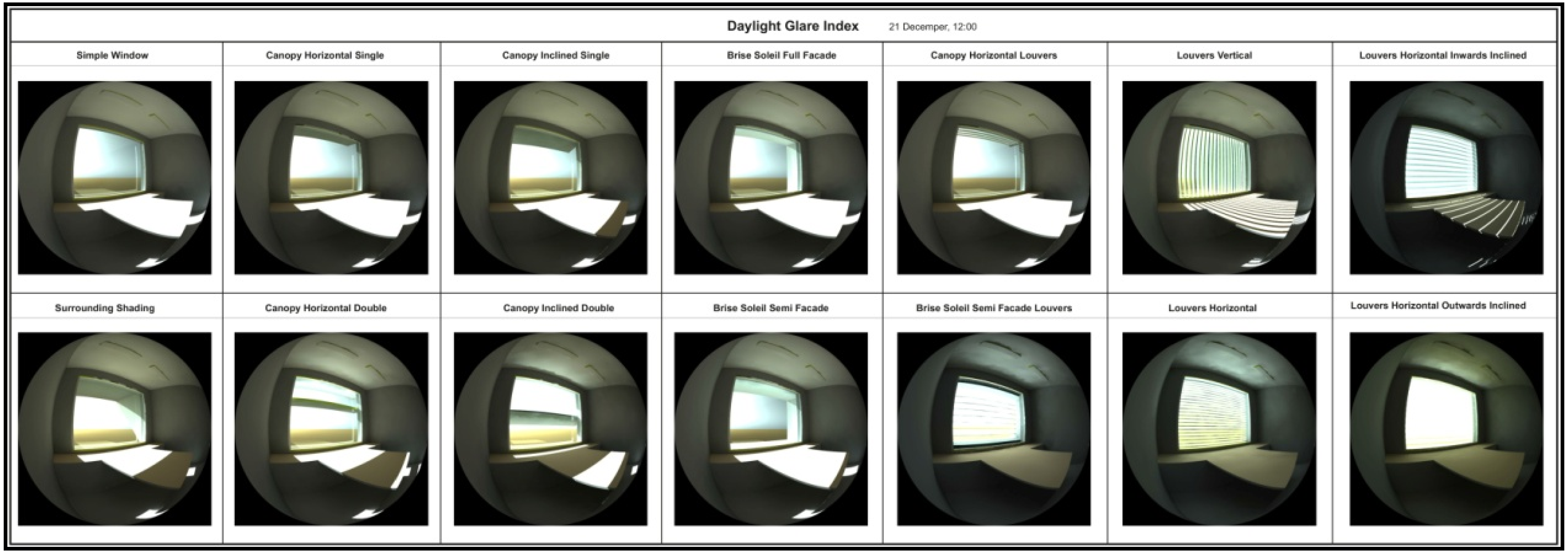


Fig. 4.20. *Fish eye camera for the 21 December at 12:00 o'clock for all examined systems in relation to the angle of view for camera near the window*

It is remarkable that according to glare values façade systems do not perform better than transparent systems, as expected (Fig. 4.20). It is also remarkable that the system of **Louvers vertical** which is not considered to be an appropriate system for south orientation is the only one to perform very well in terms of low glare values. A combined evaluation of the assessment of all visual factors is presented in the next paragraph.

4.7. Conclusions regarding daylighting properties of the examined shading systems and the method of assessment used

We shall present here the conclusions of our research in the two main areas of our study. The first area concerns the performance of the examined shading systems in relation to daylight quality and the second concerns the evaluation of the tools used according to the requirements of each design phase.

We showed that daylight quantity variables such as DF and DA cannot be used for an accurate evaluation of the daylight quality. More variables to assess daylight quality are needed, especially for complicated shading systems. We showed that **Canopy Louvers** and **Brise soleil full façade** systems have high DF and DA values but at the same time they have Low UDI values compared with other systems. At the same time these two systems result in a "detectable difference/improvement" according to the table of (Baker & Steemers, 2001) in daylight environment as measured by the DGI value for positions at the back of the room.

These two variables concerning daylight quality are completely different. The UDI value expresses the daylight levels between 100 to 2000 lux for the whole of the year while the DGI value expresses possible glare values for the specific time of the year examined from a specific point of view (in our case for the most remote position). We concluded that **Canopy Louvers** and **Brise Soleil** systems are the most appropriate systems for positions of occupants away from the window (Fig. 4.15 and Fig.4.19). For positions of occupants near the window almost all systems perform very well except form the systems of systems of louvers Horizontal inwards inclined and Brise Soleil Louvers. The rest of the systems perform very well and amongst these **Canopy Inclined Double, Brise Soleil Full and Semi facade, Surrounding Shade** additionally performs well for positions at the back of the room.

In general we conclude that some transparent systems can result in good daylight quality space for positions of occupants near and away from the window and that façade systems are appropriate when occupants are near the window. It is remarkable that the system of **Louvers Vertical** that is not considered an appropriate system for south orientation performs well for both near and away from window positions. We can see that the DGI values are below 16 at 12.00 o'clock and that at 9.00 and 15.00 hours these values are acceptable. This can be improved if the vertical inclination of the louvers changes, so that the reflections form the side sun rays do not raise the DGI values (Fig. 4.23).

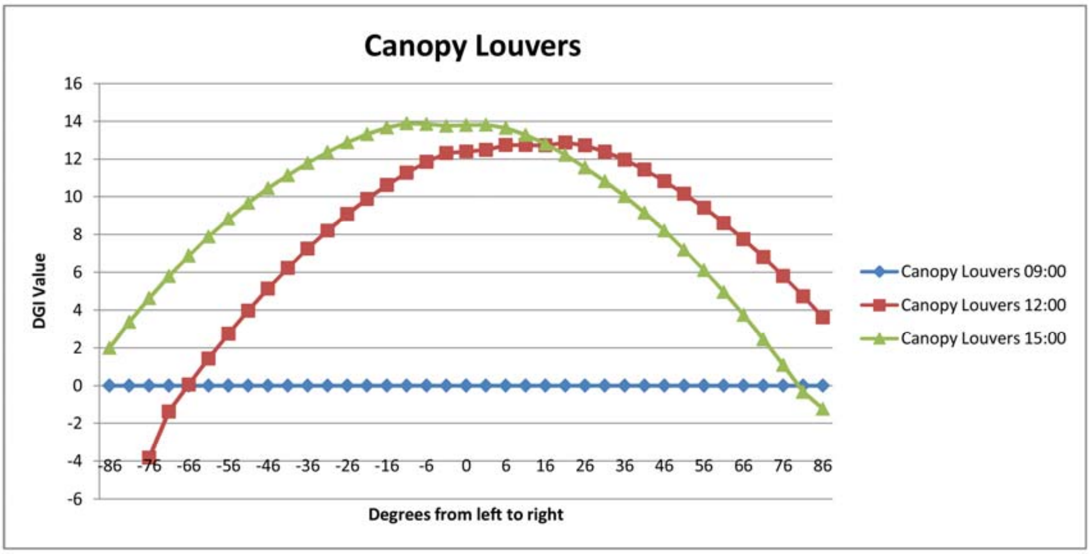


Fig. 4.21. *DGI Values for Canopy Louvers for 21st of December*

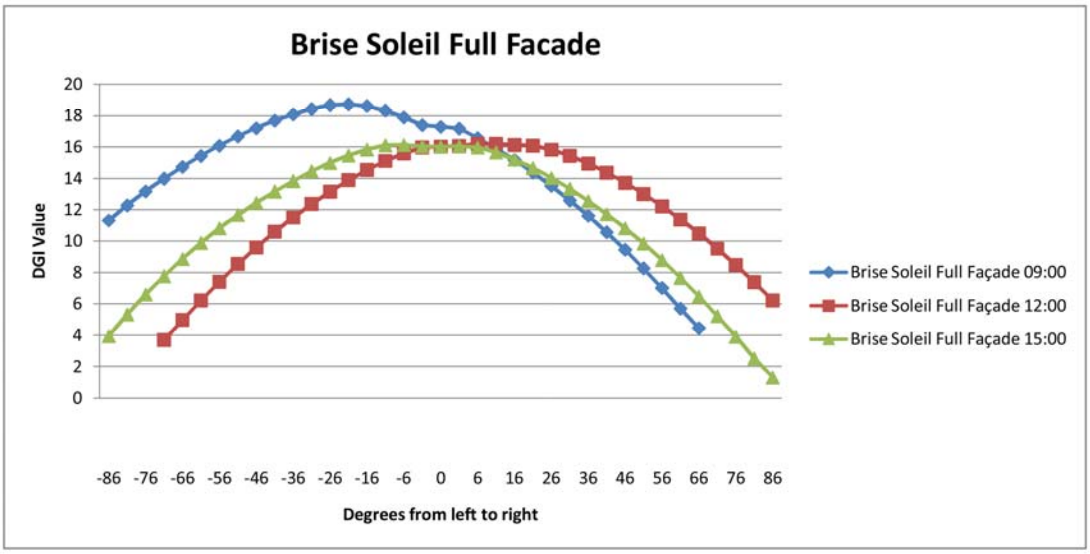


Fig. 4.22. *DGI Values for Brise Soleil Full Facade for 21st of December*

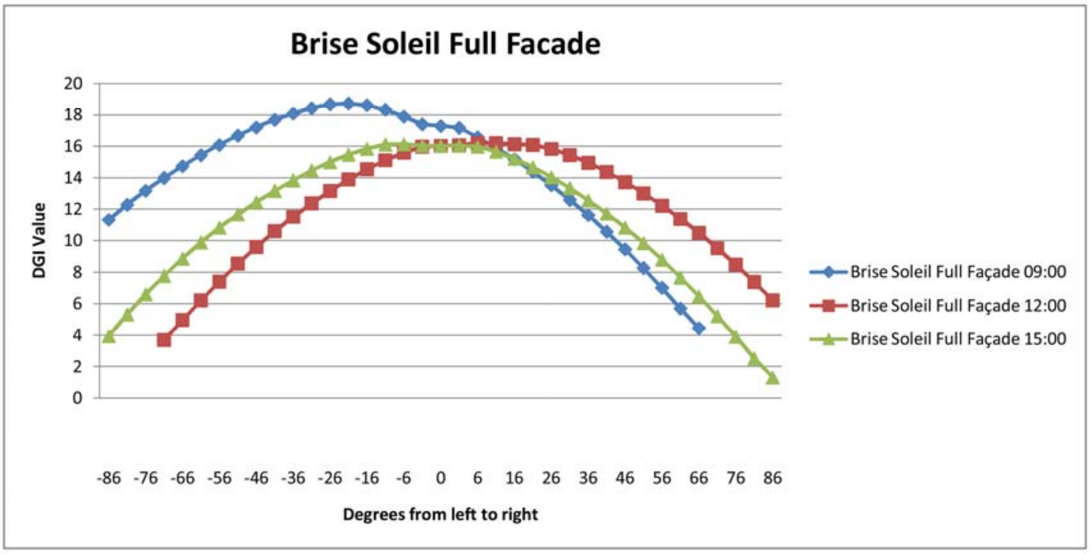


Fig. 4.23. *DGI Values for Brise Soleil Full Facade for 21st of December*

It is remarkable though, that some transparent systems in contrast with all other transparent systems as mentioned in paragraph 4.6.6, do not perform well in relation to glare caused for positions away from the window: these are **Surrounding Shade** and **Canopy Inclined Double**. These systems perform better (UDI values) for positions near the window compared to other transparent systems. This fact points out the inaccuracy of UDI value in terms of emerging glare problems.

One of the objectives of this research is to compare the results of the different methods used when we evaluate daylight quality. It is important to note that a part of quantitative information can be used to describe qualitative factors. One of these is daylight levels or daylight Factor (DF) and another is daylight autonomy (DA). In the paragraph 4.3.2 we explained that some daylight levels factors can describe the quality of daylight in the space if examined in relation to some quality variables, such as DA.

These two values can be easily measured using either physical models or simulation tools. We showed that physical models in real sky conditions overestimate daylight levels. It is safe to use physical models to measure daylithg levels for positions in the front of the room. In these cases the differences are 50% to 70%. For the case of the back of the room (away from the light source) the overestimation is lower than 50% till 9%. So when using physical model for daylight levels calculation, these levels, at the back of the room will have a small divergence from the real conditions but without any standard difference.

Simple computer simulation tools (e.g. Ecotect) can be used to evaluate daylight autonomy (DA) levels. For daylight levels, physical models can be used but special equipment is needed. Simple models can be used to evaluate DF, but this factor only gives information about the performance of the shading system in overcast sky conditions disregarding other possible sky conditions. More complicated simulation ray tracing models are needed for detailed analysis.

For the assessment of the early design stage these two factors (DF, DA) are efficient enough because they can be simulated with simple tools (Ecotect) with a relative accuracy. We showed for example, using a simple computer simulation tool, that **Canopy louvers** and **Brise Soleil systems** have the highest DA values in comparison with the other systems. We can use this fact when conducting energy saving assumptions during the early design phase. Further on we show that the same systems perform very well in relation to resulting low glare (DGI) values even if they do not perform very well in terms of UDI.

Additionally, as we argue in paragraph 4.3.6, user acceptance studies are needed in order to incorporate subjective factors in the results.

It is worth mentioning here that the DGI method of evaluation should be used in the detailed design stage, due to the fact that it demands detailed modelling and it is time consuming. Additionally the designer should be familiar with these values in order to be able to evaluate the results.

5. Generating energy through the use of Shading systems

We showed that the subject of shading systems and their efficiency has been extensively analysed is terms of their effect on energy performance and daylight quality. Moreover, our knowledge on the subject is developing rapidly as a result of on-going research, keeping in pace with the progress made in science, technology and materials. During this evolution, the issue of integration of solar energy systems within buildings' components and specifically on shading devices (SD) is extensively analyzed and developed. Starting points of this research are the traditional design methods of shading systems.

5.1. Integration of PV in buildings' facades

5.1.1. The basics of BIPV systems

In order to exploit solar radiation we must first ensure a basic preposition. The surface or material used should be energy producing or solar energy storage material. This means that replacing most of the buildings' envelope materials with others that produce or store energy can be an efficient solution.

Recent advances in technology have helped to utilize most of the buildings elements as energy producing systems. Buildings' facades can be transformed into energy producing machines.

Amongst a wide array of materials that have the potential to produce energy, a well known one is the PV panel. The French physicist, Alexandre Edmond Becquerel, was the first to observe and record the PV effect (*photo* denotes light and *voltaic* denotes the generation of electricity) in the 19th century. Today's PV semiconductor materials include silicon, gallium arsenide, copper indium dieseline cadmium sulfide, and cadmium telluride (Eiffert P. and Kiss J.G., 2000).

Since then, many scientists have worked to develop technologies to produce energy based on this effect. PV effect has been already applied to building industry. There is a variety of facades that have integrated PV materials. The sector of building science that deals with integration of PVs in buildings' elements is called BIPV. These solar systems are thus multifunctional construction materials (Eiffert & Kiss, 2000).

The basic PV material is silicon. Silicon is highly abundant; it constitutes more than 25% of the Earth's crust. Silicon is used in more than 90% of all PV applications. Silicon solar technologies can be grouped in three basic areas: single-crystal silicon, polycrystalline silicon, and thin-film amorphous silicon. The main differences between these three technologies are their sunlight-to-electricity conversion efficiency rates, the methods by which they are manufactured, and the associated manufacturing costs (op.cit).

The efficiency of each PV product is specified by the manufacturer. Efficiencies range from as low as 5% to as high as 15%, 16% (op.cit). The mono – crystalline silicon material has the highest efficiency (12 – 15%), the poly- crystalline material have slightly lower efficiency (11 – 14%) and the amorphous silicon or thin film technology have the lowest efficiency between 6 – 8% (Luque & Hegedus (ed), 2003).

The basic element of a BIPV system is the PV module. Individual solar cells are interconnected and encapsulated on various materials to form a module. Modules are strung together in an electrical series with cables and wires to form a PV array (Fig.5.1). Direct or diffuse light (usually sunlight) shining on the solar cells induces the PV effect, generating electric power in the form of unregulated Direct Current (DC). This Direct Current (DC) power can be used, stored in a battery system, or fed into an inverter which will transform and synchronize the power into Alternative Current (AC) electricity. This electricity is then either used in the building or is exported to a utility company through a connection with the (national) grid (op. cit).

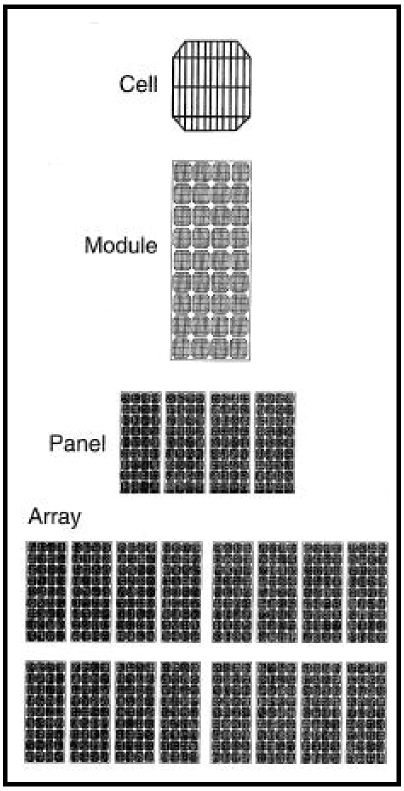


Fig.5.1. *Cell combined to form modules, modules form panels, and panels combine to form an array*
(Lechner, 2001)

The issue of Building Integrated PV (BIPV) has been developed extensively since the 90s. Two are the main groups of BIPV systems: facade systems and roofing systems. Facade systems include curtain wall products, façade panels, glazings and shading devices. Roofing systems include tiles, standing seam products, and skylights (Fig. 5.2., Fig. 5.3., and Fig. 5.4.).

Fig.5.2. *The APS building in Fairfield, California, USA. Thin – film PV technology integrated into curtain wall system. Curtesy Kiss and Cathcart architects.* (Lechner, 2001)

Fig.5.3. *Tilt PV shading Devices in Center for Environmental Sciences and Technology Management building (CESTM) in New York, Courtesy Kawneer Company Architcts.* (Lechner, 2001)

Fig.5.4. *Opaque PV cells mounted on clear glass. The space between the cells determines the degree of shading. Aquatic Center at Georgia Institute of Technology, (left). Semitransparent PV glazing as skylight glazing in APS Factory in California, Courtesy Kiss and Cathcart, architects (right).* (Lechner, 2001)

A fundamental approach in any BIPV application is to maximize energy efficiency within the building's energy demand or load.

These Holistically designed BIPV systems will reduce a building's energy demand from the grid and will generate electricity on site – a "weathering skin" of the building. Windows and facade shading systems with integrated PVs can be designed to increase the use of daylight in interior spaces and to reduce unwanted glare and heat. This integrated approach brings together energy conservation, energy efficiency, building envelope design, and PV technology and placement, maximizing energy savings (Eiffert & Kiss, 2000).

Besides the energy production another important parameter for the PV integration, is their appearance; this appearance depends on the detailed design and their technology of construction. Single-crystalline PV modules are dense blue (almost black), with a flat, uniform appearance. Polycrystalline modules are multicolored, having a variety of sparkling blue tones (Fig.5.5.). Thin-film amorphous silicon modules are reddish-brown to black (Fig.5.6.); the surface may appear uniform or non uniform, depending on how the modules are made. Some manufacturers can provide coloured PV modules, like gold, green of magenta, but their efficiency is decreased in comparison to standard PV modules.

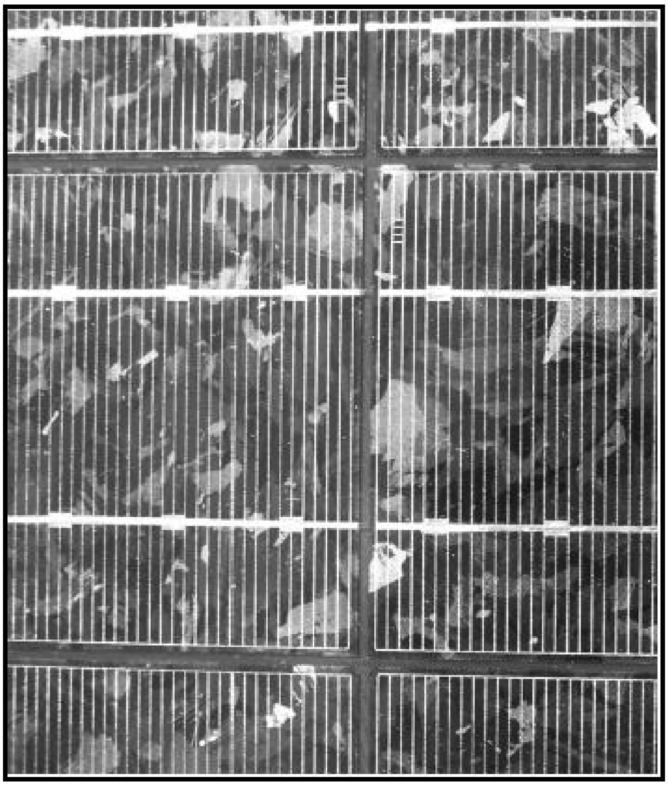


Fig. 5.5. *Blue Pattern Polycrystalline silicon cells* (Lechner, 2001)

Fig. 5.6. *Thin film module (are flexible and are easily integrated into curved surfaces)* (Lechner, 2001)

5.1.2. Design issues

There are restrictions that must be adhered to in the design of the integrated PV systems; these restrictions concern mostly their efficiency and less the aesthetics. These restrictions concern solar access, system orientation and tilt, electrical characteristics, and system sizing. The incidence of solar radiation (insolation) that reaches a PV surface at any given time, determines the potential electrical output of a BIPV system. Statistical estimations of average daily insolation levels for specific locations are commonly used in the BIPV design process and measured as kilowatt-hours per square meter per day (kWh/m2/day). These parameters are implemented in building simulations computer applications.

In order to maximize solar access and power output, the physical orientation of the BIPV system and the tilt angle of the array should be considered relative to the geographical location of the building site. As a general rule of thumb, BIPV installations north of the equator perform optimally when oriented south and tilted at an angle equal to the site latitude for annual production (Eiffert & Kiss, 2000). This can change if we need to make specific seasonal requirements for the systems. For example, a system might be designed for maximum power output production only in the summer months in order to reduce peak electricity costs for the air conditioning; in this case its tilt must be the average for summer power output. For south oriented vertical facades losses can be higher than 30% and for horizontal installations losses can be about 10% in comparison to installations with tilt angle equal to the latitude of the location.

Another characteristic of PV that can influence its effectiveness is the association between current and voltage. The amount and intensity of solar insolation affects the current (I) and the temperature of the solar cells affects the voltage (V) of the PV installation. The requirement is that the installation works as close to its peak power as possible. The peak power point is defined as the maximum power that the PV module produces when exposed to artificial solar radiation of 1000 W/m2 under standard testing conditions (STC) (Lechner, 2001). These conditions are described as Standard Reference Environment (SRE) and are the following**:** **Tilt angle**: At normal incidence to the direct solar beam at local solar noon, **total irradiance**: 800W/m2, **ambient temperature**: 20^{o}C, **wind speed**: 1 m/s,

Electrical load: 0A (open circuit, thus no current flowing), open rack mounted PV modules with optimized inclination (IEC, 2005).

The size of the system is another important design factor; this mainly depends on the energy needs of the building. The balance between the amount of power required and the amount of surface area available can determine the type of PV technology that will be used. For example, systems made of amorphous silicon require a larger surface area but cost less than equivalent systems composed of single crystal solar cells (Eiffert & Kiss, 2000). Additionally, different geometrical configurations can be introduced in order to increase the efficiency of the system. These are presented a next paragraph.

Additionally the electrical system adapted is crucial for the efficiency of the installation of the BIPV system. This primarily involves the performance and reliability of the inverters. Modular, "micro," or "mini" inverters allow each module to be tested (each has its own address) through the use of a power line carrier signal injected into the building's electrical distribution system. This way, each unit's performance can be easily measured. Modular inverters can work independently and enable PVs to be integrated into complex, geometric building designs due to the fact that when one or more modules are shaded the power output of the whole array remains unaffected. The connection of the modules with each other and their connection to the inverters is an issue of paramount importance for BIPV's and particularly for in BIPV's installed on shading devices, because the type of connection affects the output power of the system (op. cit.).

We are not going to analyze in detail the adapted electrical system for the shading systems examined within the framework of the research. We assume that modular inverters are used, in order to achieve comparable results concerning the performance of the examined shading systems with integrated PV.

5.1.3. Efficiency of facade PV systems

The first pieces of research on BIPV's concerned their integration into vertical elements in façades and the optimum ratio of window to PV façade area to achieve the most energy benefits (Yun et al., 2007; Vartiainen et al., 2000).

The issue of maximizing the energy production of PVs is a crucial factor of the efficiency of the installation. There is a field of research involved in techniques or geometries that can increase the absorption of the PV modules and the electricity production.

An important parameter that influences the efficiency of the PV modules is the temperature levels developed on the PV's surface. There is a complex relationship between PV, heat and sunlight. Solar power works better when the sun is shining but at the same time everything becomes hotter. The problem is focused on the fact that PV semiconductors become less efficient when hot. The difference in the efficiency is at the level of 10%. Newer technologies like thin film which don't rely on crystalline silicon to produce electricity—are less susceptible to heat-related efficiency losses.

The semiconducting materials used in PVs, particularly in crystalline silicon PV cells, lose efficiency as temperatures increase. As temperature in a conducting material increases, photons are excited and move throughout the material, impeding the uniform movement of electrons. The prevention of the electrons movement is what reduces efficiency in PVs when it gets too hot.

Newer technologies like thin-film PV use different semiconductor materials like Copper indium gallium selenide (CIGS), which don't lose as much efficiency under heat. Huld et al. (2009) found that CIGS produced 0.5% to 2.5% more power over a year period, "with the largest differences found in hotter climates." Another form of thin-film PV, using Cadmium Telluride as the semiconducting element to produce electricity, performed better than crystalline or CIGS PV cells did in high temperatures. The study said that "The performance of Cadmium Telluride is consistently higher than the two other technologies, by a margin of 5-12 percent depending on location". Additionally we should mention that there is a new nanophotovoltaic technology that actually captures infrared (heat) radiation from the sun and operates with higher efficiency in the heat but is still not on the market (http://www.cleanenergyauthority.com/solar-energy-resources/heat-and-pv).

Further on, different researches have experimented with various geometrical configurations that can increase the efficiency of the proposed system. For example Brogren et al. (2003) developed a system designed as a ready-to-use wall element with an insulating backside and intended to substitute a part of a south-facing wall. The system includes a Cu(In, Ga)Se2- based Siemens ST5 thin-film module, aluminum reflectors which receive all incoming irradiation from south projection angles between 25^o and 90^o, and an insulation for building integration. The specific geometrical configuration helps in keeping the angular relation between the reflector and the PV module constant in order to increase the PV energy absorption. A “Z” shape unit is multiplied in order to cover the whole facade. Nonetheless the increase in productivity is not the one expected. The measured maximum electric power from the modules is only 1.9 times that of identical vertical modules without reflectors, due to optical losses and a decrease in fill-factor(Fill- factor: the ratio of maximum power of solar cell to the product of Voltage and Current Power) from 0.6 to 0.5 under concentrated light.

The use of PV concentrators is another method of increasing the power generation of integrated PVs. An asymmetric compound parabolic PV concentrator has been designed by Mallic et al. (2004). The system is tested with different numbers of PV strings connected in series with and without concentrator. The results showed that the production of the parabolic PV concentrator integrated in building facade in the UK, can be increased by 62%, when compared to a similar non-concentrating PV panel (op.cit.) (Fig.5.7).

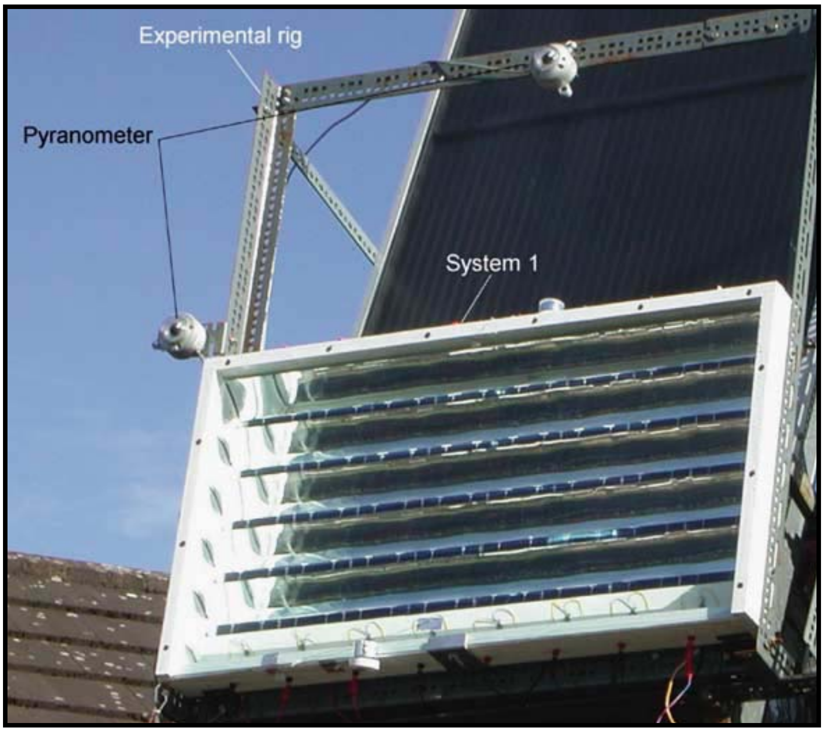


Fig. 5.7. *Asymmetric compound parabolic PV concentrator under outdoor experimental characterization at the University of Ulster.* (Mallic et al., 2004)

Another important parameter of the PV modules is the function and the operation schedule of the building upon which they are being installed. As PVs produce electricity only during the day, and for this reason, high energy loads of building should be limited during day time in order to reduce energy demand from the grid and maximize energy produced by the PV. The schedule of organizations occupying office buildings is generally suitable for the function of the PVs, due to the fact that office buildings are mostly operational during daytime when energy production from the PVs is high.

In 2007 Yun et al. introduced the term "effectiveness of a PV Facade (PVEF)" which is used to evaluate the overall energy performance of a PV façade. PVEF takes into account the energy produced from PV, the reduction in electric lighting needs due to daylight control, and the heating and cooling consumption. The formula they used is:

PVEF = $L_{saving} + E_{output} / H_{energy} + C_{energy}$ (1),

Where:

L_{saving} is the Energy saving in lighting,

E_{output} is the Output Energy of PV modules,

H_{energy} is the Energy spent for heating and

C_{energy} is the Energy spent for cooling.

This research focuses on shading systems with integrated PV, installed on office buildings' facades. We use the formula above to evaluate the effectiveness of the shading device.

5.2. Integration of PV in shading systems

Over the last century the proportion of the office buildings' envelope that is transparent has increased significantly. Due to the low thermal insulation property of glass in comparison to mass opaque building materials the larger the transparent fraction of the building's envelope the more important is the control of solar energy inflow, in order to keep thermal and visual conditions indoors in acceptable levels. Transparent facades need an additional control system, one that helps avoid solar radiation during the overheated period, allows enough thermal loads during the underheated period and ensures comfortable visual conditions during operating hours. Due to the fact that passive design is most of the times not totally efficient for the control of solar and thermal gains, additional active systems are used to balance the interior thermal and visual comfort conditions. As a result, today's buildings are dominated by technical systems for heating, cooling, ventilation and artificial lighting often resulting in high conventional energy consumption (Karkanias et al., 2010). Integration of PV systems in shading devices can help limit the overall energy consumption in two ways: by reducing direct solar gains during the cooling period and by producing electricity to be utilised for the function of cooling, heating and lighting systems.

The evolution of BIPV is the incorporation of active systems in SDs as a method to reduce the energy consumption of the building. Shading systems can be part of the mechanism of the energy producing system. They have an additional advantage: due to the fact that their purpose is to block direct solar light, they are in receipt of a huge amount of solar radiation which can be utilized.

Integration of PVs in shading devices is an intermediate solution falling between the BIPV (Building Integrated PV Panels) and BAPV (Building Attached PV Panels) systems as described by Peng et al. (2011). This integration of PVs has the advantages of the former (BIPV), is architecturally clean and attractive and offsets the cost of roofing, facade or glazing materials and the advantage of the latter (BAPV); in case they are damaged the buildings' internal function is not affected.

The potential of replacing conventional building materials with PV structural materials (especially SDs) has been researched for Finland, Austria, Denmark, Switzerland and Germany as an aesthetically appealing and energy saving solution (Hestnes, 1999). For Norwegian Office Buildings some PV systems are analyzed from the aesthetic point of view according to PV types, colour and final surface. The thin film technology as a competitor to the crystalline silicon technology is being proposed as a lower cost solution (Hermstad, 2006).

Integration of PV materials to Shading systems was proposed in 1998 (Yoo et al., 1998) (Fig.5.8). Since then various shading types have been used mostly according to their energy balance and less according to aesthetics and interior comfort conditions. A canopy inclined system with integrated PV with semi-transparent modules (single crystal with efficiency 14%), has been studied for a south facade for the climate of Korea. The tilt and orientation of a PV panel influences the power generation; the 'ideal' tilt of the PV array in the area is 32° (for Seoul). Due to aesthetics, cost, and safety reasons, the inclination was fixed at 55.5°. The influence of shadows cast by other PV panels and the accumulated dirt are crucial for the efficiency of the system. The ratio of direct to diffuse solar radiation also influences the power generation of the PV system. On a typical summer day the aforementioned PVs are only able to cover 10% of the required building's lighting energy (op.cit).

Fig. 5.8. *Samsung Institute of Engineering and Construction Technology (SIECT), in the Gihung area, Seoul* (Yoo, S.H., Lee, E.T. and Lee, J.K., 1998)

The same system has been examined in Greece, Italy and Spain. Bloem et al. (2005) presented an analysis based on simulation results using Esp-r software. They designed a building and subsequently simulated the shading devices in three (3) European cities: Athens, Barcelona and Milan. They proved that PV systems used as shading devices can reduce overheating in a building which is air-conditioned. Apart from overheating, PV used as shading devices can also reduce glare. The installation is proven to be economically viable for private installations above 1 kW_p, particularly when these are connected to air conditioning systems.

The idea of combining a window with SDs that can work both as an energy production and energy reduction system is introduced by Khedaria et al. (2004). They presented experimental work with a new type of PV-slat window (PV-SW) facing south, in Thailand (Fig.5.9). The PV slat window can produce power up to 15 W, can decrease indoor temperature compared to transparent slats and can provide sufficient light for the house. The power output of the PV slat window depends on inclination and on overshadowing. Cell temperatures more than 60° C affect the power output of the PV. Inclination of 60° to 68° is optimum in terms of internal illumination for the specific latitude.

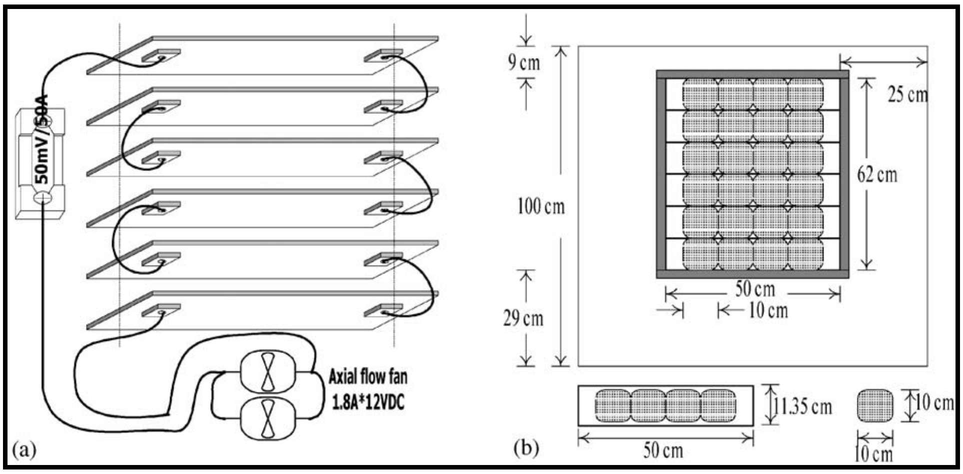


Fig. 5.9. *(a) The PV-slats window configuration and (b) the southern wall of lab-scale testing room with the PV-SW* (Khedaria, J., Waewsakb,J., Suphengc, W., Hirunlabha, J., 2004)

The environmental impact and the aesthetics of the integration of PV are important factors. Tsoutsos et al. (2005) point out the potential of PVs as a method to reduce the building's environmental impact (visual, noise, pollution, waste management, economical impact) making them more cost effective.

PV modules applied as shading devices have been designed and used in many buildings all over the world. Since 1996, in Albany University PV modules have been used as sunshades providing 15 kW_p of energy simultaneously reducing cooling loads (Eiffert & Kiss, 2000).

The way that BIPVs are installed as shading devices differ between modern and traditional buildings. This is due to differences in available proportion of facades and different needs in electricity. BIPVs can be installed as external fixed venetian blinds facing south and having proper angle, reducing maintenance costs due to lack of user contact. Another solution is internal PV venetian blinds requiring less supporting structure (Reijenga, 2002)

5.2.1. Research of integrated possibilities on the market – build examples

In order to make the shading devices more competitive in the market the glass content of the PV louvers was minimized. Weight reduction was achieved by replacing glass components of PV modules (at least in part) with flexible membranes (Zentrum Fur Sonnenenenergie, 2007). The only resulting disadvantage was that these types of flexible PV modules have a lower efficiency factor due to the type of material of the PV used. Amorphous silicon was used to substitute the glass PV components, in order to make them flexible. Due to their disadvantage of low efficiency the progress in the market penetration of these types of systems is not the one anticipated, as can be seen for example in Korea, according to Hwang at al. (2012). So, one of the main reasons why we examine PV shading systems composed of glass and Si polycrystalline technology is the use of the most efficient technology of PVs.

A simulation analysis of an office is presented by Bloem (2008) with 99 PV modules mounted on a horizontal spandrel enclosure on the south façade. The system works as a window shading system producing 36 W_p in Standard Test Conditions. Natural ventilation was assumed in the module enclosure via vents in the upper and lower surfaces. He claimed that although PV modules cover only part of the energy demand, their performance can be improved by changing their inclination according to the season of the year. The combination of produced electricity with the improvements in the indoor quality conditions makes the use of BIPV on shading systems a very promising application of technology (op.cit.).

Another application that has been proposed in the market is the integration of PV louvers between two sheets of glass. The main advantage of these applications is that PV blinds are fixed between two sheets of glass and consequently cannot get dirty. The PV slats consist of tandem amorphous silicon cells deposited on glass, and have, according to company specifications, an efficiency of 6 percent. Since amorphous silicon cells operate more efficiently at higher temperatures than crystalline silicon cells, the placement of the PV slats between the insulating glass sheets, where temperatures of 70° C are easily reached, leads to very good performance (http://www.photon-international.com/products/products_01-03_syglas.htm / accessed 20.12.2012) (Fig.5.10).

***Fig.5.10**. The novel window of PV slats by the German Company Syglas (http://www.photon-international.com/products/products_01-03_syglas.htm / accessed 20.12.2012)*

The use of PV integration in shading systems has been promoted by various researchers. In Brazil, (Cronemberger, J., Caamano-Martın, E., Vega Sanchez, S., 2012) argued that “for non-vertical façades (40º ≤ β ≤ 90ºS) the solar potential represents between 60% and 90% of the maximum global solar irradiation, even when facing south, indicating that the use of sloped building envelope surfaces, such as atriums and shading elements on façades and windows should be promoted”.

Apart from PV systems, there are other systems studied for integration on SDs. One such example is the solar thermal systems. Palmero-Marrero & Oliveira (2006) studied the integration of solar thermal systems in canopy louver SDs that also proved to be an energy efficient solution. These systems are not a subject of this research.

5.3. Experimental work of energy production

On the other hand, we examine two different types of PV integration in relation to the interior visual comfort conditions. We examine the integration of two types of PV panels in louver systems. The first system is constructed with market PV panels with metal frames of 3cm final thickness and the second one consists of glass louver system with integrated PVs. The glass louvers consist of two glass panes with and inter PV foil of monocrystalline material (1.5 cm thickness). Basic visual comfort aspects are examined for both cases and are presented in chapter 6.

As a final step of the overall assessment of the examined shading systems we evaluated their efficiency in terms of determining the geometry that has the potential to produce maximum energy. We used three different evaluating methods: a simple model method using two different computer application methods (one is called in this research as "simple" and the other as "complete") and a more complicated model that incorporates real market products. A basic objective of this research is to evaluate the method of assessment used in comparison to simulating methods and further on to evaluate the accuracy of simple methods used. These methods can be easily used in primary design processes in order to give basic feedback on decision on the type of geometry which will influence the final shape of the building and its energy performance.

Another reason that we evaluated the energy production of the PV shading systems with three different evaluation methods is to improve the validity of the results. For the same reason we subsequently validated the results with measurements of energy production of real PV installations in both examined latitudes. The methodology can be schematically seen in Fig. 5.11.

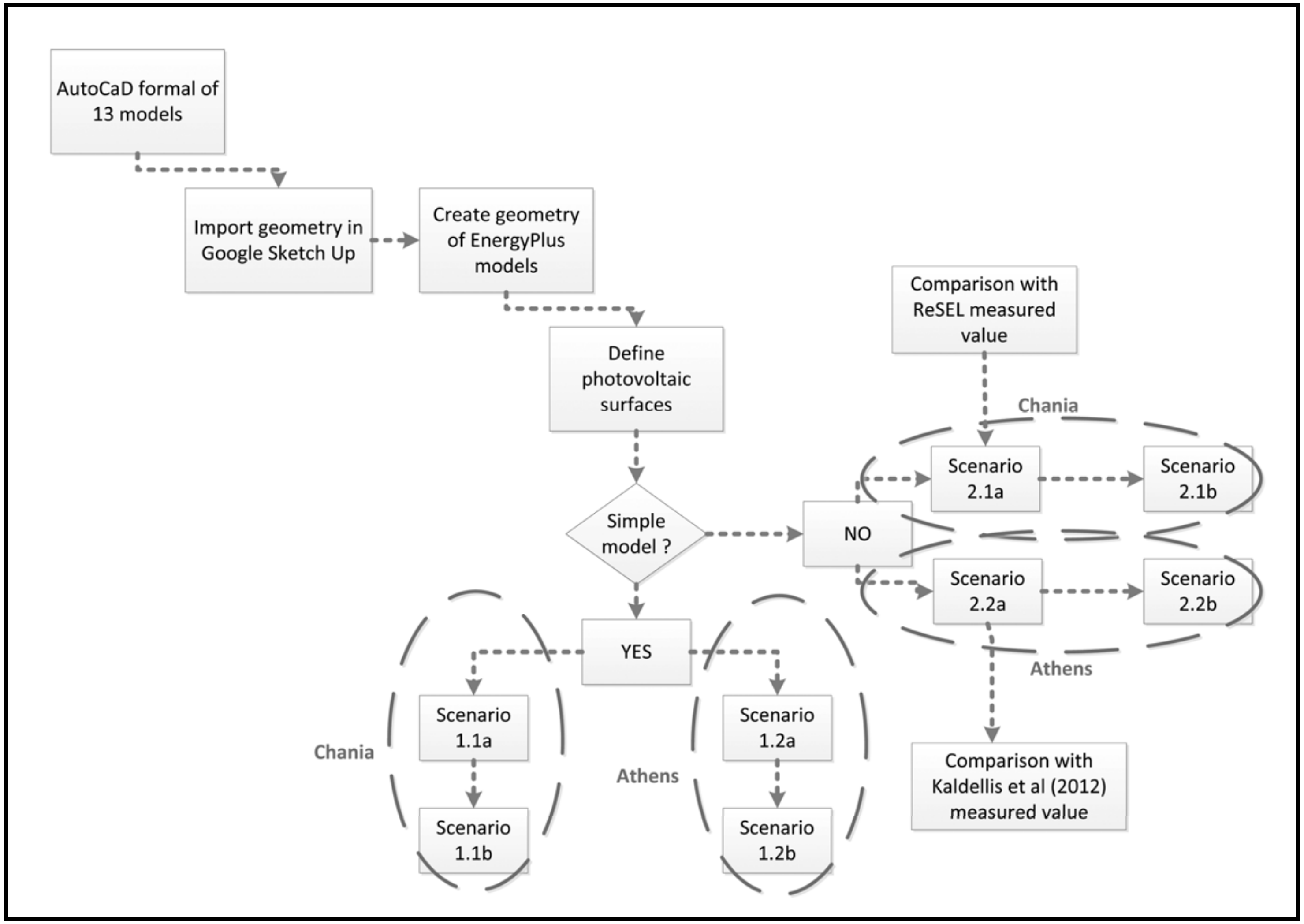


Fig.5.11. *Methodological diagram of method used for evaluating the performance PV integrated shading system*

As we already mentioned in paragraph 5.1.3 change in temperature affects the efficiency of the product. The higher the temperature the lower the energy production compared with the measured peak produced energy. For this reason we reexamined the thirteen shading systems moved 5 cm from the building's façade in order to measure the difference in energy production when temperature changes. We assumed that the temperature of PV cells will decrease when the air circulation behind the PV modules increases.

Specific parts of the shading systems were used as PV surfaces**.** The shading devices which we used for simulation and assessment are shown in (Fig. 5.12). All simulations are compared for both Chania and Athens latitude.

Weather files are used in the simulation in order to provide Dry Bulb temperature, Humidity, Radiation, Wind Speed and Wind Direction, parameters necessary for thermal modelling. In order to have a proper comparison, between the analysis results on the energy production from PV simulated by EnergyPlus - 32 MP and AutoDesk Ecotect v5.60., the weather files for both areas of Chania (35^o 31N, 24^o 01E) and Athens (37^o 59N, 23^o 43 E) are similar to those used in the paper of Mandalaki et al. (2012). A summary of the weather data used for the simulation for the area of Chania is depicted in Table 5.1.

We used the already modeled 3D office units that we described in Chapter 3 and we calculated their energy production in AutoDesk Ecotect v5.60. When using the detailed simulation analysis application (EnergyPlus-32MP) we used the geometry of the typical offices with the shading devices that have been provided in 3D dxf format and we imported them in Google Sketch Up 7 in order to work with the OpenStudio Plug-in. Further on, we developed models using EnergyPlus software, one for each shading device having in total 13 models to simulate the energy production from their corresponding shading devices.

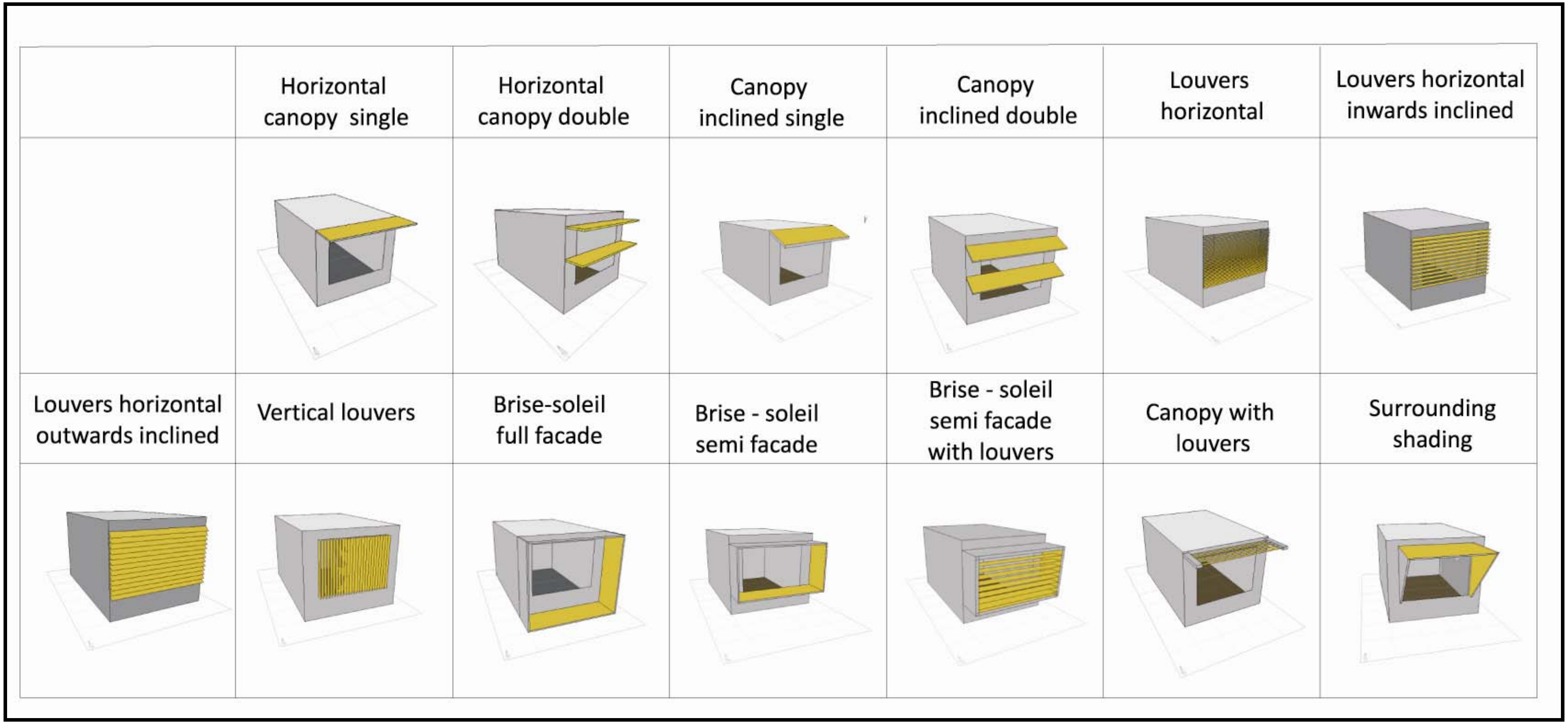


Fig. 5.12. The examined shading systems with integrated PV

Meteorological station: **Chania, Crete**
Longitude/ Latitude: **24° 02' / 35°3'**
Station Height: **62 m**

Month	Hours of sun	Atmospheric pressure	Av.Air temperature	Abs. max temperature	Abs. min temperature	Relative Humidity	Av. Cloudiness	Rainfall	Wind direction	Total Horizontal Radiation	Diffuse Hori Radiation	Wind speed
	h	**mm Hg**	**C°**	**C°**	**C°**	**%**	**8**	**mm**				**m/s**
1	111.7	1016.8	11.6	25.6	0.5	71.7	5.1	122.9	SW	62.1	33.1	3.2
2	128.9	1015.3	11.8	29.4	0	69.3	5	108.6	N	78.2	38.3	2.8
3	174.4	1015.1	13.2	34	0.4	68.4	4.4	71.9	SW	120.0	54.9	3
4	228.5	1013.3	16.3	35.8	5	65.4	3.5	31.9	NW	153.4	61.4	2.6
5	314.2	1014.1	20.1	38.6	8.5	62.2	2.8	13.9	NW	206.8	61.3	2.3
6	357.8	1013.3	24.5	40	13	55.8	1.3	6.6	NW	224.2	56.6	2.3
7	391.7	1012	26.5	42.5	16.6	55.3	0.6	0.5	NW	237.6	60.6	2.3
8	368.4	1012.4	26.1	41.2	12.5	57.7	0.6	2.7	NW	218.1	50.4	2.1
9	276.3	1015.3	23.3	39.6	10.5	63.9	1.6	18.2	N	163.2	43.8	2.1
10	183.8	1016.9	19.4	35.6	9.2	70.4	3.5	82.1	N	104.7	43.9	2
11	157.7	1018	16.1	35	2	72.2	4.2	70.9	N	75.1	32.7	2
12	115.4	1016.3	13.1	28.8	3.6	72.1	4.8	91.3	SW	57.4	29.7	2.6

Table 5.1. Meteorological data from weather station Souda Airport

The main objective of this part of the research is concentrated in the evaluation of three well known available tools used to estimate the energy production of the PV panels integrated in shading systems. The tools available were divided into simple simulating tools, to more complete simulating tools and to measurements of real PV installations. Each tool demands special knowledge. Simple tools can be used by unspecialized designers, the complete models need special knowledge and real measurements require special instruments that are only available from specific laboratories and are involved more with research work and less with the design process. It is important for the designer to know the level of accuracy of each tool that he uses according to the design stage that he is elaborating.

Three processes have been followed in order to reach the aforementioned objective:

- Comparison of the integrated PVs' energy production results calculated by the simple simulation models with simulated results of real market products.
- Comparison of the energy production results of the simulation of real market products with measured energy production of real PVs installations
- Investigation of the sensitivity of the simulation software used to measure the air flow near the PV panels and its affect on the electricity production.

5.3.1. Efficiency of the geometry of the Shading Systems

We conducted a basic evaluation of the economy of the system, in terms of the surface area needed by the PVs and the production efficiency of it. It is obvious that the energy production of the PVs is inversely proportionate to the surface area that they cover; the PVs' energy production rather depends on the geometrical characteristics of the SD and the overshadowing between the surfaces. An interesting point is that the system **Brise–Soleil semi facade louver** carries the largest PV surface but at the same time it produces little electricity. On the other hand the amount of electricity the **Canopy inclined single** produces is large compared to the area it covers which is almost the smallest area of all PV's installed.

For the aforementioned evaluation we propose a new term: the **efficiency factor**. The efficiency factor has nothing to do with the efficiency of the PV installed. It is the ratio of area of PV installed (cm2) over the electricity production by the installed PV (kWh). The high efficiency of all **Canopy systems** (either inclined, horizontal or with louvers, single or double) can be seen in (Fig. 5.13). It is noticeable that even though the system of Canopy inclined double covers almost double area than the Canopy inclined single, it produces the same amount of electricity. This is probably due to overshadowing (Fig. 5.14). Companies involved in PV industry could focus on the geometries of SD last mentioned in order to develop BIPV technologies in shading devices.

It is important to note that the most commonly used shading systems for office buildings, the horizontal louvers, outwards or inwards inclined perform badly in terms of energy production. These kinds of systems are efficient in terms of producing energy for heating, cooling and lighting (as we have seen in paragraphs 3.7 and 4.7) but cannot contribute to the reduction of energy consumption. This is a factor that should be taken into account for future developments or energy renovations for these types of buildings and introduces a path for rethinking the shading devices in office buildings.

In the energy production diagram (Fig. 5.15) we can see a big difference in the calculated energy production between the two computer applications used for the cases of louvers. In the following paragraphs we will explain the reasons for these differences. Still this difference does not affect our conclusion that the louvers systems' energy production performance is low. Finally in the same diagram we observe the low performance of **Brise Soleil systems**. These systems perform very well in terms of reducing energy demands for heating, cooling and lighting (as we have seen in paragraphs 3.7 and 4.7) but they cannot produce enough energy in relation to the installed PV area. This is another geometrical rule that we should take into account for future development of shading systems with integrated PVs. Additionally we can see that among other well performing systems that generate acceptable visual conditions, the system of Canopy Inclined Single has a high degree of efficiency.The system of Surrounding Shade has a middle degree of efficiency. Of course in order to evaluate them thoroughly we will additionally evaluate them according to their energy needs for heating, cooling and lighting. This we will present in the next chapter.

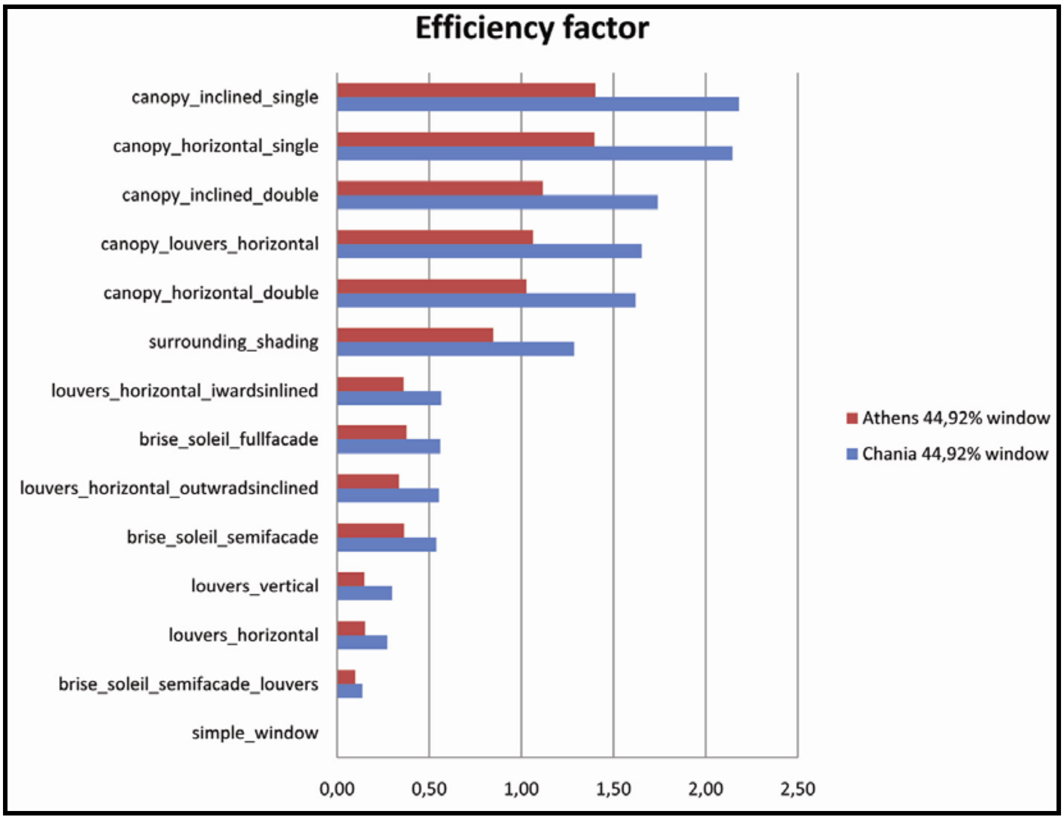


Fig. 5.13. *Efficiency factor for Chania and Athens with window 44.92% of facade area*

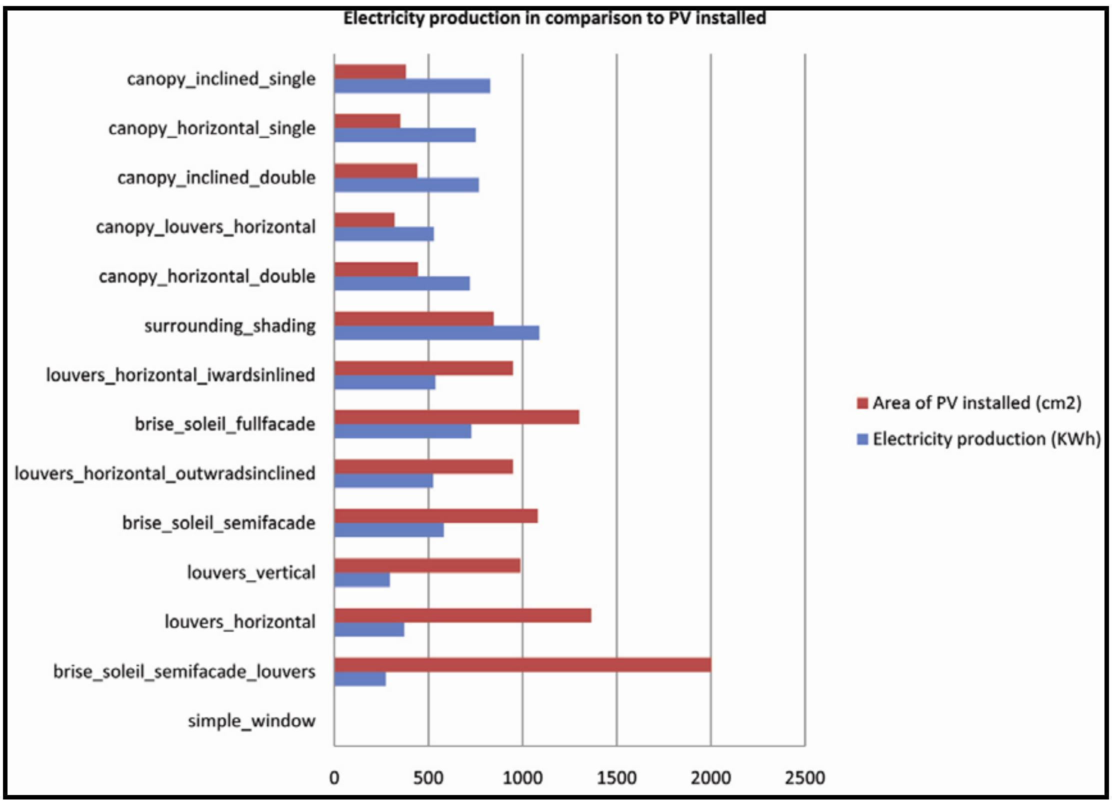


Fig.5.14. *Electricity production in comparison to area of PV installed for Chania with window 44.92% of facade area.*

Shading name	Surrounding Shading	Vertical louvres	Hor. louvres outwar. inclined	Horiz. louvres inwards inclined	Horiz. louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz.Canopy single	Horiz.Canopy double	Canopy double inclined	Canopy single inclined
EnergyPlus	**975,5**	**904,7**	**1965,2**	**376,2**	**1805,7**	**558,3**	**1069,0**	**529,1**	**706,8**	**399,4**	**705,4**	**819,1**	**765,0**
Ecotect	**717,0**	**145,7**	**319,1**	**343,0**	**207,1**	**339,5**	**489,9**	**198,0**	**392,4**	**488,7**	**556,0**	**592,3**	**532,1**
% of difference	26,5%	83,9%	83,8%	8,8%	88,5%	39,2%	54,2%	62,6%	44,5%	22,4%	21,2%	27,7%	30,5%

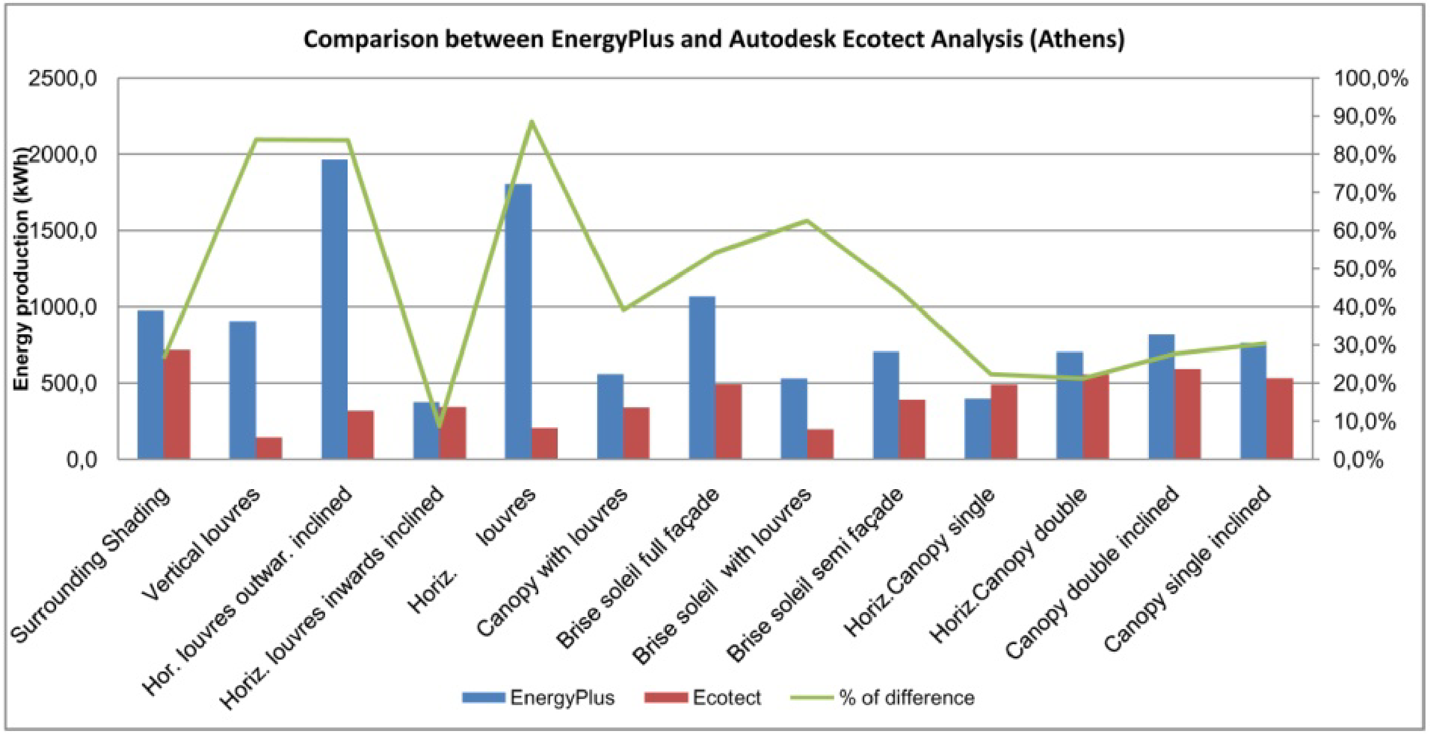


Fig. 5.15. *Comparison of the results between Autodesk Ecotect Analysis and EnergyPlus for the Area of Athens*

5.3.2. Comparison between Simple Simulation model results

As it can be seen in Fig. 5.15 the comparison between the two types of software indicates that the results for the area of Athens are different. The percentage of difference is increased for the louvers systems. In Fig. 5.16 the results for the area of Chania are presented. The percentage of difference in the results between the two types of software is much lower compared to the previous assessment. This means that the percentage accuracy in the simulated energy production is higher in areas with higher solar radiation as in the case of Chania (lower latitude), compared to areas with lower solar radiation such as Athens (higher latitude). For simple geometrical configurations of shading systems, the estimated difference is lower than 11% in the case of Chania and lower than 30% in the case of Athens. The percentage is defined by the following formula; $P = (E_a – E_b / E_a) \cdot 100\%$, where: P is the percentage difference, E_a is the energy production of PV calculated with the model a, E_b is the energy production of PV calculated with model b.

The percentage of difference increases for louvers, which are complicated shading devices. This is due to the fact that the EnergyPlus cannot simulate more than 30 PV panels connected in series and that the Ecotect cannot simulate overshadows between the PV louvers. When using EnergyPlus for complicated geometries of shading systems, like horizontal louvers, the large number of warnings and errors prevented the software from working properly and arriving at a rational result. EnergyPlus warns the user for possible calculation errors due to unaccounted shadow parameters which cannot be properly estimated by the software. This disability of the EnergyPlus could be overcome by designing the louvers system with less than 30 modules. Other louver systems that were examined (that have less than 30 PV panels connected in series) were simulated by EnergyPlus properly. Still though the percentage of difference between the two models is high but this is due to the disability of the Ecotect to simulate the louvers system properly and not due to EnergyPlus. For this reason, for the next comparisons only the energy production calculated by EnergyPlus was taken into account for all louvers systems, except for the Horizontal Louvers (that are composed with more than 30 modules connected).

An additional source of errors appears for the cases of the Brise – Soleil. The difference of the results was in the range of 22 to 49% for Chania and 44% to 42% for the case of Athens. The percentage of difference is lower for the case of louvers. The source of error in these cases is due to the fact that in Brise -Soleil systems one of the PV panels is facing downwards and uses only the reflected component of solar radiation. These types of panels cannot be correctly simulated by Ecotect and for this reason it was decided to use only EnergyPlus results for the next comparisons.

5.3.3. Comparison between Simple model simulations with complete simulation of real market products (Energy Pluss simulations)

A different, more accurate equation was used in this part of the research in order to simulate real PV modules available on the market. For this reason, PV models developed at Sandia National Lab, Albuquerque, New Mexico, have been created from real modules tested under various conditions. The equations used for the estimation of energy produced by each module are referred to the Engineering Reference of EnergyPlus software (EnergyPlus - *Engineering Reference,* 2012).The adjustment of the equations in order to be used by EnergyPlus or TrNSys (Type 101) was done by Barker & Norton (2003). The market PV modules were selected with an area similar to the area of each surface from the available modules stored in the Data-Set list of Energy Plus. In order to reduce overdependence of our results from just one product available on the market, three different products were selected and the average value of electrical power produced by the PV was calculated. The selected products used for the simulation are presented in Table 5.2.

Shading name	Surrounding Shading	Vertical louvres	Horiz.louvres outwards inclined	Horiz.louvres inwards inclined	Horizontal louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz. Canopy single	Horiz. Canopy double	Canopy double inclined	Canopy single inclined
EnergyPlus	**1053,9**	**1216,7**	**2101,3**	**379,0**	**1996,8**	**611,3**	**1009,3**	**537,4**	**750,4**	**758,1**	**959,4**	**868,3**	**823,1**
Ecotect	**1088,1**	**294,6**	**524,1**	**536,3**	**370,9**	**528,1**	**727,6**	**273,4**	**580,8**	**750,8**	**719,3**	**767,3**	**827,8**
% of difference	3,2%	75,8%	75,1%	41,5%	81,4%	13,6%	27,9%	49,1%	22,6%	1,0%	25,0%	11,6%	0,6%

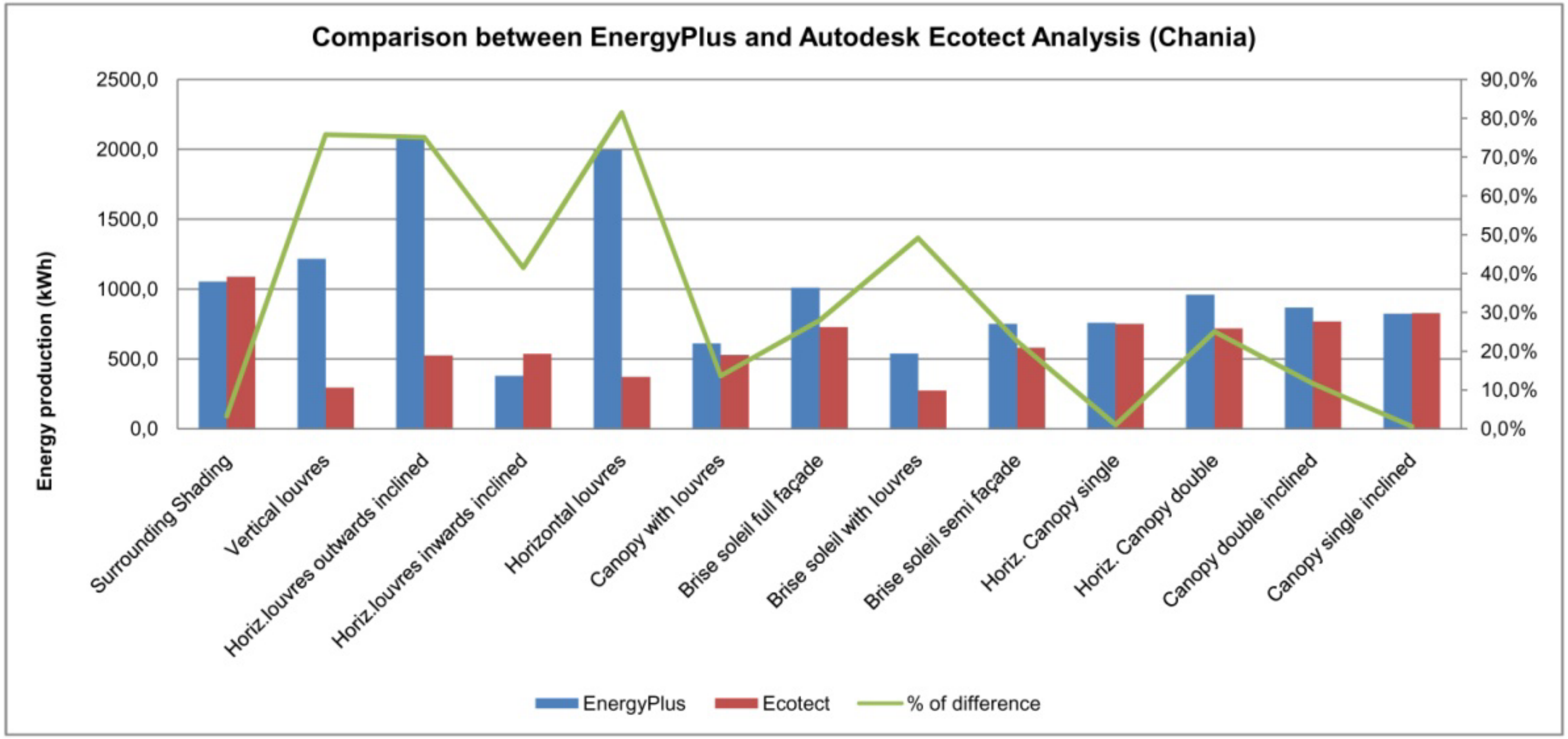


Fig.5.16. Comparison between EnergyPlus and Autodesk Ecotect Analysis (for the Area of Chania)

	Name of shading device	Different photovoltaic products available in market and selected for the simulation		
1	Horizontal canopy single	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
2	Horizontal canopy double	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
3	Canopy inclined single	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
4	Canopy inclined double	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
5	Louvers horizontal	Kyocera_KC40	Siemens_SM46	USSC_UniSolar_US-21
6	Louvers horizontal inwards incl.	First_Solar_FS-50	Photowatt_PWX750_70W	Solarex_MSX-77
7	Louvers horizontal outwards incl.	First_Solar_FS-50	Photowatt_PWX750_70W	Solarex_MSX-77
8	Vertical louvers	Kyocera_KC40	Siemens_SM46	USSC_UniSolar_US-21
9	Brise-Soleil full façade	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
10	Brise-Soleil semi façade	AstroPower_APX-90	BP_Solar_BP5130	Sharp_NEH120E1
11	Brise-Soleil semi façade louvers	BP_Solar_BP2140S	Sanyo_HIP-HO97	Schott_SAPC_165
12	Canopy with louvers	AstroPower_AP-75	BP_Solar_BP270	Kyocera_KC80
13	Surrounding shadings	AstroPower_AP-120	BP_Solar_BP980	Sharp_NEH120E1

Table 5.2. *Different PV products selected for the Shading Devices*

As it can be seen in Figs 5.17 and 5.18 the difference in energy production between real PV modules which can be found in the market and the simple model with 12% efficiency is very small, which indicates that the selection of a theoretical value of 12% efficiency approximates the overall efficiency of real PV module which can be applied on shading devices. It should be noted that the selection of real PV modules is based on the available area on the shading device and the number of modules which are in series. In the horizontal shading devices, for example the PV modules can only be connected in series. Only in cases of geometrical configurations of louvers the differences are higher, due to complicated geometry (higher than 30% difference).

Additionally it should be mentioned that the difference of energy production per m^2 between louvers outwards inclined and canopy inclined is 44.12% (higher for the case of canopy inclined). A similar observation was made by Hwang et al. (2012). They conclude that for south facing surfaces for the case of Inchon in Korea (37^o27 N and 126^o42 E) the insolation levels on louvers inclined are 42% lower than on canopy inclined. The aforementioned latitude is very close to Athens' latitude (37^o 59N, 23^o 43 E). This disadvantage of louver PV systems is probably the main reason why these types of systems have not entered into the market dynamically. New research needs to be done on the subject of increasing the energy production of PV louvers systems.

Shading name	Surroundi ng Shading	Vertical louvres	Horiz. louvres outwards inclined	Horiz. louvres inwards inclined	Horiz. louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz. Canopy single	Horiz. Canopy double	Canopy double inclined	Canopy single inclined
Simple Model	**1053,94**	**1216,7**	**2101,3**	**379,0**	**1996,8**	**611,3**	**1009,3**	**537,4**	**750,4**	**758,1**	**959,4**	**868,3**	**823,1**
Sandia Model	**993,1**	**1389,7**	**1098,1**	**190,7**	**2087,1**	**628,7**	**830,7**	**512,4**	**788,9**	**706,2**	**1113,5**	**1031,1**	**786,1**
% of difference	5,8%	14,2%	47,7%	49,7%	4,5%	2,8%	17,7%	4,6%	5,1%	6,8%	16,1%	18,8%	4,5%

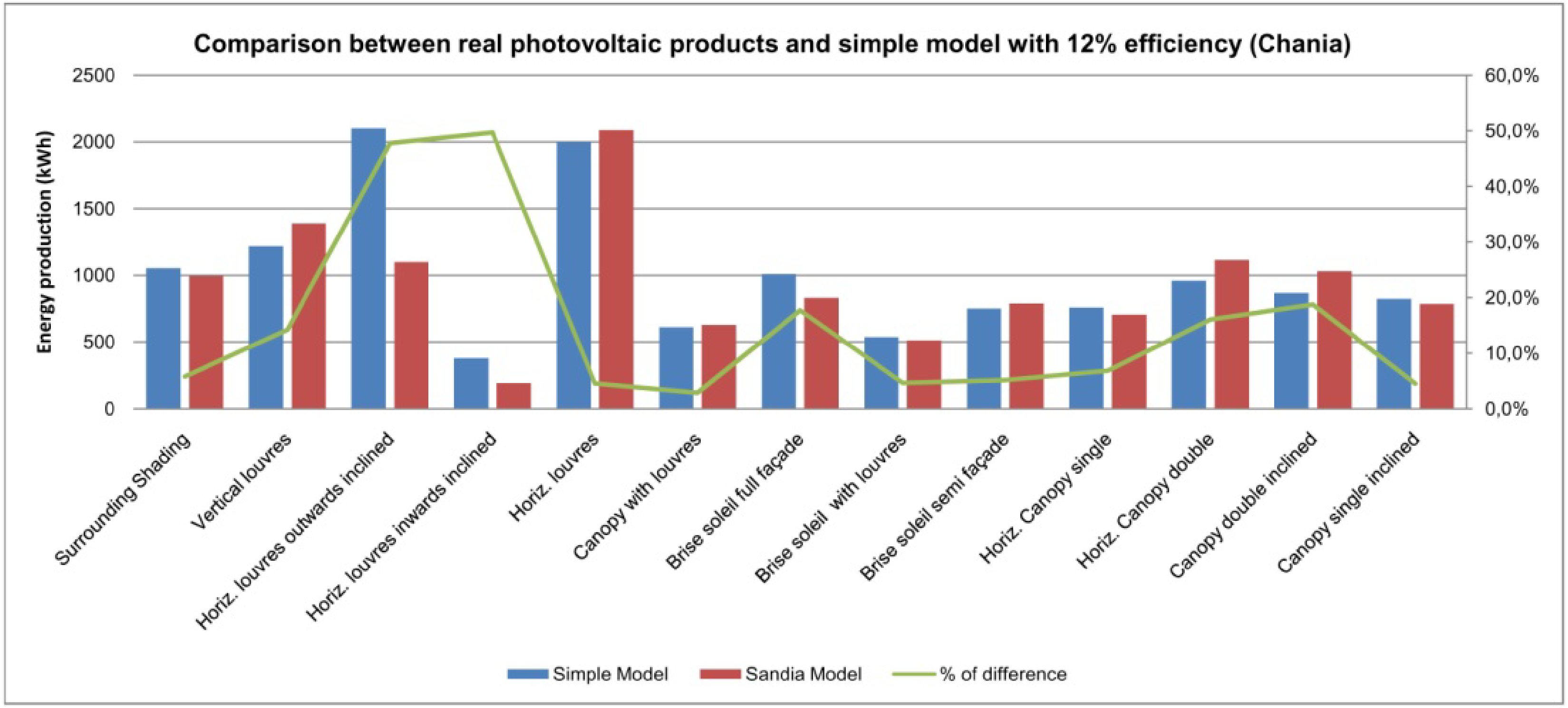


Fig. 5.17. *Comparison between real PV products and a simple model with 12% efficiency (Chania)*

Shading name	Surrounding Shading	Vertical louvres	Horiz. louvres outwards inclined	Horiz. louvres inwards inclined	Horiz. louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz. Canopy single	Horiz. Canopy double	Canopy double inclined	Canopy single inclined
Simple Mo	**975,5**	**904,7**	**1965,2**	**376,2**	**1805,7**	**558,3**	**1069,0**	**529,1**	**706,8**	**399,4**	**705,4**	**819,1**	**765,0**
Sandia Mo	**939,7**	**904,7**	**1034,7**	**187,0**	**1888,0**	**573,9**	**880,7**	**501,8**	**742,6**	**444,8**	**929,9**	**975,4**	**727,1**
% of differ	3,7%	0,0%	47,3%	50,3%	4,6%	2,8%	17,6%	5,1%	5,1%	11,4%	31,8%	19,1%	5,0%

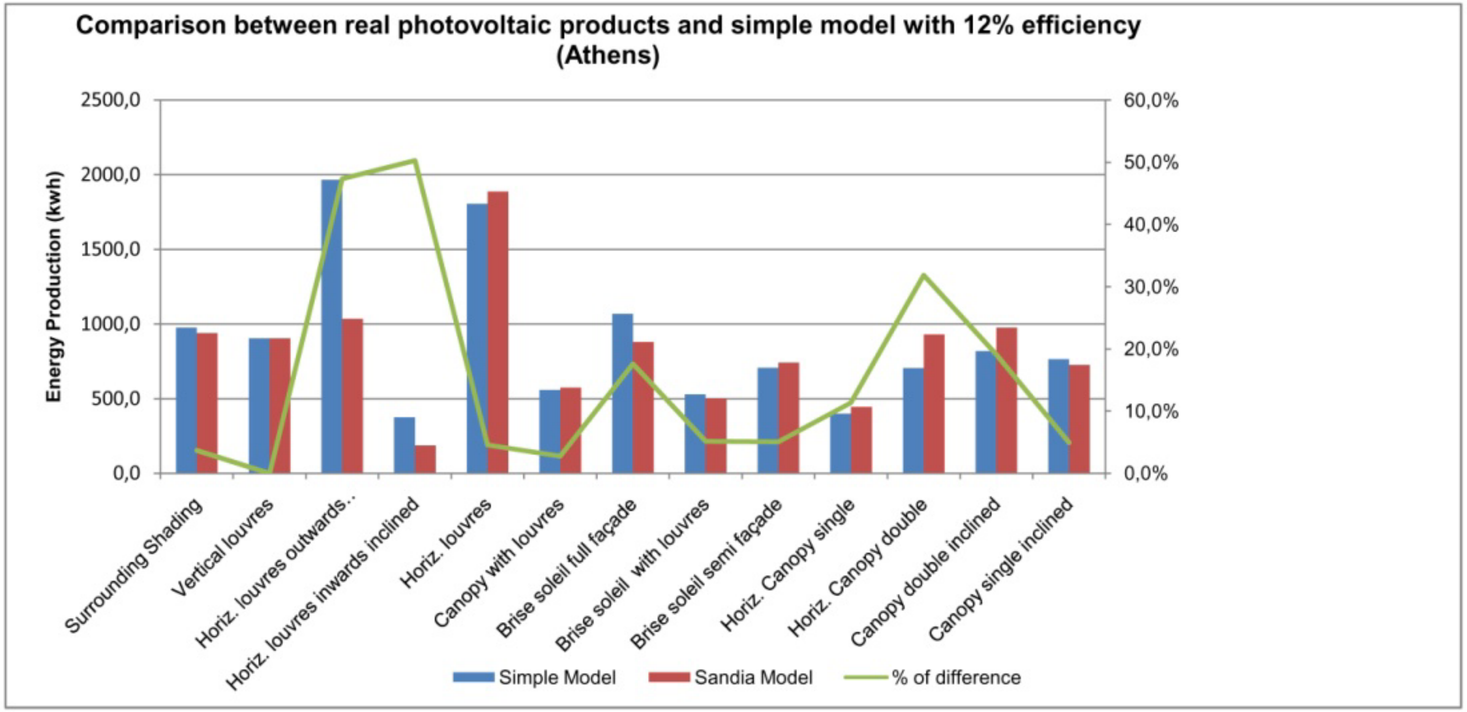


***Fig. 5.18.** Comparison between real PV products and a simple model with 12% efficiency (Athens)*

5.3.4. Comparison between simulated market products with real PV installations

We also present a comparison between the simulated results with Ecotect and EnergyPlus and the measured results for both Athens and Chania. In the case of Athens, measured values were taken from the paper of Kaldellis et al. (2012) and in the case of Chania measured values were taken from the Renewable and Sustainable Energy Lab (ReSEL), of the Environmental Engineering Department, Technical University of Crete. The environmental conditions tested are presented in the Table 5.3 for the case of Athens and in the Fig.5.22 for the case of Chania. The results of the comparisons are available in Table 5.4 and Table 5.5. Both installations (in Athens and in Chania) of PV panels are upon roofs and facing south with the inclination given in the tables. Other specific characteristics of these installations are presented in the same tables. In the absence of available in situ measurements for long periods, the comparisons presented concern only the specific days when the measurements were carried out. Small differences in tested conditions won't affect the difference of the results by more than 2% (Anderson et al., 2000).

CHANIA **23rd November**	**RaSEL Laboratory**	**Simulation**	**STC**
Temperature (^{o} C)	17,5	16,1	20
Wind Speed (m/s)	2	2	1
Inclination	0^{o}	0^{o}	55,6 ^{o}
Total Irradiation (W/m^{2})	419,5	400	800

Table 5.3. *Environmental Conditions of Comparisons for Chania Latitude (ReSEL Laboratory, TUC)*

ATHENS **23rd November**	**Kaldellis et al (2012) (DC*) Kyocera (LA361-K51S)**	**Simulation**	**STC**
Temperature (° C)	NA	16,1	20
Wind Speed (m/s)	NA	2	1
Inclination	0°	0°	55,6 °
Total Irradiation (W/m^2)	271	250	800

Table 5.4. *Environmental Conditions of Comparison for Athens Latitude (ReSEL Laboratory, TUC)*

ATHENS **23rd November for 0° inclination**	**Kaldellis et al (2012) (DC*) Kyocera (LA361-K51S)**	**Simple Model of 12% Efficiency simulated results for Canopy horizontal single (AC*)**	**Sandia Model simulated results for Canopy horizontal single(AC*) (AstroPower_APX-90,BP_Solar_BP5130, Sharp_NEH120E1)**
PV Area (m²)	2,655	3,500	3,500
Energy production (Wh)	172,00	256,00	257,00
Energy production (Wh/m²)	64,78	73,14	73,43

Table 5.5. *Comparison of measured and simulated results. Energy production of PV panels for Athens area on 23rd of November *(AC=alternative current and DC=Direct current)*

CHANIA **23rd November for 0° inclination**	**Laboratory *ReSEL* at TUC measured results (AC*) Sharp NA-F121G5**	**Simple Model of 12% efficiency simulated results for Canopy horizontal single (AC*)**	**Sandia Model simulated results for Canopy horizontal single) (AC*) (AstroPower_APX-90, BP_Solar_BP5130, Sharp_NEH120E1)**
PV Area (m²)	26	3,5	3,5
energy production (Wh)	7.561,00	933,00	937,42
energy production (Wh/m²)	290,81	266,57	267,83

Table 5.6. *Comparison of measured and simulated results. Energy production of PV panels for Chania area on the 23rd of November *(AC=alternative current)*

It is obvious that both measured and simulated results are similar. There is a 9% to 11% difference between the results. Possible small differences can be attributed to different PV brand type used in each case and due to the final current output.

Moreover, the type of PV modules used in all cases is similar (monocrystalline and multicrystalline ones). Additionally PV panels installed in TUC laboratory are the same brand with one type of PV simulated with EnergyPlus (Sharp).

The results of the estimated energy production by TUC and EnergyPlus are very close to each other; so we conclude that there are no big differences between various types of PV in terms of energy production. Only when a detailed study is needed the examined PV models should be same brand – type and the environmental conditions should identical. It is also remarkable that installations in shading devices have the same potential with roof installations to produce energy, and this emphasizes the potential of BIPV in shading systems.

5.3.5. The temperature effect

Figs 5.19 and 5.20 show that there is indeed a little change in the PV module efficiency when the distance between exterior wall and shading increases. This change in the PV modules' efficiency is due to increased wind speed between the modules According to EnergyPlus Engineering Reference (2012) in order to calculate the energy production of the PV the full geometric model for solar radiation is used, including sky models, shading, and reflections, to determine the incident solar resource are taken into account. Additionally the strength of the DC current source is dependent on solar radiation and the IV characteristics of the diode are temperature-dependent. When moving the shading system away from the facade Energy Plus uses the same algorithms but the resulting shading parameter and temperature are different.

According to recent bibliography reports, an increase in the performance should be expected. The circulation of wind between the modules was expected to decrease cell temperatures therefore increase energy production (Bloem, Colli, & Strachan, 2005). The small increase in the energy production of some PV modules can be explained because in this case there is less shading in the beginning and the end of the day and because there is an increase of air circulation. For most of the cases of façade occupied systems (i.e. the louvers and canopy inclined or horizontal double) the difference in energy production is about 1% (this is acceptable for a shading device of 0.05 m distance from the façade). Similar results exist in the literature, for example the harvested energy per square meter is almost the same when changing the distance between louvers frame and outer window up to a 40 mm (Kang, Hwang, & Kim, 2012)**.** There is no difference in temperature in systems that do not cover the glazing (i.e. canopy horizontal or inclined), as expected. We found no difference in energy production for the case of Brise- Soleil full façade with louvers, probably due to the high mass of the shading system in relation to the small gap of 0.05 m.

In Fig. 5.21 are presented the temperature differences of the PV modules when increasing the gap between the south wall and the shading device in the case of Canopy Inclined Double, simulated for Chania latitude. The maximum temperature difference is in the middle of the year (summer time) and is about 0.4^{o} C. Similar results are found for other examined shading geometries.

Shading name	Surrounding Shading	Vertical louvres	Horiz.louvres outwards inclined	Horizontal louvres inwards inclined	Horiz. louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz.Canopy single	Horiz. Canopy double	Canopy double inclined	Canopy single inclined
Typical Shade	**993,1**	**1389,7**	**1098,1**	**190,7**	**2087,1**	**628,7**	**830,7**	**512,4**	**788,9**	**706,2**	**1113,5**	**1031,1**	**786,1**
0.05 m gap	**997,8**	**NA**	**1109,1**	**192,5**	**2127,1**	**630,3**	**834,7**	**512,4**	**795,2**	**706,2**	**1127,2**	**1041,2**	**786,1**
% of difference	0,5%	NA	1,0%	0,9%	1,9%	0,3%	0,5%	0,0%	0,8%	0,0%	1,2%	1,0%	0,0%

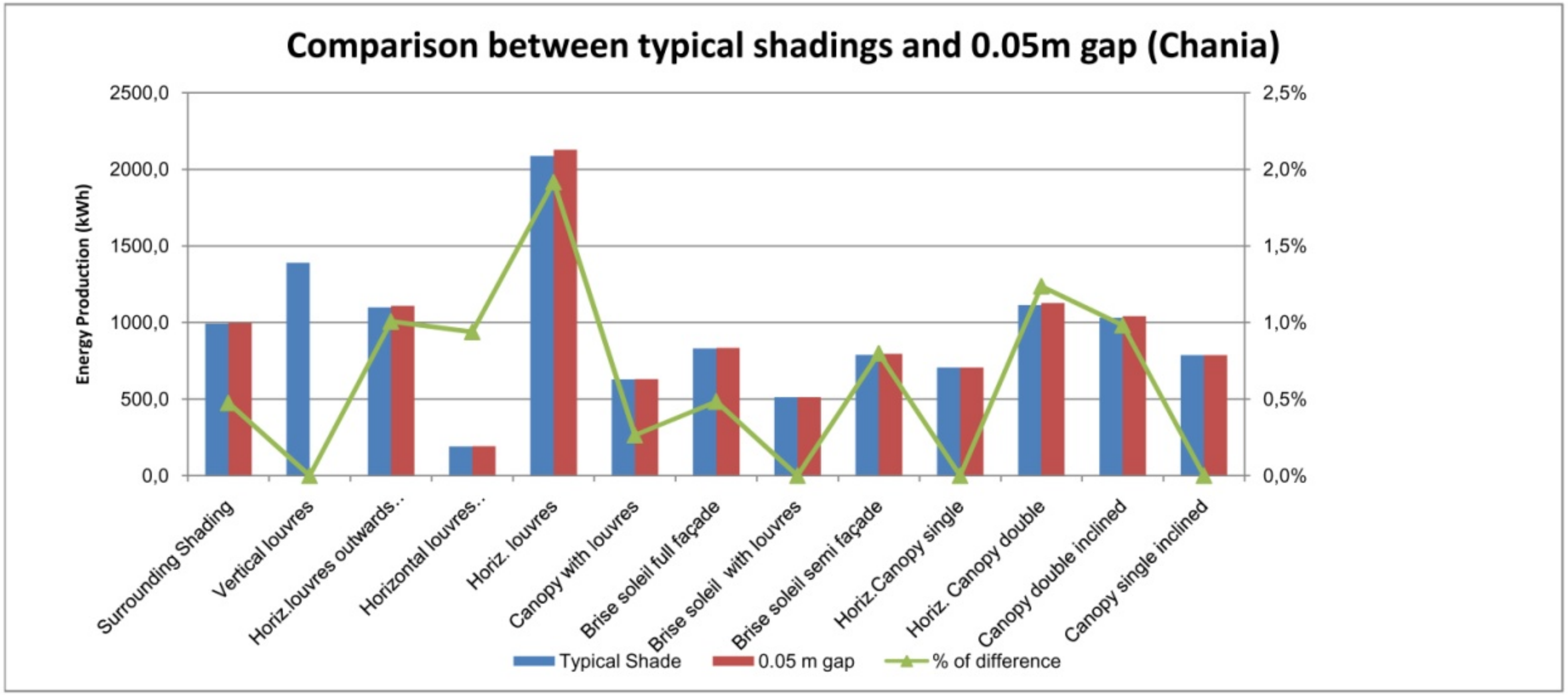


Fig.5.19. *Comparison between typical shadings and 0.05m gap (Chania)*

Shading name	Surroundi ng Shading	Vertical louvres	Horiz. louvres outwards inclined	Horizontal louvres inwards inclined	Horiz. louvres	Canopy with louvres	Brise soleil full façade	Brise soleil with louvres	Brise soleil semi façade	Horiz. Canopy single	Horiz. Canopy double	Canopy double inclined	Canopy single inclined
Typical Shad	**939,7**	**904,7**	**1034,7**	**187,0**	**1888,0**	**573,9**	**880,7**	**501,8**	**742,6**	**444,8**	**929,9**	**975,4**	**727,1**
0.05 m gap	**944,2**	**NA**	**1045,2**	**188,8**	**1926,6**	**575,7**	**885,5**	**501,8**	**748,1**	**444,8**	**944,4**	**982,2**	**727,1**
% of differen	0,5%	NA	1,0%	0,9%	2,0%	0,3%	0,5%	0,0%	0,7%	0,0%	1,6%	0,7%	0,0%

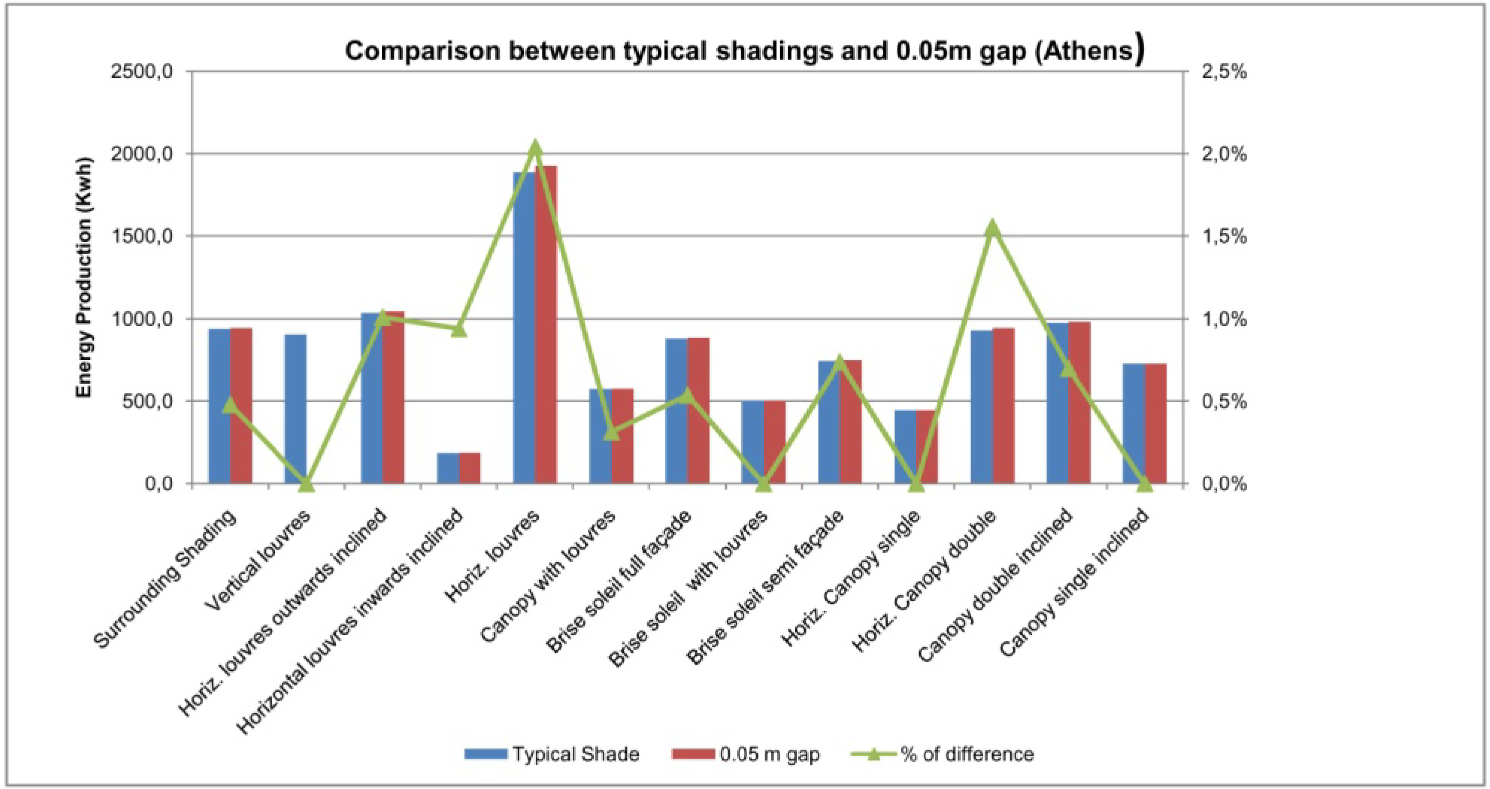


Fig.5.20. *Comparison between typical shadings and 0.05m gap (Athens)*

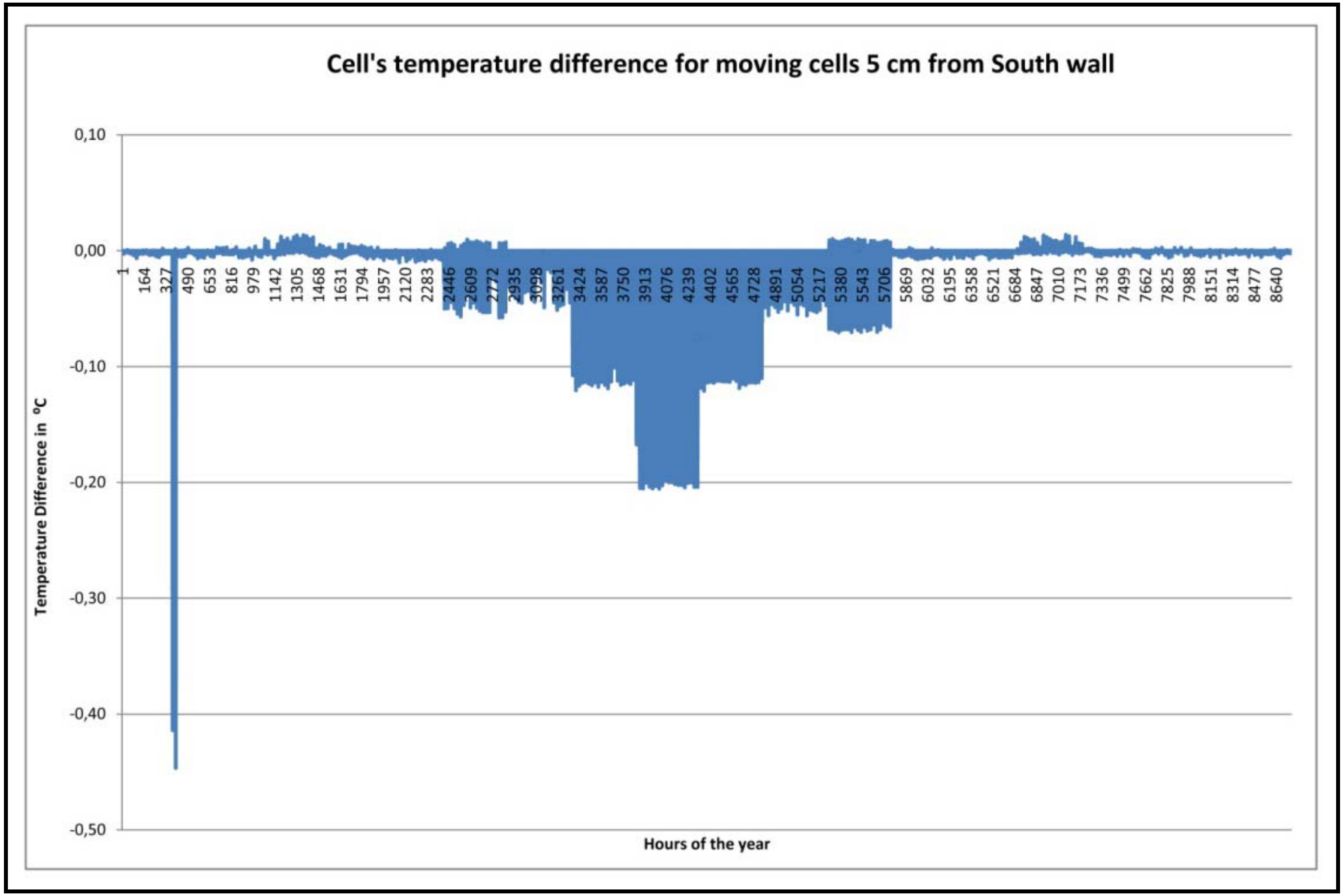


Fig.5.21. *Cell's temperature difference when moving cells 5 cm from south wall for Canopy Inclined Double simulated with Sandia PV models for Chania*

5.4. Conclusions and remarks

The work carried out was an analysis on the subject of solar energy production by PV modules integrated in typical shading devices and the methods of evaluation used.

It is concluded that the method of evaluation used depends on the desired accuracy of the results and the comparative or absolute research done. Further on the accuracy of the results depends on the designer's wishes in relation to the design stage that the project has developed. The theoretical efficiency of 12% used in simple model equation is accurate enough only for simple geometrical configurations of shading devices. It is noteworthy however, that even the complete model for measurements in relation to real market products, is accurate enough only for simple geometrical configurations. For more complicated geometries other types of research are needed. For venetian blind systems, for example, only the in situ measurements are accurate enough when exact values of energy production are needed. For systems with integrated PV that produce energy through reflected solar radiation both the simple model simulation done with a sensitive application and the simulation of real market products are accurate enough.

For a comparative analysis between different geometrical configurations of shading systems with integrated PV modules (and not a value level dependent analysis) the complete model that used real market products is accurate enough. It was observed in simulations using the complete model that the difference of energy production per m^2 of venetian blind outwards inclined system and of canopy inclined system is 44,12 % higher in the case of canopy inclined. This result is similar to the 42% that (Hwang et al., 2012) observed for the same cases of shading systems This fact proves the accuracy of the energy production results (comparative) of the complete model for cases of complicated geometries such as the venetian blind systems.

It was showed as well that the complete model is "sensitive" to air circulation between the façade shading system and the glazing. The model calculates the temperature differences when the gap between the shading system and the exterior wall is increased and the consequent increase in the PV energy production.

Further work could be done for shading devices of complicated geometries with high amount of connected panels and for systems that use only diffuse solar radiation, in terms of accuracy of the resulting values in relation to real PV installations.

Further work to be conducted on venetian blind systems with integrated PV is suggested in order to increase their efficiency, in levels similar to that of simple inclined systems. Additional research of in situ measurements will be required in order to cover all cases of complicated geometries of shading devices as for example for systems with more than 30 modules connected in series and for the case that only diffuse radiation falls upon the PV panels.

Brise Soleil systems have proven to be very efficient in terms of daylight quality and this fact should be taken into account when carrying out further research on optimum shading devices that can produce energy and can obtain high indoor environmental quality. Furthermore, experimental work is needed in order to evaluate movable shading systems that are considered to be more efficient in terms of daylight quality and quantity and have the potential to be more energy producing.

It was additionally showed that the efficiency of simple geometry shading systems such as canopy inclined single is not lower than roof stand alone PV installations. This proves the potential of BIPV integration in shading systems to be a technically efficient solution amongst other types of PV installations. This is due to the PV module’s dual mode of action: as an energy producing system and as a system that reduces the cooling loads. Instead of installing additional systems attached to buildings’ envelope that can work only as energy producers, shading systems with integrated PV do this, having the same efficiency and at the same time can substitute other shading elements.

According to the above mention facts in order to thoroughly evaluate the Shading Systems with integrated PV we will take into account the values of energy production taken from the complete model of Energy Plus. We will use these values for the comparative analysis between these systems. This analysis it will presented in the next chapter.

6. The combined approach: energy balance and visual comfort afforded by different shading systems

In this chapter we shall present the combination of the results of the experimental work. The main objective is to evaluate the shading systems with integrated PV according to their ability to save energy and to provide visual comfort. For this purpose, as described in the introduction, the experimental work mainly focuses on three areas: balancing energy consumption with the resulting thermal comfort, daylight quality and energy production.

The conclusions in each area of focus are presented in the related chapters. In this chapter we will summarise these conclusions focusing on the effect of the integration of the PV on their geometrical configurations. For this purpose two are the main parameters: the relation of the energy needs of the building (where the examined shading systems with integrated PV are placed) with the possible energy production by the SD's and the effect of the changeability of the examined PV geometry on both energy consumption and visual comfort.

6.1. The relation of energy needs to the energy produced

In previous chapters we examined three different areas of study for the examined shading systems (in relation to the space they shade): the building's energy needs for heating and cooling, the resulting daylight quantity and quality and the electricity production through the integration of the PV systems.

In this chapter we shall endeavour to reach some conclusions in relation to the aforementioned areas, the balance of energy production by the SD with the energy saved during its use, taking into consideration the additional parameter of the building's energy needs for electric lighting (part of this energy can be produced by the SD)

The position of the luminaries can be seen in the plan (Fig. 6.1).

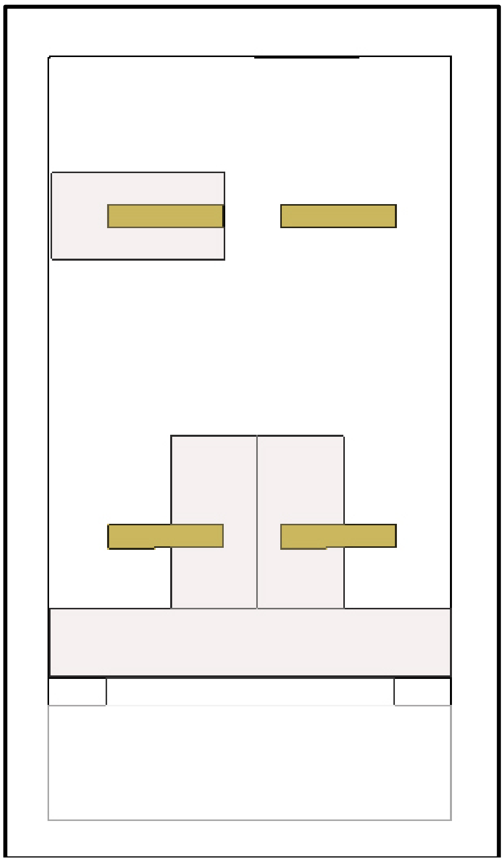


Fig. 6.1.*Plan showing the Position of the luminaries*

4 x 50 W, High Frequency (HF) tubes, mirror-luminaries are used to save electricity. For the electric light system a continuous electric light dimming strategy has been assumed for our calculations. Whenever the daylight luminance falls below the required level (during the lighting demand period), the shortfall must be provided by electric lighting. If only an on/off control were used, the electricity used for lighting would be far greater (Vartiainen, 1998). The demand for electricity due to artificial lighting in each reference office is a function of different shading devices and is calculated using the daylighting simulation formula: $E_L = P_L \cdot t_y A (1 - DAR)$ where:

P_L is the installed light power (W/m2),

t_y is the number of working hours in a year, A is the floor area (m2).and

DAR is the Daylight Autonomy Ratio defined as the proportion of working time (multiplied by 100%) in a year during which sufficient daylight (more than a pre-specified set point, for example 500 lx) is available on the work plane surface (Tzempelikos & Athienitis, 2007).

DAR has been calculated using either a simple model simulation tool (Ecotect) or a more complicated ray tracing simulating tool (DaySim). The differences between these tools have been analyzed in paragraph 4.6.4. In order to improve the reliability in the results we calculated the electricity needs for lighting for both Athens and Chania and for two types of window to wall area percentage, for 44.92% and 61.77% WWA.

We have to mention at this point that due to the fact that we are interested in the 100% of the time for the entire year we are taking into account DA levels calculated by Dyasim, even if these levels are higher than these calculated by Ecotect. Additionally we are taking into account the electricity produced as calculated by the Complete model of real market products that we proved to be the most efficient calculated method, except for the cases of blind system. Due to the fact that the analysis is a comparative one

In Fig. 6.2 we can see that all systems of PV can support the electricity needs during the hours when the daylight level falls below 500lux. During the peak conditions of demand for electric light, sunlight is at a low level and the energy production by the PV is also low. But still, the production is enough to support at least the electric lighting of the reference office room; see the diagrams of electricity production.

In order to evaluate the SDs according to their performance, we introduce a new variable: the **independence factor**. We define independence factor as the ratio of the building's needs for electricity over the electricity produced by the integrated PV. The independence factor reaches its highest value for the system **Surrounding shading.** That value gradually dwindles and eventually diminishes for the Canopy horizontal single, Canopy inclined single, Brise–Soleil full facade and for Canopy inclined double, in sequence (Fig. 6.3). From these systems, as we show in the 5th chapter the inclined ones are these that can produce the most with less area of PV installed.

Due to the fact that all possible surfaces of each shading are covered by PV and that this is the outcome of the geometry of the shading device that is an invariant factor, we are not exploiting further this fact. Additionally we should mention that the economy of the system not a subject of this research.

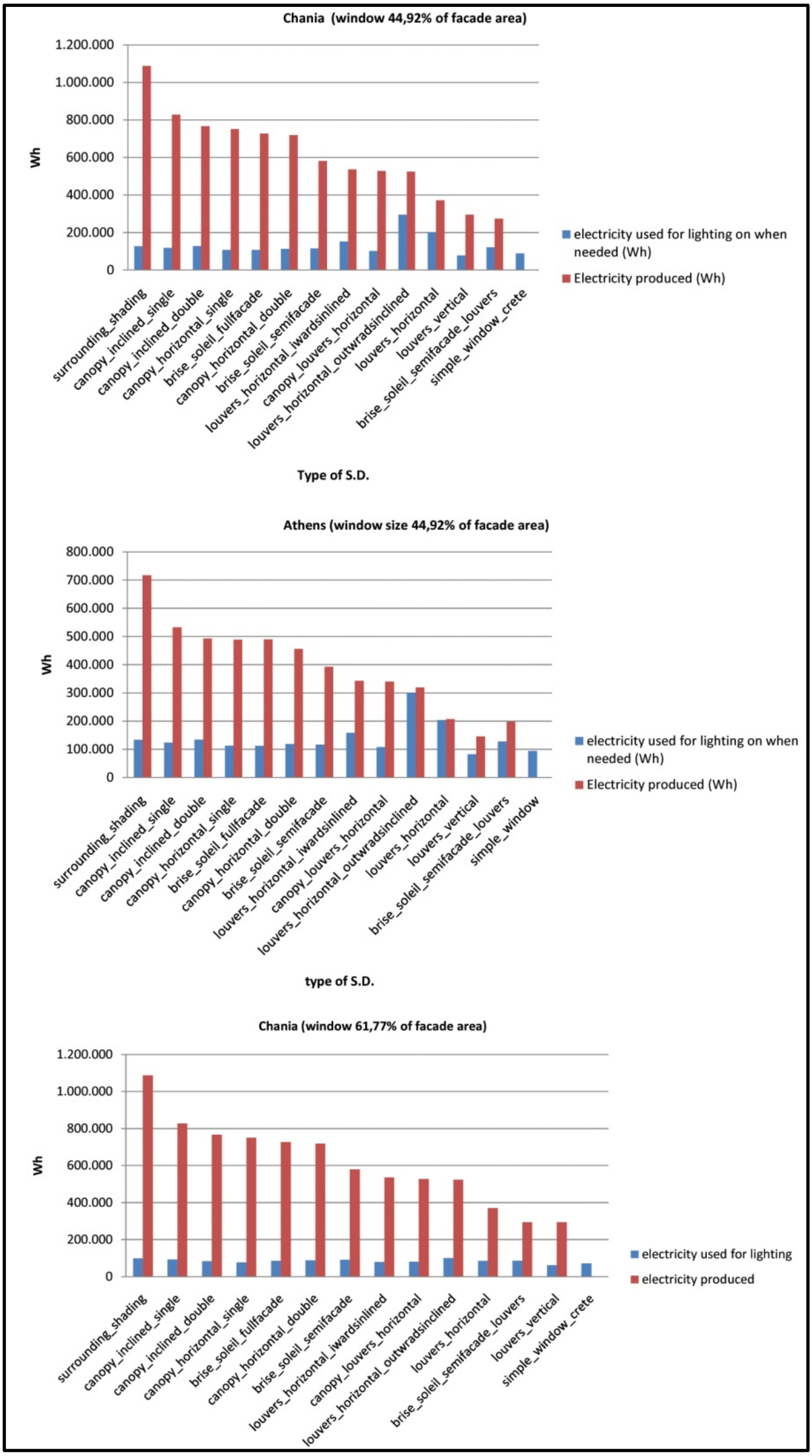


Fig. 6.2. *Relation of electricity production to electricity needs*

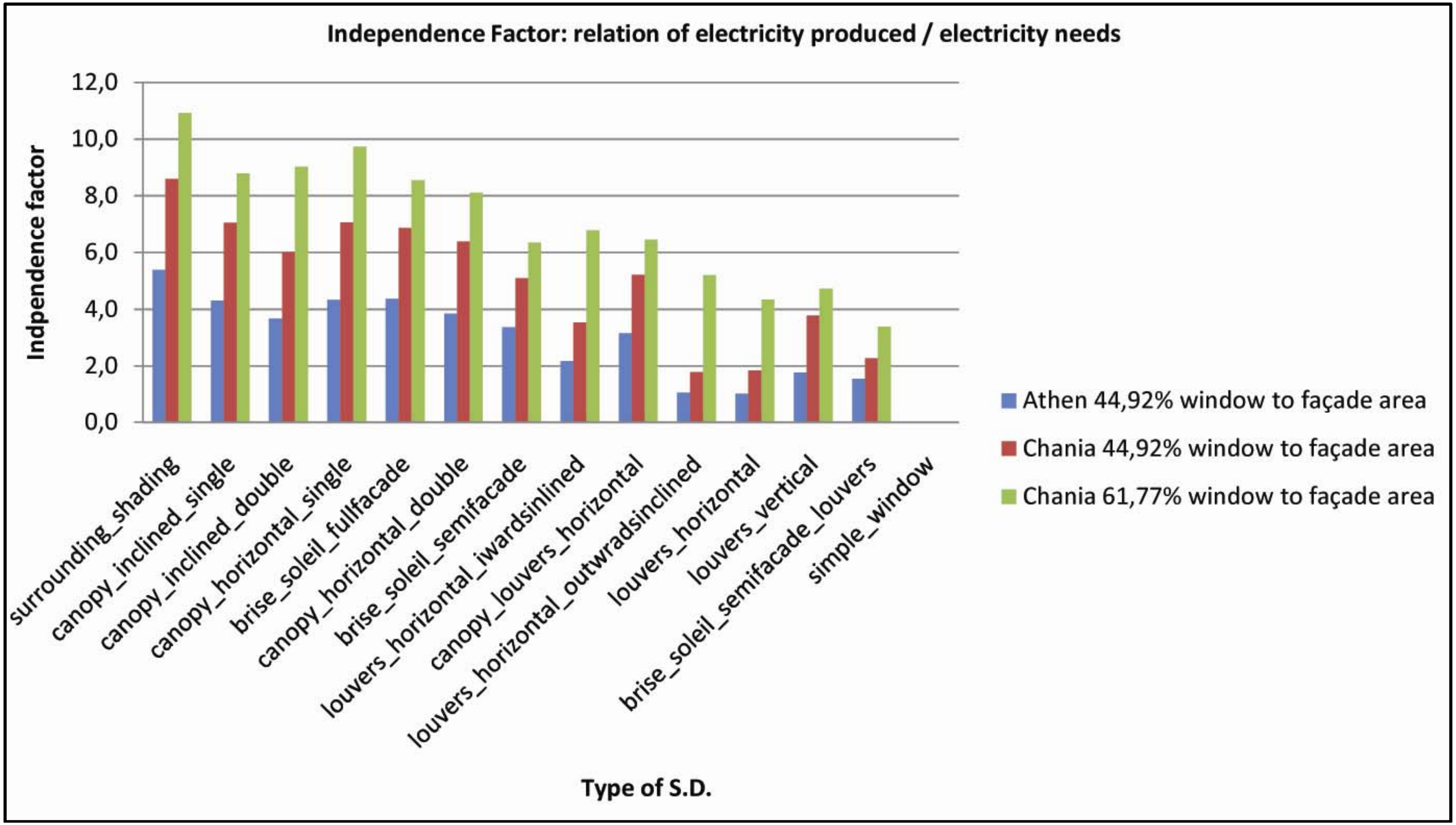


Fig. 6.3. *Relation of electricity produced to electricity needs*

In Fig. 6.4. (total energy needs), we can see that the lowest energy that the building needs (for heating, cooling) and lighting is achieved by using the **Surrounding shade.** For Chania latitude these energy needs of the building gradually increase when we use, **Brise–soleil full facade, Brise–soleil semi facade, Brise–Soleil semi facade louvers and Canopy inclined double,** in sequence. For Athens latitude the SD's rank differently in relation to energy savings afforded but still the systems of Surrounding shading, Canopy Inclined double and Brise–Soleil full facade are among the best performing.

Assuming that the electricity produced from the PV will be used to heat and cool the internal space, the most energy efficient system (the system using the most energy from non renewable sources), is the system of **Surrounding shade** for both latitude points (Fig.6.5 – 6.7). The systems of **Brise–Soleil full facade**, **Canopy inclined double** and **Canopy inclined single** are also considered to be energy efficient. Among these systems the **Canopy inclined systems** are the most efficient, according to the way we defined efficiency in paragraph 5.3.1 (relation of energy production to area of PV). Companies involved in PV industry could consider focusing on the geometries of SD last mentioned in order to allow BIPV to be placed on the SD's.

An important point is that **Surrounding shade**, **Brise Soleil System** and **Canopy inclined double** have proved to perform well in terms of daylight quality for positions away and near the window. Among these the system of **Canopy Inclined Double** is the most efficient in terms of electricity produced in relation to the PV area installed. This we will take into account as a concluding remark for the overall assessment of the Shading Systems with integrated PV.

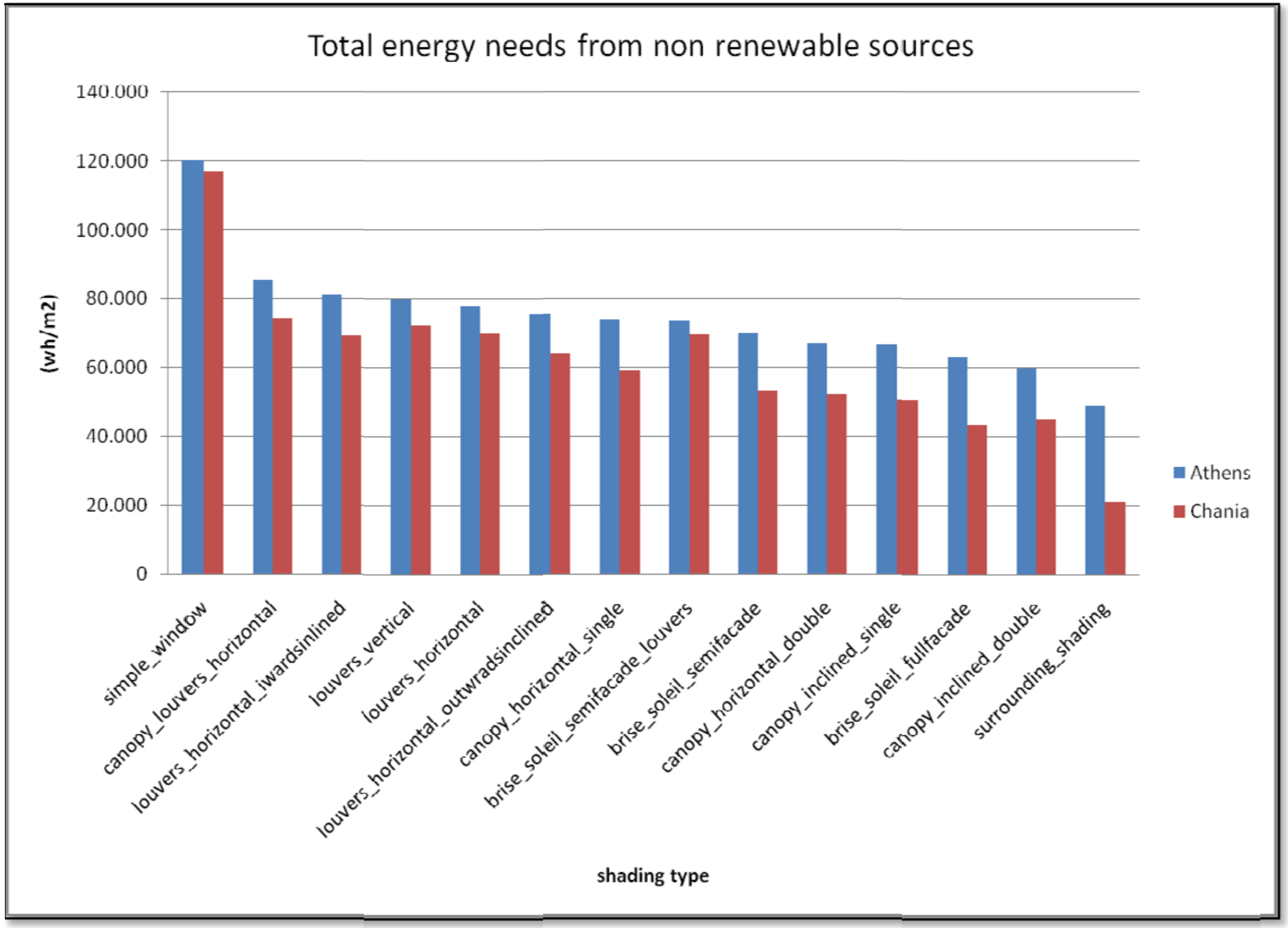


Fig.6.4. *Total energy needs (heating, cooling, and lighting) for Athens and Chania*

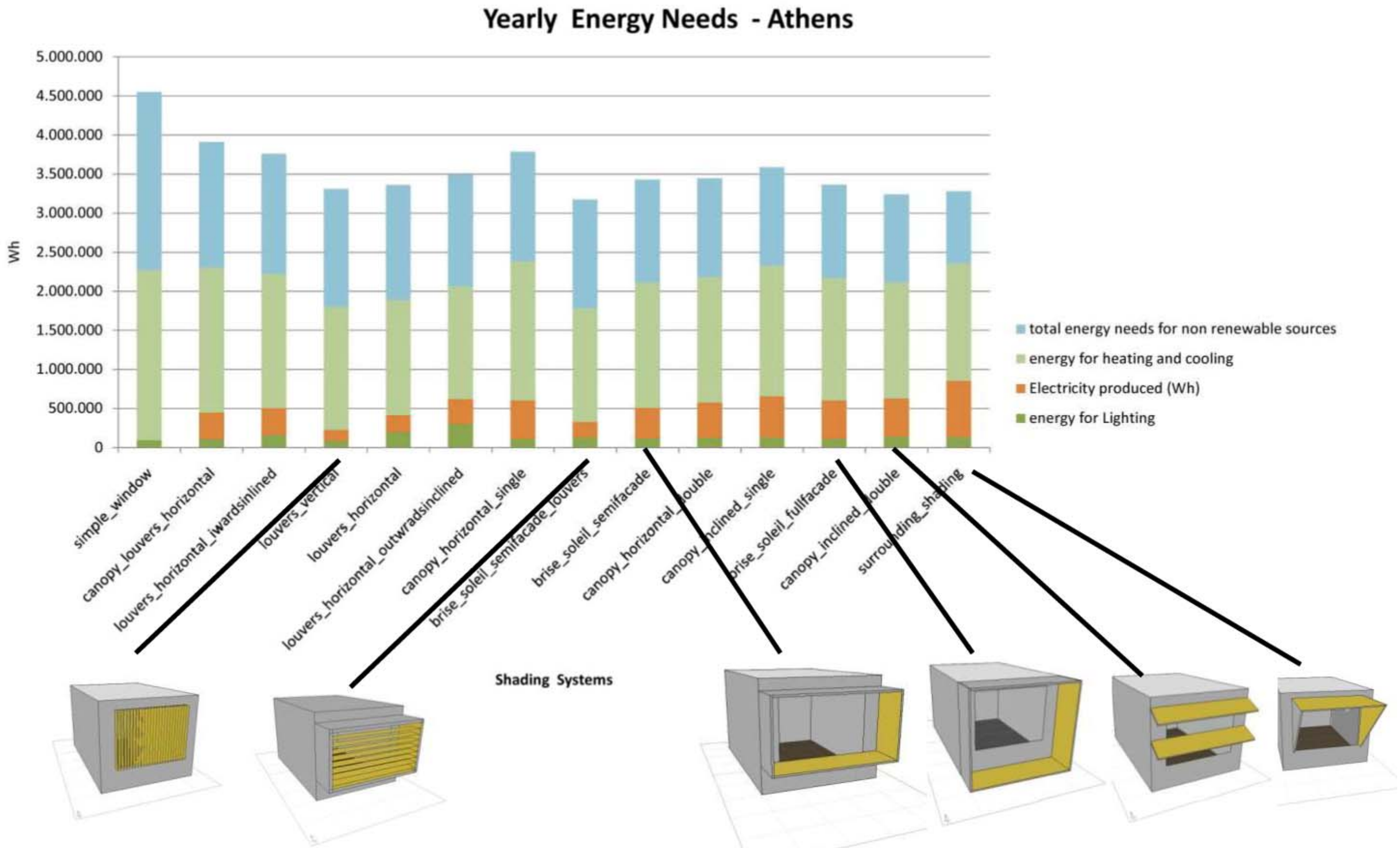


Fig. 6.5. *Total yearly energy needs for Athens Latitude analyzed by different needs*

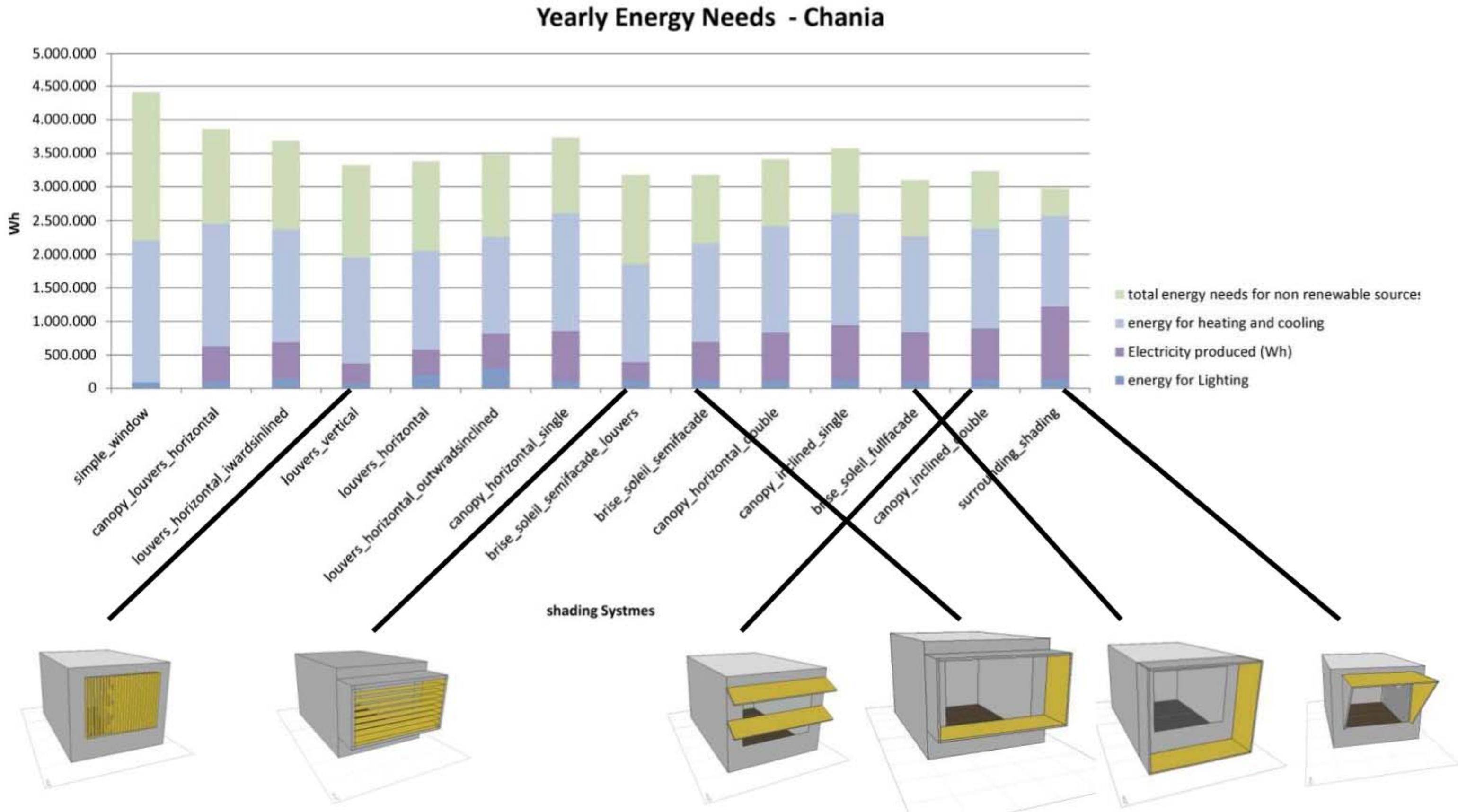


Fig. 6.6. *Total yearly energy needs for Chania Latitude analyzed by different needs*

6.2. Other factors (the effect of the thickness of the PV installed on the interior visual comfort conditions and on the energy produced)

In order to take into account the effect of the integration of the PV on the SDs', we re-evaluate the SDs' performance in relation to daylight quality and to energy needs, using PV systems which can be integrated on them in many different modes. In this research we proposed the use of framed PV systems in all shading devices. This means that all examined elements have 3cm of thickness that especially for the cases of louvers systems is crucial. For this reason, we re-evaluated all louver systems with integrated PV of 1.5 cm thickness, in terms of daylight quantity and quality.

The areas of the experimental approach are the following:

1. The effect of changing the thickness of the PV on the daylight levels in the interior as measured with the simulation tool.
2. The relation of the building's energy needs for electric lighting with the energy produced by the PVs, comparison of calculated Daylight Autonomy DA (Daysim) of the new PV panels.
3. The comparison of UDI (calculated with Daysim) and DGI (calculated with Radiance) of the new shading systems (with PV panels of 1.5cm) in relation to those already examined.

To evaluate the physical models method used and the influence of the change of the thickness of the PV louver systems, we conducted a second set of simulations with louvers of 1.5cm thickness in contrast with the 3cm thickness used in the physical model during the first set of simulations. The resulting interior daylight levels were greater, as expected, in almost all cases. From this we also conclude that the results of the simulations are in general closer to the results when we use physical model. In particular the results from physical models and the results from simulations are close to each other in the back of the room for almost all cases. When near the window the results from simulations differ significantly from those of the physical model for the Brise soleil Louvers system only (Fig. 6.7).

This means that for assessing visual environment of PV louver systems using physical model, higher thickness of louvers should be integrated than originally proposed. The overestimation in the daylight levels that the Physical models are normally measuring can be reduced when the thickness of the louvers are higher than these that are going to be used in the real building (and the simulated ones). The above meantioned conclusion is accurate for Louvers Vertical and for most of the case for the back of the room.

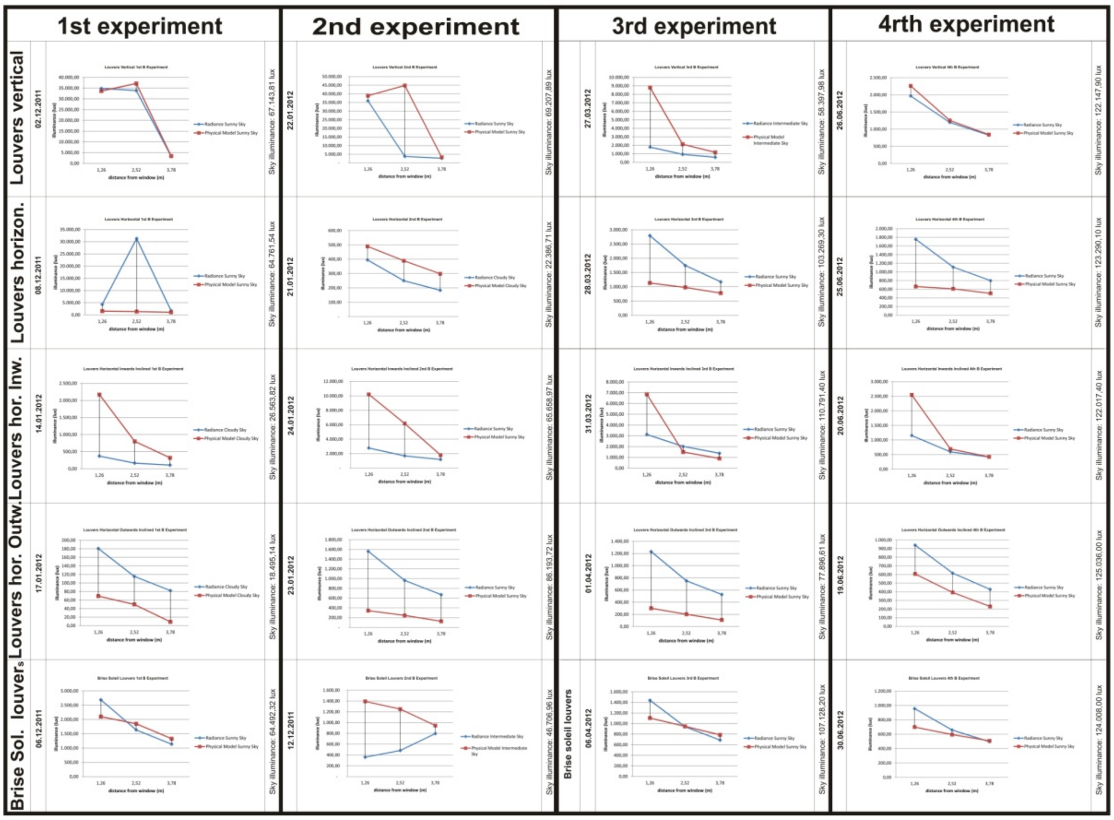


Fig.6.7. Comparison of Measurements of Physical Models with simulation application (Radiance). Thickness of PVs used in the Simulations is 1.5cm

In relation to daylight autonomy (DA) we can see that all DA values increase for all examined shading systems, and this means that the electricity needs for daylight decrease (Fig.6.8).

In relation to glare values for cases away from the window it is remarkable that almost all systems with PV louvers of 1.5cm thickness do not generate glare in contrast with PV louvers of 3cm thickness (Fig.6.9 and 6.10). Only Vertical Louvers with both1.5 or 3 cm width perform very well.

However, for positions near the window almost all systems generate glare except of Louvers Horizontal, Louvers Vertical and Brise - Soleil Louvers (Fig. 14). We conclude that Louver systems with lower thickness of PV perform better for positions near the window. (Fig. 6.11).

By comparing Fig. 6.12 and Fig. 6.13 we also conclude that the UDI values remain constant regardless of the thickness of the louver except in the case of Louvers horizontal when UDI 100 – 2000. This fact shows that the change of the thickness of the PV louvers – panels does not significantly affect the daylight quality of the interior space but at the same time they decrease the needs for electric light.

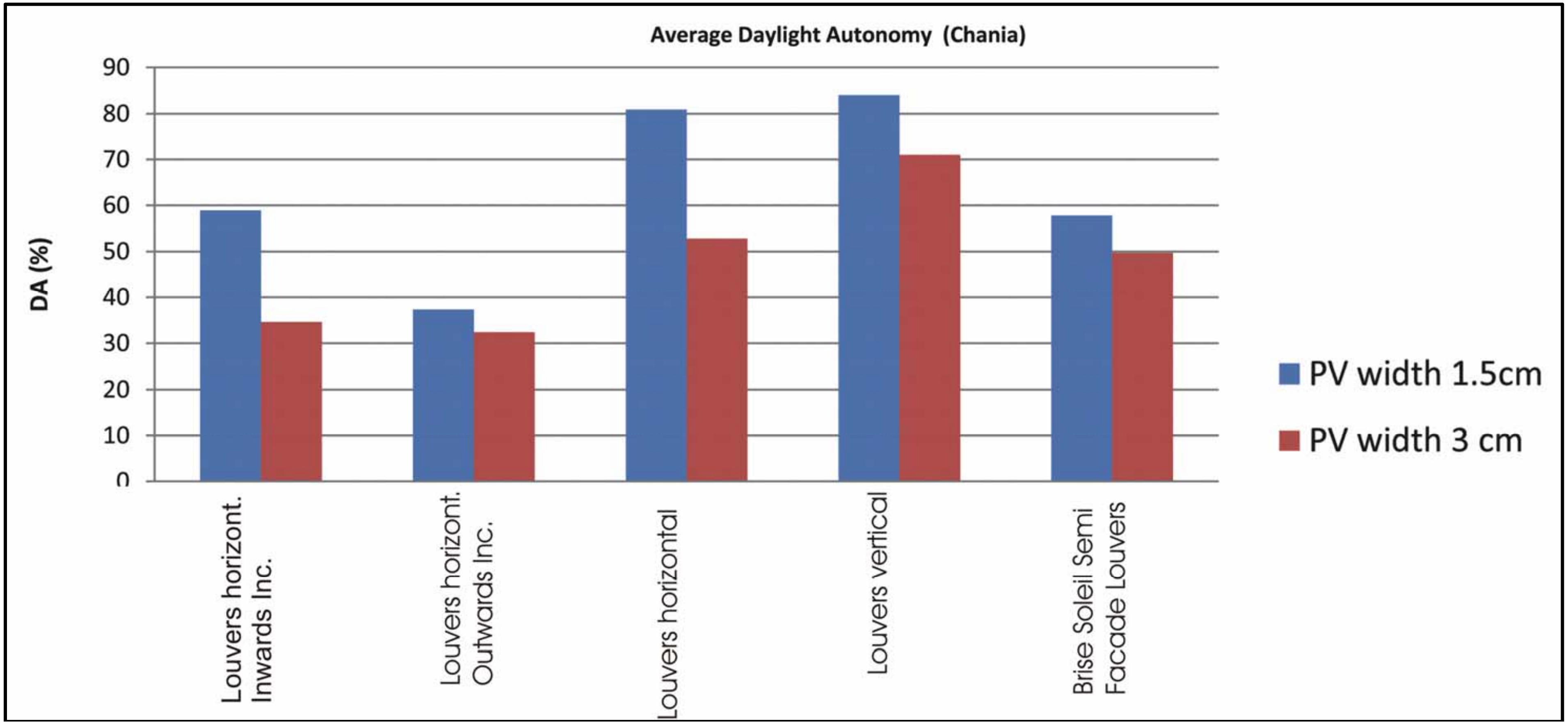


Fig. 6.8. Comparison of DA for two PVs' thickness (1.5 and 3 cm)

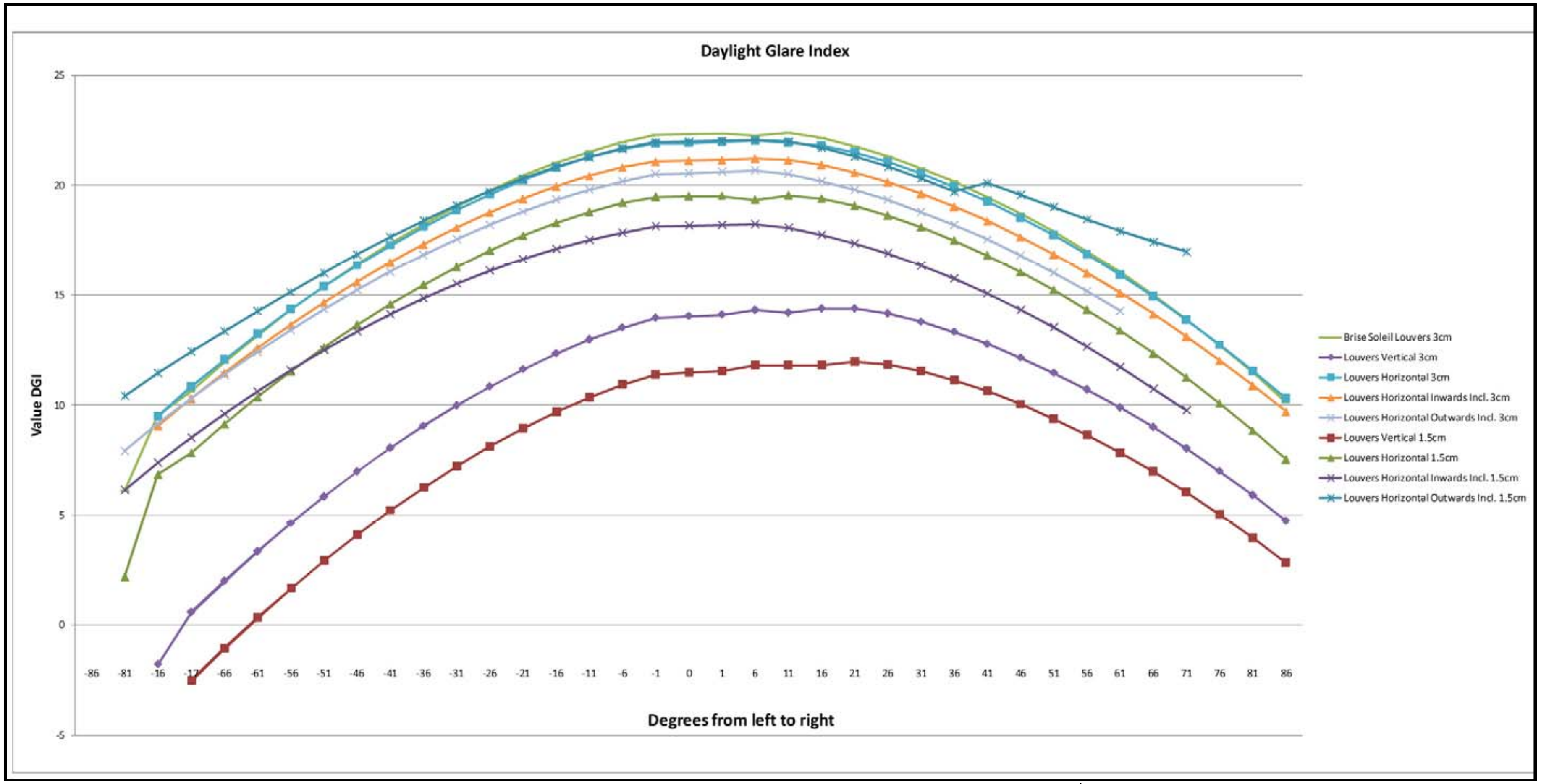


Fig. 6.9. *Comparison of DGI values for the case of thickness 1.5 and 3 cm for camera away from the window for the 21st December at 12.00 o'clock*

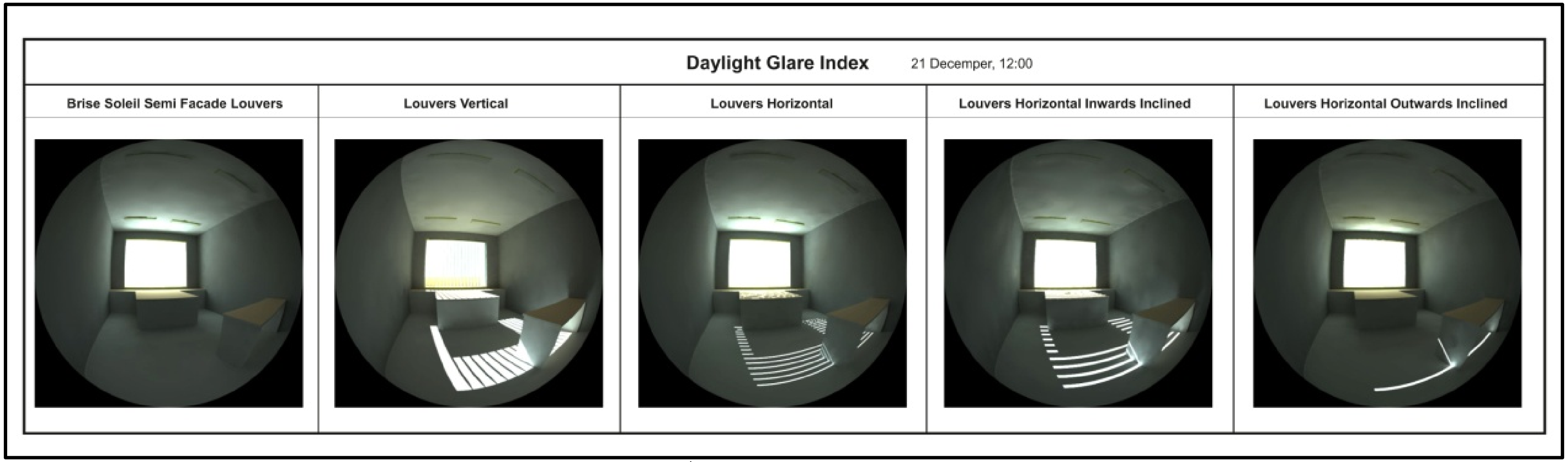


Fig. 6.10. Fish – eye camera for 1.5 cm thickness systems for December 21st at 12:00

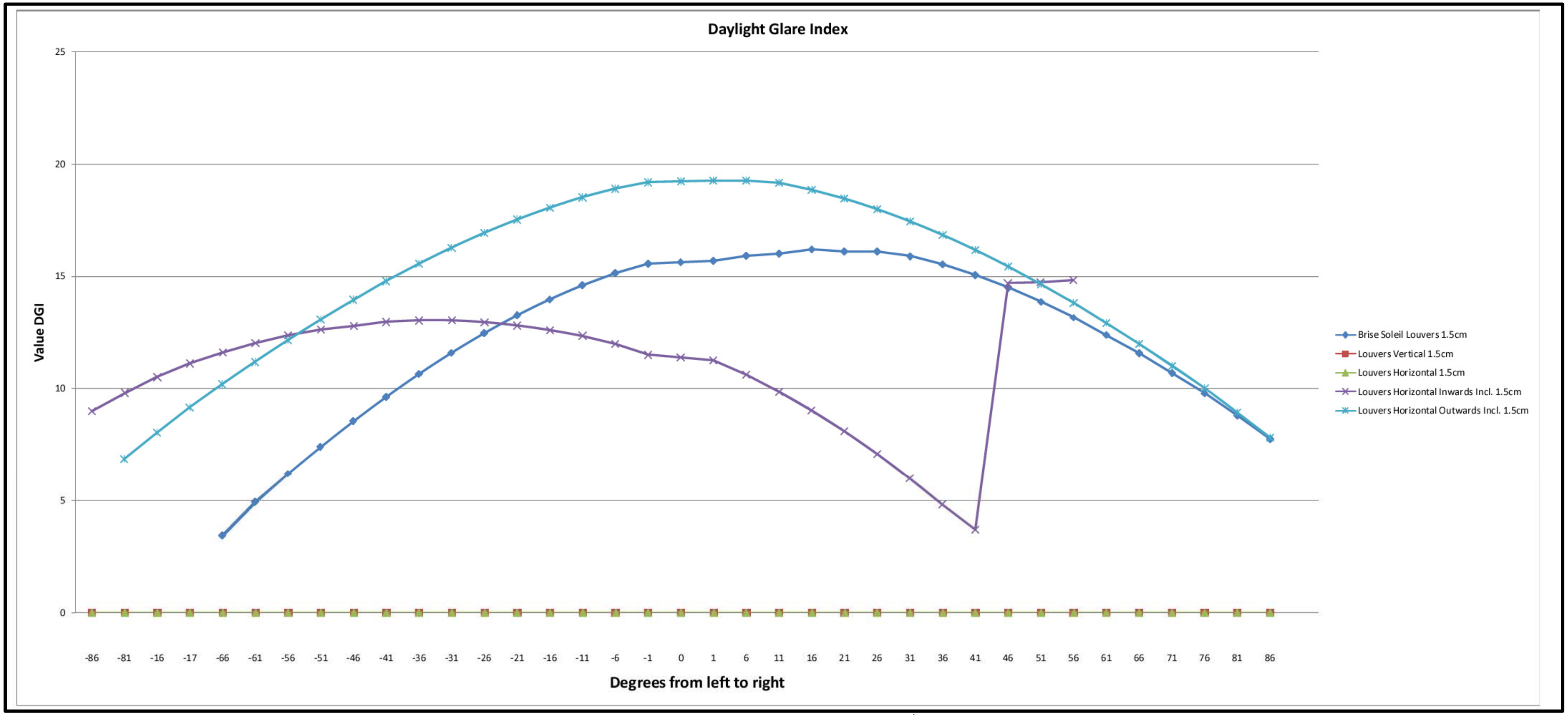


Fig. 6.11. *DGI values for SDs for the case of thickness 1.5 and 3 cm for camera near the window for the 21st December at 12.00 o'clock*

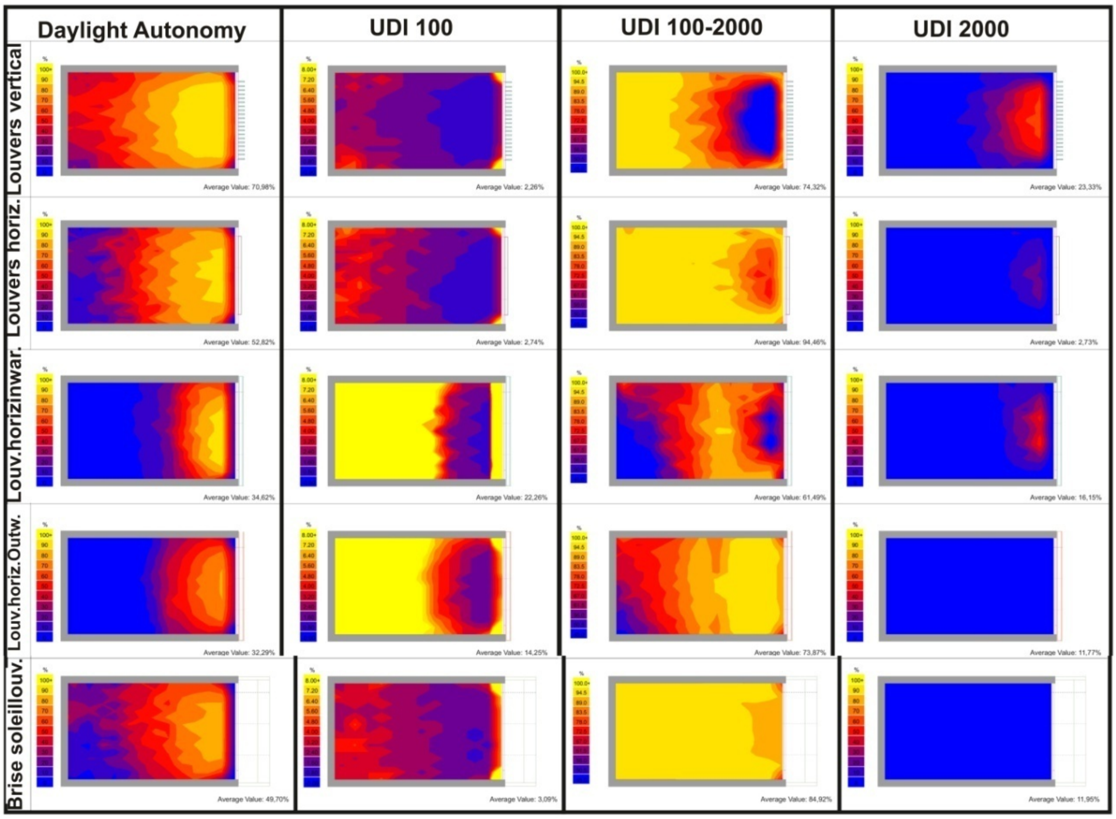


Fig. 6.12. DA and UDI values for Louver Systems with 3 cm thickness

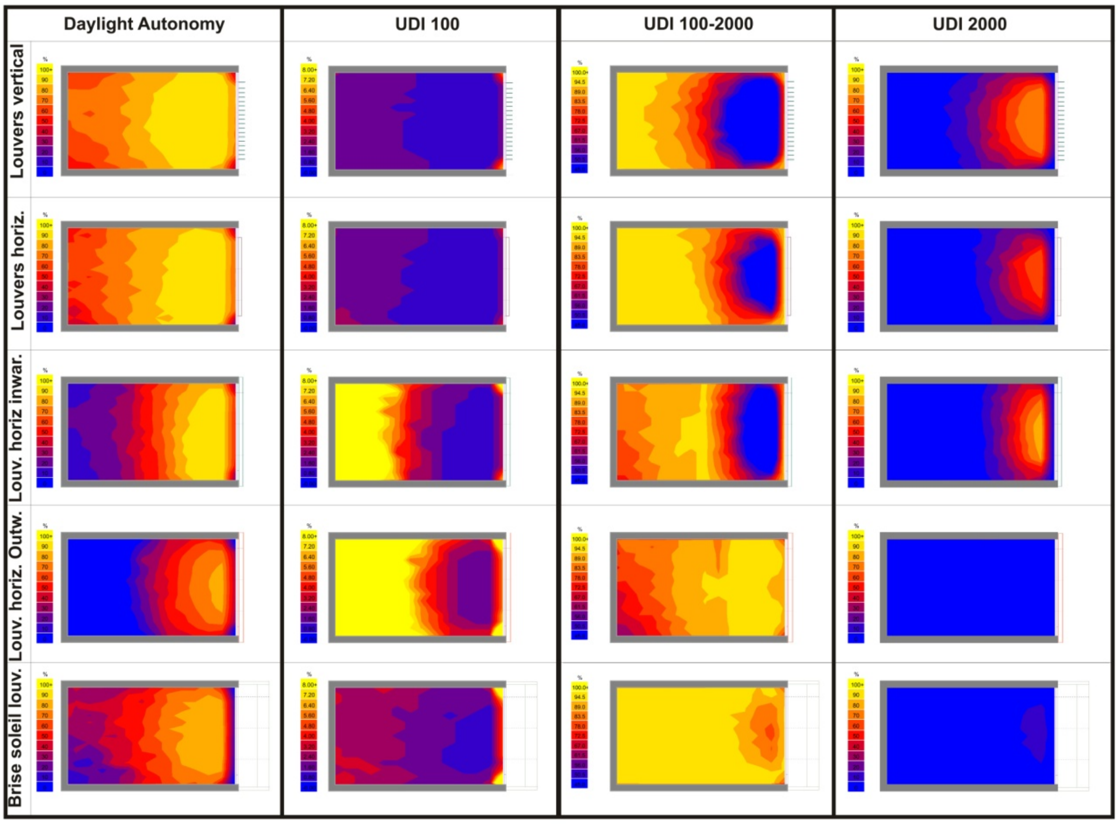


Fig. 6.13. DA and UDI values for Louver Systems with 1.5 cm thickness

6.3. Discussion and conclusions

We have attempted to bring together the different and occasionally contradicting properties of the various shading systems examined in relation to their ability to save energy and to provide high quality of daylight (Table 6.1). The measuring scale is based on three basic categories starting from the most efficient in terms of the factor examined: Best - Middle – Low. When values of the same examined factor for some Shading systems are very close the can belong to the same level, example two systems belongs to the BEST category for UDI factor. BEST – 1 means lower quality of the examined factor and BEST – 2 even lower. Their difference is not high enough, to position them in a completely different level: to the MIDDLE. The same applies for the rest of the reference values.

We have concluded that the systems of **Surrounding shade** and of **Canopy inclined single and double** can best achieve these two goals

It is remarkable that the systems of **Louvers** which have proved to perform very well in office units (Bulow - Hube, 2001; Dubois, 1997), are unsuitable for integration of PV, due to the fact that their energy production becomes very low when PVs are integrated. An interesting result occurs when changing the thickness of the PV. First of all the need for electricity needs reduces, the quality of daylight becomes better for positions near the window and with the additional movement of the whole system further away from the façade skin, as we saw in paragraph 5.3.5 their energy production becomes higher. Still the energy production does not become high enough to rate the louver systems amongst the most efficient SDs with integrated PV.

We recommend that when considering PV integration for shading systems in office buildings **Surrounding shade**, **Brise – Soleil Systems and Canopy Inclined Systems** should be considered as a valuable solution in order to achieve visual comfort and sufficient energy production.

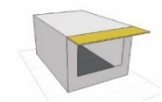
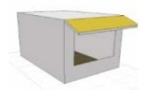
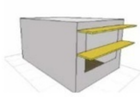
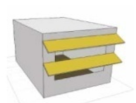
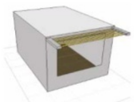
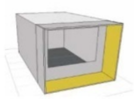
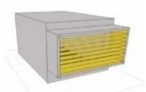
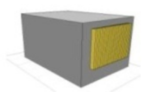
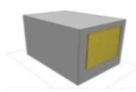
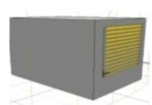
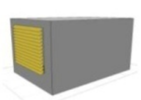
	UDI	DGI Away from window	DGI Near the window	DA	Energy Needs For H + C + L from NRS
	LOW - 1	BEST - 2	BEST - 2	BEST - 2	MIDDLE - 3
	MIDDLE	LOW - 4	MIDDLE	BEST - 5	BEST - 3
	MIDDLE	MIDDLE	MIDDLE	BEST - 3	MIDDLE
	BEST	MIDDLE	MIDDLE	MIDDLE	BEST - 1
	LOW - 2	BEST	MIDDLE	BEST	LOW
	MIDDLE	BEST - 3	BEST	BEST - 1	BEST - 2
	MIDDLE	MIDDLE	BEST - 1	BEST - 1	MIDDLE -1
	BEST	LOW	LOW	LOW - 1	MIDDLE -2
	BEST	LOW - 3	MIDDLE	BEST - 3	BEST
	MIDDLE	BEST - 1	BEST - 3	LOW- 2	LOW - 2
	BEST	LOW - 1	MIDDLE	LOW- 2	LOW- 3
	LOW	LOW - 2	LOW - 1	LOW	LOW - 4
	LOW	LOW -3	MIDDLE	LOW	LOW -1

Table 6.1. Comparative *assessment of shading systems (NRS = non renewable sources)*

Additionally in order to examine the accuracy of the used measuring tool of energy production and energy needs we compared result that are the outcome of different tools used. We created three different scenarios as can be seen in Table 6.2.

	Energy Production	**Energy Needs (H+C+L)**
Scenario 1	Ecotect	Ecotect
Scenario2	Energy+ Simple	Ecotect
Scenario3	Energy+ Market	DaySim

Table 2. 6. *Description of measuring scenarios Used*

The results of the Scenario 1 are presented in Figs 6.5 and 6.6. In Figs 6.14 and 6.15 the results of the scenario 2 and 3 are presented. As we can see the results are similar for almost all the scenarios for the cases of simple geometries. Only for the cases of blind systems there are high differences between Scenario 1 that uses the simple tools and Scenario 2 and this fact points out the need of using accurate simulation tools for the cases of complicated geometries and when detailed analysis is needed.

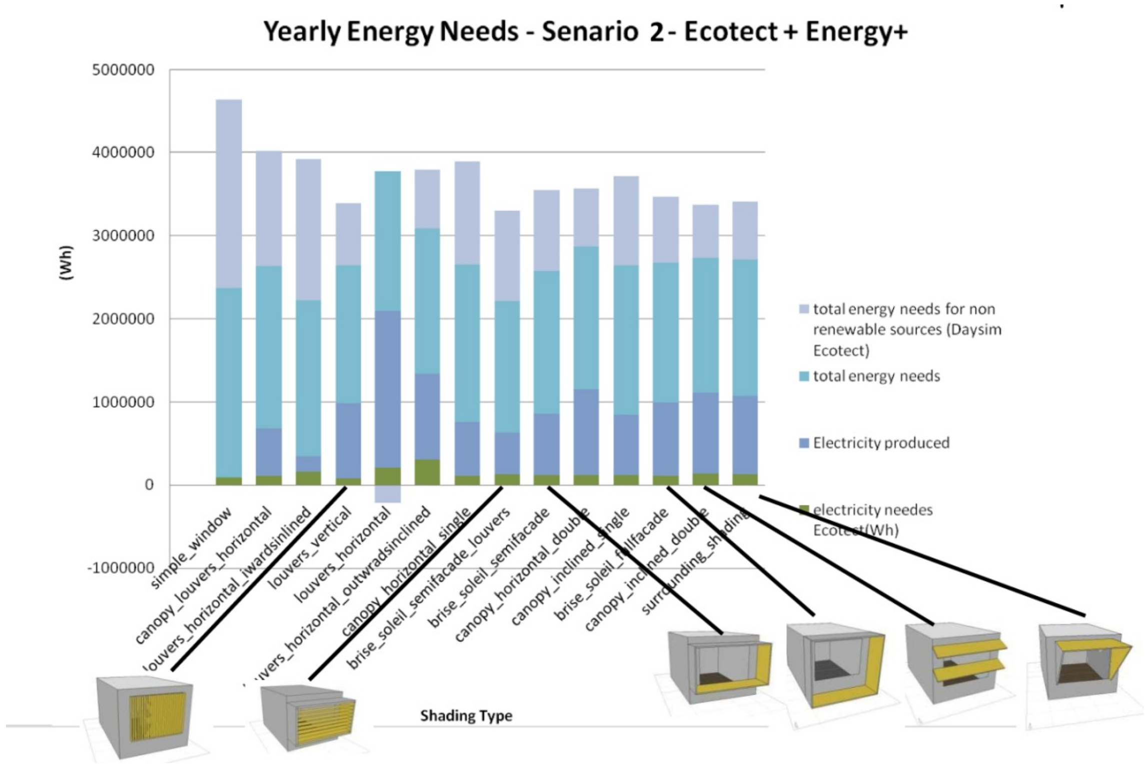


Fig. 14. *Total energy needs measured by Scenario 2.*

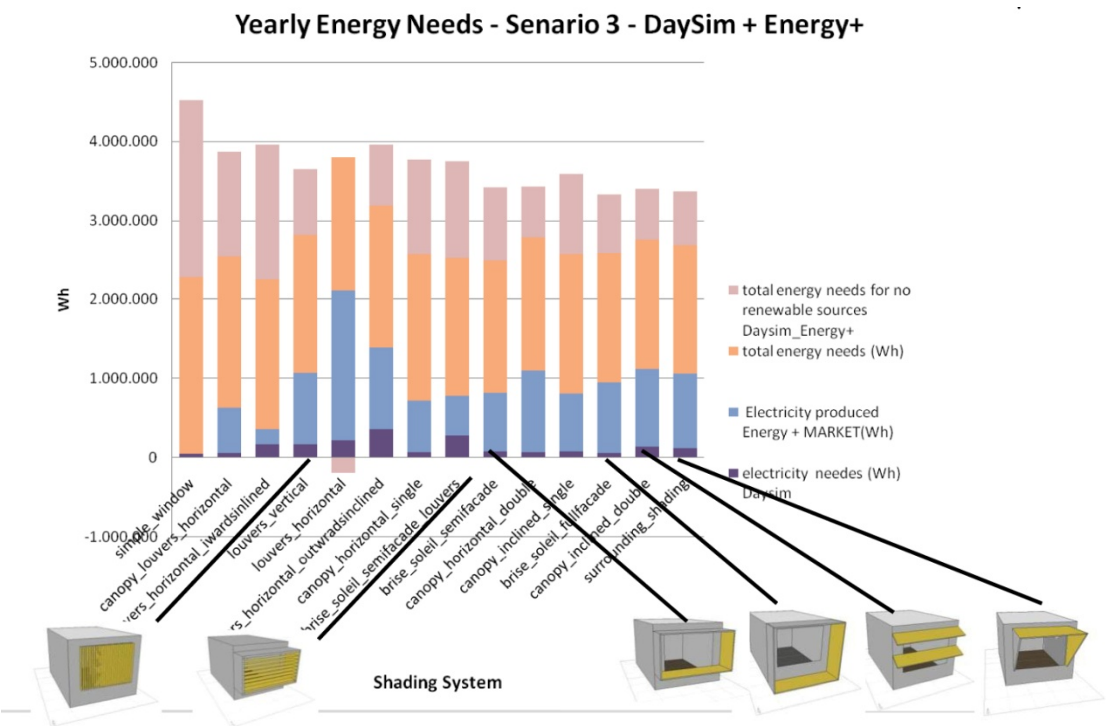


Fig. 15. *Total energy needs measured by Scenario 3*.

PART III

7. Conclusions and Remarks

Over the last century the proportion of the office buildings' envelope that is transparent has increased significantly. Due to the low thermal insulation property of glass in comparison to mass opaque building materials the larger the transparent fraction of the building's envelope the more important is the control of solar energy inflow, in order to keep thermal and visual conditions indoors in acceptable levels. Transparent facades need an additional control system, one that helps avoid solar radiation during the overheated period, allows enough thermal loads during the underheated period and ensures comfortable visual conditions during operating hours. Due to the fact that passive design is most of the times not totally efficient for the control of solar and thermal gains, additional active systems are used to balance the interior thermal and visual comfort conditions. As a result, today's buildings are dominated by technical systems for heating, cooling, ventilation and artificial lighting often resulting in high conventional energy consumption.

Integration of PV systems in shading devices can help limit the overall energy consumption in two ways: by reducing direct solar gains during the overheated period and by producing electricity to be utilized for the function of cooling, heating and lighting systems.

7.1. Overview

As argued in Chapter 1 two are the main objectives of this research: the first objective is to assess different geometrical configurations of Shading Devices with integrated PV in terms of energy performance for heating, cooling and lighting. The second objective is to asses different methods used to evaluate the energy performance of the shading system in relation to the design stage. Three main methods were assessed: the use of simple equations and simple computer models, the use of complete simulation models and the use of real measurements.

In order to fulfil these two objectives, three main areas of research were proposed: the evaluation of energy consumption for thermal comfort, the evaluation of energy consumption for visual comfort (quantity and quality of light) and the energy production of the integrated PV.

For the research done in each field two basic methods were followed: bibliography research and experimental work (Fig.7.1).

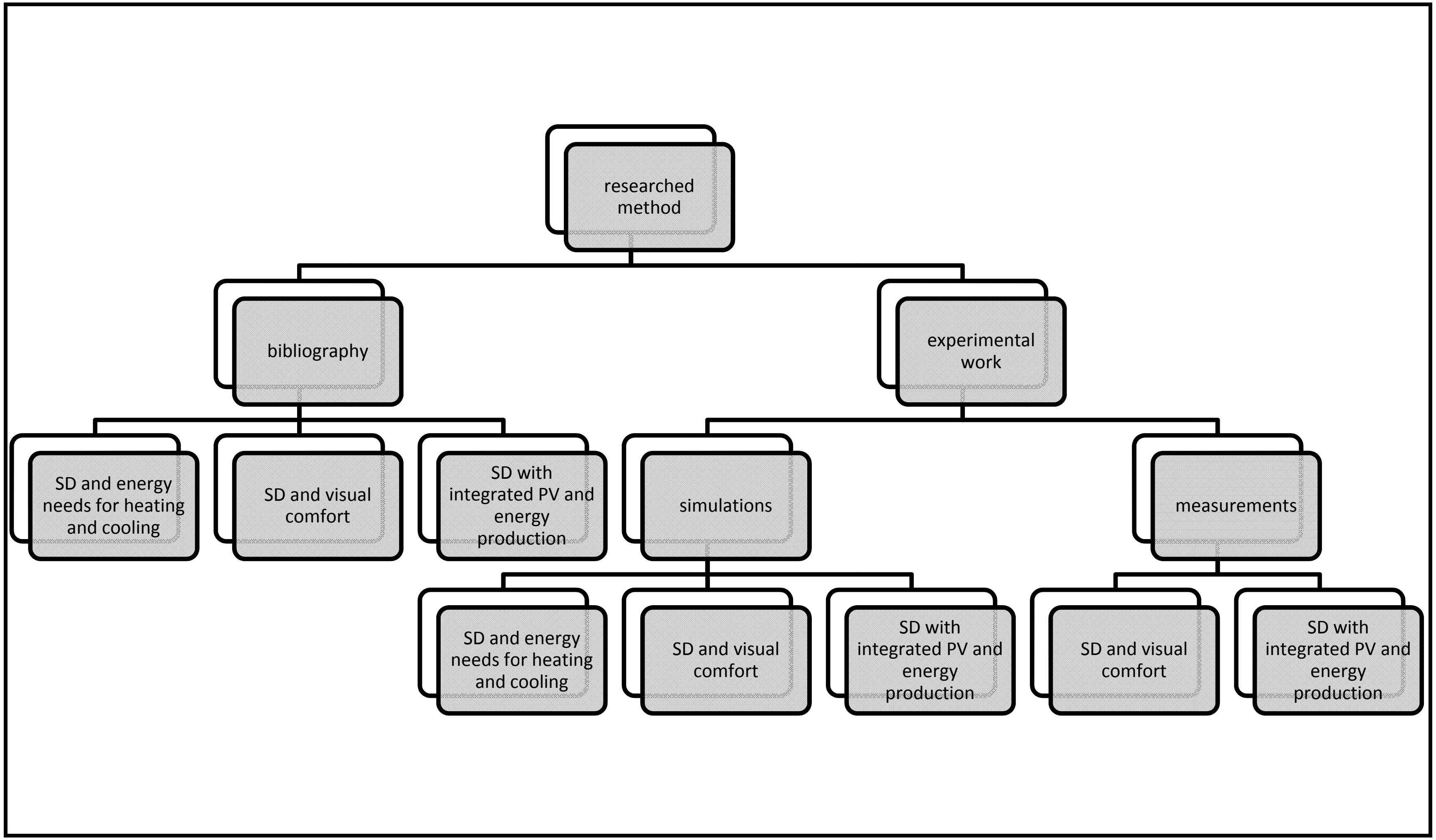


Fig.7.1. Researched Method

Bibliography research was conducted in order to:

- Define the relation between shading systems, thermal comfort and energy needs of the office unit (Chapter 3).
- Define the influence of shading systems to the interior visual environment. (chapter 4),
- Define the relation of the energy production of the integrated PVs in the shading systems and the geometry of these systems (Chapter 5).

Experimental work has been conducted for each area of research:

- For the evaluation of the energy needs for heating and cooling the office unit (**thermal comfort**), simulation work was done using a validated computer application (EnergyPlus). It is a complete model application (Chapter 3).
- In Chapter 4, experimental work was conducted for the evaluation of **visual comfort** conditions. The work includes measurements of daylight levels of physical models of the office unit with various shading systems and simulation work done with simple and complete computer model applications. We validated the results of the experimental work in relation to the design stage that they can be used.
- Finally in Chapter 5, the energy production of the thirteen shading systems with integrated PV under examination has been measured using two computer applications: a simple model application and a complete model application that uses real market products. Additionally the results are compared to measurements of real PV roof installations. Further on we related the results of each method used to the details needed for each design stage.

In Chapter 6 a comparative analysis is presented between the parameters examined in previous chapters and the energy needs for heating, cooling and lighting the examined office unit. The basic grouping of the shading systems is presented in this chapter: the transparent systems and the facade covering systems. The additional parameter of detailing the PV integration is also examined in this chapter. Two different louvers' thicknesses of facade systems are examined: 3cm thickness for the framed PV and 1.5cm thickness for the PV integrated in glass louvers. Differences in the visual performance of the systems have been observed. General conclusions of the overall energy performance of the shading systems are presented.

In the next paragraph the conclusions of Chapter 6 are presented and combined with the conclusions of Chapters 3, 4, and 5.

7.2. Conclusions

Simulation methods, measurements of physical models and real PV roof installations are used in order to evaluate the energy performance of various geometrical configurations of shading systems with integrated PV for an office unit.
Even though differences between the results of the methods used have been observed and presented in the related chapters, some general conclusions have be extracted and presented here. The conclusions are either related to the method used or to the examined researched field (energy for thermal comfort, energy for visual comfort or energy production). Some generalized conclusions are presented as well that involved the overall assessment of the examined south facing SD with integrated PV, as valuable "machines" of energy balance.

- The lowest energy consuming systems for heating and cooling are the **Surrounding Shade**, the **Brise Soleil** systems with and without louvers and the louver system with different inclination depending on the latitude.

  Small differences are observed between the two different latitude points examined, as expected. The conclusions can be generalized for Mediterranean climate, but small geometrical adjustments might be needed. These systems, that like others block direct and reflected sun radiation and can obviously be efficient enough in terms of minimizing cooling loads, block at the same time part of the beneficial winter solar radiation. For this reason there is an increased complexity in the calculation of their overall performance.

- Systems with high lighting independence factor, meaning that they produce much more energy than necessary for the electric lighting of the space during the periods that daylight falls under 500 lux, are: **Surrounding Shade** and **Canopy Horizontal and Inclined double** in that order.

  Almost all systems can produce enough electricity to support the electric light needed for both latitude points and for both window sizes examined.

- The lowest energy needs for all heating, cooling **and** lighting are measured for the systems of **Surrounding Shade, Brise Soleil Full, Semi facade** and **Canopy Inclined Double,** in that order.

- None of the systems can produce all the energy needs for heating cooling and lighting. Systems that are having the lowest energy needs from non renewable sources are **Surrounding Shade, Brise Soleil Full and Semi façade**.

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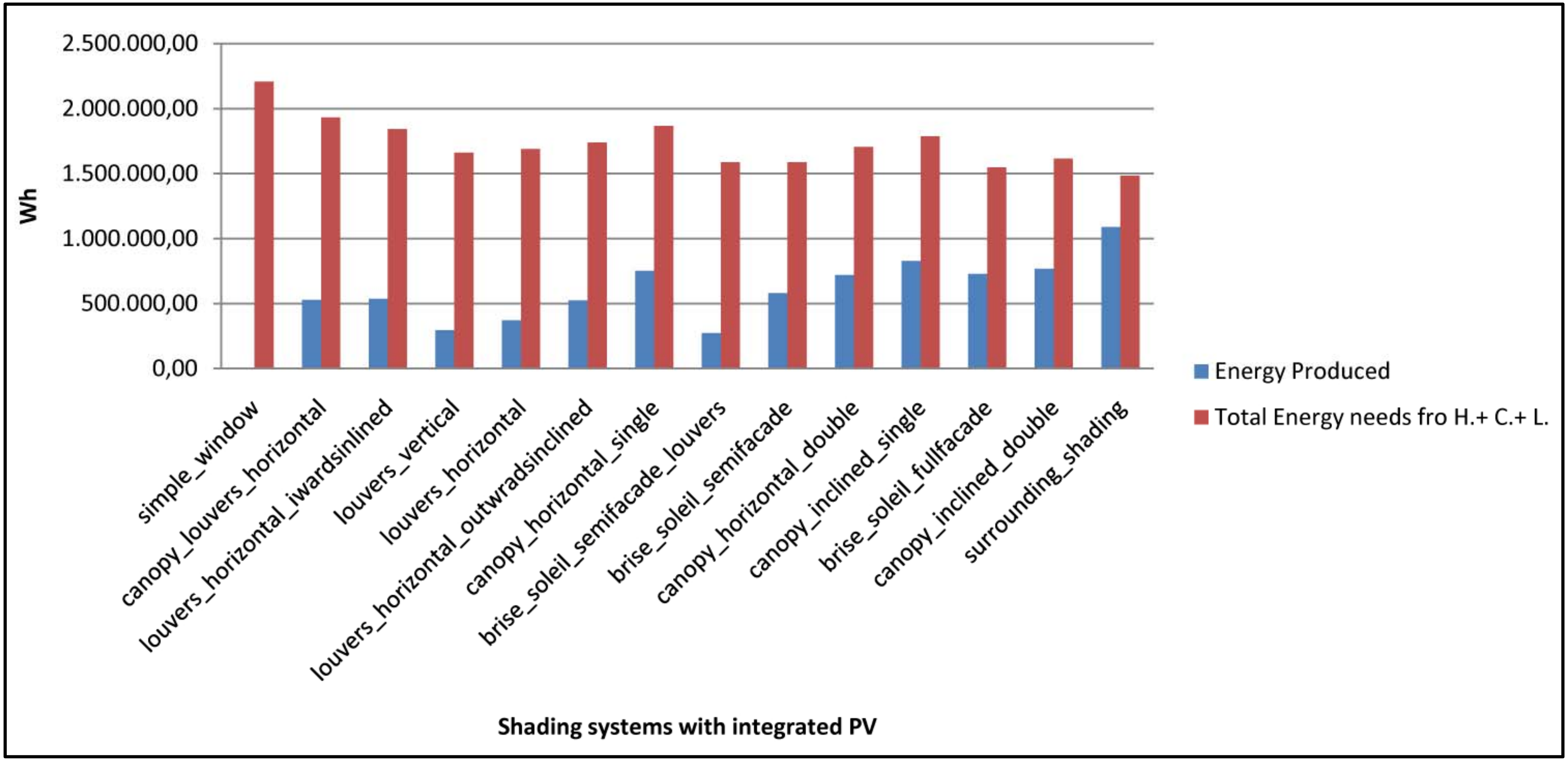

Fig.7.2. *Energy production and energy needs of the office unit with various shadings systems in the south façade*

We examined the daylight quality in terms of two factors: the Useful Daylight Illuminance (UDI) and the Daylight Glare Index (DGI). UDI factor shows percentage of time that the daylight in area of the examined room is between the ranges of 100 – 2000 lux. These are the limits of visual comfort zone. DGI is a factor that shows possible glare caused in a specific position in the room for the examined time of the day. We examined all shading systems in relation to the glare they produce for two possible positions in the room: one away from the window that has the maximum view towards the light source (window) and one near the source of light.

- The systems of **Surrounding shade** and **Canopy Inclined double και τα Brise Soleil** produce daylight environment of high quality.

  All the above mentioned systems have very good performance in terms of UDI values. Additionally the systems of **Surrounding shade** and **Brise Soleil** of has good performance in terms of DGI values.
  The only disadvantage is that Useful Daylight Illuminance (UDI) is a value that shows percentages of comfortable environments but it does not show possible positions of glare.

- For positions away from the window almost **all transparent systems** perform very well in terms of glare produced. The systems of **Canopy Louvers, Brise Soleil Full and Semi Façade, Canopy Horizontal Single and Double** do not produce glare. Additionally the system of Louvers vertical performs very well for the time period examined (12:00 o'clock the 21st of December).

  For positions near the window the systems of **Brise Soleil Semi Façade, Canopy Inclined Double, Souriounding Shade** and from façade covering systems of Louvers Horizontal Inwards Inclined and Brise Soleil Louvers do not produce glare. We simulated low DGI values for **them.** For the systems of **Canopy Horizontal, Canopy Horizontal Double, Canopy Inclined Single, Canopy Louvers, Surrounding Shade, Brise Soleil Full façade, Louvers Vertical and Louvers horizontal and outwards inclined** we simulate zero values of DGI. Technical problems do not allow au to simulate the glare value for them.

- The combination of the above mentioned facts supports the argument that the system of **Canopy Inclined Double** is performing better in terms of low energy consumption due to the energy produced by the PV. Canopy Inclined Double also generates good quality of daylight environment for positions near the window (examined by two values DGI and UDI).

  Additionally the System of **Surrounding Shade** is a system that can better support the energy needs of the room and guarantee visual comfort for positions near the window (examined by two values DGI and UDI).

  It is worth to mention that the system of **Brise Soleil Full façade** performs very well in terms of low glare values for positions near and away from the window. At the same time this system cannot fully support the energy needs of the office unit that it shades. The difference between the energy needs and production is very low, and this fact allows us to consider the Brise Soleil Full façade system amongst the efficient shading systems with integrated PV. Among these three systems, **Canopy Inclined Double** is the most economical due to the fact that with the same square meters of PV the energy production is maximized.

- When the thickness of the integrated PV of façade covering shading systems changed from 3cm to 1.5 cm, the results of their visual performance changed as well.

  For positions away from the window none of the systems produce glare, and for positions near the window all systems produce glare except of **Louvers Horizontal**, **Louvers Vertical** (for 12:00 o'clock only) and **Brise Soleil Louvers**. On the other hand the main disadvantage of these systems is that they perform very low in terms of energy production and very high in terms of energy needs for heating, cooling and lighting.

- In order to assess visual comfort conditions in the early design stage, daylight factor (DF) and daylight autonomy (DA) are appropriate values.

  These two values can be easily measured using either physical models or simulation tools. Both methods are accurate enough. Simple computer simulation tools (e.g. Ecotect) can be used to evaluate daylight autonomy (DA) levels. For daylight levels, physical models can be used but special equipment is needed. Simple simulation models can be used to evaluate DF, but this factor only gives information about the performance of the shading system in overcast sky conditions disregarding other possible sky conditions.

- The DGI method and UDI value for evaluating visual conditions should be used in the detailed design stage, due to the fact that they demand detailed modelling and are time consuming. Additionally the designer should be familiar with these values in order to be able to evaluate the results.

  In order to calculate both values, more complicated applications are used (Radiance, Daysim) that demand special knowledge of modelling. Additionally, these values are very much influenced by the final finishes and detailing, parameters that become known in the late design stage.

- Physical Models as a means to evaluate interior visual comfort can be used in the late design stage.

  Physical models for daylight analysis need detailed modelling and special knowledge for the construction of the model. The detailing can be done in the late design stage. Additionally, in order to measure daylight levels specialized equipment is required. This equipment is expensive to obtain and demands special skills to use. These types of measurements are done for research purposes or in very late design stages in specially equipped laboratories supported by trained staff.

- Even if physical model required special treatment, it is a basic tool to achieve visual assessment. In general physical model overestimate the daylight levels in comparison to simulations. The percentage of overestimation depends on the position of the sun in the horizon and the point in the space examined in relation to the depth of the room. For High sun position and high sky illuminance the differences between physical model and simulation are smaller. The differences are even small for case at the front of the room that the intereflections are smaller.

- To evaluate the energy production of integrated PV in Shading Systems the method used depends on the desired accuracy of the results and the comparative or absolute nature of the conducted research. The choice of the best performing geometry depends on the preferred factor examined and the priorities of the designer (Fig. 7.3).

SD	Total Energy Needs(KWh)
S	667
LHI	806
CI	817
BSL	830
BS	845
BSS	992
CID	1210
LV	1236
CD	1290
CL	1306
C	1320
LH	1459
LHO	1544
SW	1670

SD	Energy Production (KWh)
LH	2087
LV	1390
CD	1113
LHO	1098
CID	1031
S	993
BS	831
BSS	789
CI	786
C	706
CL	629
BSL	512
LHI	191

SD	UDI (100 - 2000)
LH	94
BSL	85
CID	80
S	78
LV	74
LHO	74
CI	66
LHI	61
CD	61
C	58
BSS	54
BS	52
CL	50
SW	46

SD	Away
BSS	1
C	1
CL	1
BS	1
LV	1
CD	2
CID	3
S	3
BSL	3
LHI	3
CI	3
LH	3
LHO	3
SW	NA

SD	Near
BSS	1
CID	1
S	1
BSL	3
LHI	3
C	NA
CL	NA
BS	NA
LV	NA
CD	NA
CI	NA
LH	NA
LHO	NA
SW	NA

Impereceptible	Below 16	1
Perceptible	16 - 20	2
Accepteble	20-24	3
Uncomfortable	24 - 28	4

Fig.7.3. *Comparative assessment of all examined systems*

The accuracy of the results depends on the designer's wishes which are related to the design stage that the project has developed. The theoretical efficiency of 12% used in the simple simulation model equation is accurate enough only for simple geometrical configurations of shading devices.

The complete simulation model for measurements in relation to real market products, is accurate enough only for simple geometrical configurations. For more complicated geometries other types of research are needed. For venetian blind systems, for example, only the in situ measurements are accurate enough when exact values of energy production are needed. For systems with integrated PV that produce energy only through reflected solar radiation both the simple model simulation executed with a sensitive computer application and the simulation of real market products are accurate enough.

For a comparative analysis between different geometrical configurations of shading systems with integrated PV modules (and not a value level dependent analysis) the complete model that used real market products is accurate enough.

- We showed that the performance of shading systems with integrated PV in relation to energy savings and to visual conditions can be examined in the early design stage using basic simple tools with a high level of accuracy.

The results in this case are accurate enough for simple geometrical configurations. For more complicated geometries detailed physical and digital modeling is needed and the use of complete simulation tools.

- The overall conclusion can be summarized in the following remark: This research pointed out the need and propose the method for the development of a computer simulation software that will be user friendly, appropriate for architects for the early and detailed design stage and that would propose solutions of Shading Systems appropriate of their design wishes, the climate of the examined case study and the priorities of the project.

7.3. Further Research

It is important to note that the most commonly used shading systems for office buildings, the horizontal louvers, outwards or inwards inclined perform badly in terms of low energy consumption. These kinds of systems cannot contribute to the reduction of energy consumption. This is a factor that should be taken into account for future developments or energy renovations for these types of buildings and introduces a path for rethinking the shading devices in office buildings.

This research highlights the fact that the way of conceiving SDs in buildings should be changed. Nowadays, the needs for energy and for the reduction of conventional energy sources in the building sector are high. Shading devices can be considered as valuable machines of energy balance. Their geometric characteristics are a result of the avoidance of incident solar radiation in the interior, reduction of cooling, thermal and electricity loads and the maximization of energy production through the integrated PV.

The way that SDs used to be designed has to be changed. It is a new parameter that should be further developed by the building industry, PVs industry and research institutes, in order for this type of product to enter the building market. For a more definitive conclusion regarding the use of SDs as valuable machines of improvement of the quality of interior space in office buildings, with less energy consumption, further research needs to be done: it will include more quantitative measurements of the SD, plus other, qualitative ones. We recommend a cost/benefit analysis of introducing SDs as well as a study on the aesthetic effects of the PV installation and their visual impact to the users. Additionally an assessment of visual contact with the outside, air infiltration rate through fenestration that each SD can provide should be done.

In relation to energy production values, further work could be done for shading devices of complex geometries with high amount of connected panels and for systems that use only diffuse solar radiation, in terms of accuracy of the resulting values in relation to real PV installations.

Moreover, further work on venetian blinds systems with integrated PV is suggested in order to increase their efficiency, in levels similar to those of simple inclined systems. Additional research of in situ measurements will be required in order to cover all cases of complicated geometries of shading devices as for example for systems with more than 30 modules connected in series and for cases that only diffuse radiation falls upon the PV panels. Besides, the system of Canopy Inclined Double that we conclude to perform well in terms of energy savings and daylight quality is actually a specific case of venetian blind system. It has only two blinds inclined.

Furthermore, experimental work is needed to evaluate movable shading systems that are considered to be more efficient in terms of daylight quality and quantity and have the potential to be more energy producing.

User acceptance studies are needed in order to validate the results, especially for the cases of visual comfort conditions, glare problems in different positions within the room and view contact to the exterior in relation to the PV material and geometry used.

7.4. Closing remarks

The main objectives of this research are presented in the introduction and concern the evaluation of different geometrical configurations of shading systems and the assessment of different methods used in relation to the required details of the design stage.

In order to follow these objectives some statements achieved by other researchers were rejected and some others were confirmed.

One basic assumption used in the research and still in dispute among researchers involved in the assessment of shading systems is that fixed external shading systems are user accepted more than movable shading systems. This is the main reason why we are assessing fixed shading systems with integrated PV.

Some new statements have been achieved within the framework of this research:

- The shading systems of Surrounding Shade and of Canopy Inclined Double with integrated framed PV are the best performing in terms of energy Savings and Visual Comfort conditions. Especially the system of Canopy Inclined Double has high degree of efficiency in relation to the PV area installed.
- Fixed Horizontal Louvers of glass with integrated PV performs very well in terms of Visual Interior conditions. On the other hand it performs poorly in relation to energy production and energy needs.
- Generally we show that different types of systems perform well for different needs. The preferred selected Shading System depends on the design stage, the priorities of the design and the factors examined.

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Appendix A

Basic Standard Skies

There are fifteen types of Sky as introduced by the CIE. We are mainly focusing on four of them. These are the following:

Clear sky

The luminance of the standard CIE clear sky varies over both, altitude and azimuth. It is brightest around the sun and dimmest opposite it. The brightness of the horizon lies in between those two extremes.

Intermediate sky

The standard CIE intermediate sky is a somewhat hazy variant of the clear sky. The sun is not as bright as with the clear sky and the brightness changes are not as drastic.

Overcast sky

The luminance of the standard CIE overcast sky changes with altitude. It is three times as bright in the zenith as it is near the horizon. The overcast sky is used when measuring daylight factors. It can be modelled under an artificial sky.

Uniform sky

The standard uniform sky is characterised by a uniform luminance that does not change with altitude or azimuth. It is a remains from the days when calculations were done by hand or with tables. Today, it is still used for Rights of Light cases.

Differences between Physical model and Simulations

Differences in the Results

"Differences that may arise between measured and modelled sky luminance patterns can result from one or both of the following:

1. The model was unable to reproduce the underlying continuous luminance pattern of the measured sky.

2. The underlying luminance pattern of the measured sky may have been accurately reproduced, but the model did not account for the random-discontinuous features that were present in the measurements.” (Mardaljevic, 1999)

Comparison of Physical Model to simulated one (Radiance) –

The difference of solar time and clock time

LAT
35N LOG 24 E
For Crete when the sun is on the highest point the clock shows
11.36
For every 15 degrees there is 1 hour difference
Every 1 degree there is 4 min difference

The Difference of Magnetic North to the real one

We used a magnetic compass for orient our model. The difference of the magnetic North to the real one is 8° degrees for Crete. So from the Compass’ North the real one is 8 degrees to the east.

PV Shading Types defined:

Information concerns PV comes from the Kyocera website (www.kyocerasolar.com) and Schuco Technical Data (www.schuco–usa.com)

Fresnel’s equation

The **Fresnel equations** (or Fresnel conditions), deduced by Augustin-Jean Fresnel describe the behaviour of light when moving between media of differing refractive indices. The reflection of light that the equations predict is known as **Fresnel reflection**.

When light moves from a medium of a given refractive index n_1 into a second medium with refractive index n_2, both reflection and refraction of the light may occur. The Fresnel equations describe what fraction of the light is reflected and what fraction is refracted (i.e., transmitted). They also describe the phase shift of the reflected light.

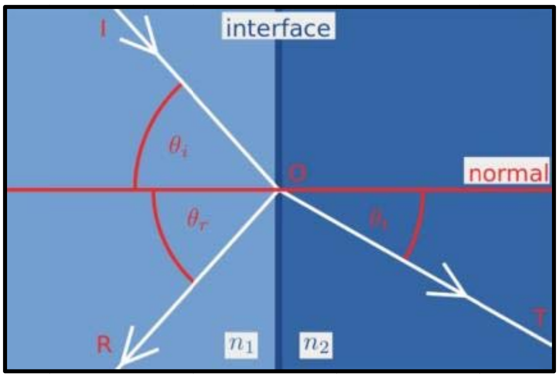


Fig. A.1. Variables used in the Fresnel equations.

The equations assume the interface is flat, planar, and homogeneous, and that the light is a plane wave.

In the diagram on the right, an incident light ray **IO** strikes the interface between two media of refractive indices n_1 and n_2 at point **O**. Part of the ray is reflected as ray **OR** and part refracted as ray **OT**. The angles that the incident, reflected and refracted rays make to the normal of the interface are given as ϑ_i, ϑ_r and ϑ_t, respectively.

The relationship between these angles is given by the law of reflection:

$$\theta_\mathrm{i} = \theta_\mathrm{r}$$

and Snell's law:

$$\frac{\sin\theta_\mathrm{i}}{\sin\theta_\mathrm{t}} = \frac{n_2}{n_1}$$

Source: http://en.wikipedia.org/wiki/File:Fresnel.svg (accessed 28.1.2013)

EnergyPlus Engineering reference

Wavelengths (microns) corresponding to above data block
0.3000,0.3050,0.3100,0.3150,0.3200,0.3250,0.3300,0.3350,0.3400,0.3450,
0.3500,0.3600,0.3700,0.3800,0.3900,0.4000,0.4100,0.4200,0.4300,0.4400,
0.4500,0.4600,0.4700,0.4800,0.4900,0.5000,0.5100,0.5200,0.5300,0.5400,
0.5500,0.5700,0.5900,0.6100,0.6300,0.6500,0.6700,0.6900,0.7100,0.7180,
0.7244,0.7400,0.7525,0.7575,0.7625,0.7675,0.7800,0.8000,0.8160,0.8237,
0.8315,0.8400,0.8600,0.8800,0.9050,0.9150,0.9250,0.9300,0.9370,0.9480,
0.9650,0.9800,0.9935,1.0400,1.0700,1.1000,1.1200,1.1300,1.1370,1.1610,
1.1800,1.2000,1.2350,1.2900,1.3200,1.3500,1.3950,1.4425,1.4625,1.4770,
1.4970,1.5200,1.5390,1.5580,1.5780,1.5920,1.6100,1.6300,1.6460,1.6780,
1.7400,1.8000,1.8600,1.9200,1.9600,1.9850,2.0050,2.0350,2.0650,2.1000,
2.1480,2.1980,2.2700,2.3600,2.4500,2.4940,2.5370

Table 27: Photopic response function.

Photopic response function values corresponding to wavelengths in following data block. Based on CIE 1931 observer; ISO/CIE 10527, CIE Standard Calorimetric Observers; derived from Optics5 data file "CIE 1931 Color Match from E308.txt", which is the same as WINDOW4 file Cie31t.dat.
0.0000,0.0001,0.0001,0.0002,0.0004,0.0006,0.0012,0.0022,0.0040,0.0073,
0.0116,0.0168,0.0230,0.0298,0.0380,0.0480,0.0600,0.0739,0.0910,0.1126,
0.1390,0.1693,0.2080,0.2586,0.3230,0.4073,0.5030,0.6082,0.7100,0.7932,
0.8620,0.9149,0.9540,0.9803,0.9950,1.0000,0.9950,0.9786,0.9520,0.9154,
0.8700,0.8163,0.7570,0.6949,0.6310,0.5668,0.5030,0.4412,0.3810,0.3210,
0.2650,0.2170,0.1750,0.1382,0.1070,0.0816,0.0610,0.0446,0.0320,0.0232,
0.0170,0.0119,0.0082,0.0158,0.0041,0.0029,0.0021,0.0015,0.0010,0.0007,
0.0005,0.0004,0.0002,0.0002,0.0001,0.0001,0.0001,0.0000,0.0000,0.0000,
0.0000 /
Wavelengths (microns) corresponding to above data block
.380,.385,.390,.395,.400,.405,.410,.415,.420,.425,
.430,.435,.440,.445,.450,.455,.460,.465,.470,.475,
.480,.485,.490,.495,.500,.505,.510,.515,.520,.525,
.530,.535,.540,.545,.550,.555,.560,.565,.570,.575,
.580,.585,.590,.595,.600,.605,.610,.615,.620,.625,
.630,.635,.640,.645,.650,.655,.660,.665,.670,.675,
.680,.685,.690,.695,.700,.705,.710,.715,.720,.725,
.730,.735,.740,.745,.750,.755,.760,.765,.770,.775,
.780

Calculation of Angular Properties

Calculation of optical properties is divided into two categories: uncoated glass and coated glass.

Angular Properties for Uncoated Glass

The following discussion assumes that optical quantities such as transmissivity, reflectvity, absorptivity, and index of refraction are a function of wavelength, λ. If there are no spectral data the angular dependence is calculated based on the single values for transmittance and reflectance in the visible and solar range. In the visible range an average wavelength of 0.575 microns is used in the calculations. In the solar range an average wavelength of 0.898 microns is used.

The spectral data include the transmittance, T, and the reflectance, R. For uncoated glass the reflectance is the same for the front and back surfaces. For angle of incidence, ϕ, the transmittance and reflectance are related to the transmissivity, τ, and reflectivity, ρ, by the following relationships:

$$T(\phi) = \frac{\tau(\phi)^2 e^{-\alpha d/\cos\phi'}}{1-\rho(\phi)^2 e^{-2\alpha d/\cos\phi'}} \quad (170)$$

$$R(\phi) = \rho(\phi)\left(1+T(\phi)e^{-\alpha d/\cos\phi'}\right) \quad (171)$$

The spectral reflectivity is calculated from Fresnel's equation assuming unpolarized incident radiation:

$$\rho(\phi) = \frac{1}{2}\left(\left(\frac{n\cos\phi-\cos\phi'}{n\cos\phi+\cos\phi'}\right)^2 + \left(\frac{n\cos\phi'-\cos\phi}{n\cos\phi'+\cos\phi}\right)^2\right) \quad (172)$$

The spectral transmittivity is given by

$$\tau(\phi) = 1-\rho(\phi) \quad (173)$$

The spectral absorption coefficient is defined as

$$\alpha = 4\pi\kappa/\lambda \quad (174)$$

where κ is the dimensionless spectrally-dependent extinction coefficient and λ is the wavelength expressed in the same units as the sample thickness.
Solving Eq. (172) at normal incidence gives

$$n = \frac{1+\sqrt{\rho(0)}}{1-\sqrt{\rho(0)}} \quad (175)$$

Evaluating Eq. (171) at normal incidence gives the following expression for κ

$$\kappa = -\frac{\lambda}{4\pi d}\ln\frac{R(0)-\rho(0)}{\rho(0)T(0)} \quad (176)$$

Eliminating the exponential in Eqs. (170) and (171) gives the reflectivity at normal incidence:

$$\rho(0) = \frac{\beta-\sqrt{\beta^2-4(2-R(0))R(0)}}{2(2-R(0))} \quad (177)$$

where

$$\beta = T(0)^2 - R(0)^2 + 2R(0) + 1 \quad (178)$$

The value for the reflectivity, $\rho(0)$, from Eq. (177) is substituted into Eqs. (175) and (176). The result from Eq. (176) is used to calculate the absorption coefficient in Eq. (174). The index of refraction is used to calculate the reflectivity in Eq. (172) which is then used to calculate the transmittivity in Eq. (173). The reflectivity, transmissivity and absorption coefficient are then substituted into Eqs. (170) and (171) to obtain the angular values of the reflectance and transmittance.

Angular Properties for Coated Glass

A regression fit is used to calculate the angular properties of coated glass from properties at normal incidence. If the transmittance of the coated glass is > 0.645, the angular dependence of uncoated clear glass is used. If the transmittance of the coated glass is ≤ 0.645, the angular dependence of uncoated bronze glass is used. The values for the angular functions for the transmittance and reflectance of both clear glass $(\overline{\tau}_{clr}, \overline{\rho}_{clr})$ and bronze glass $(\overline{\tau}_{bnz}, \overline{\rho}_{bnz})$ are determined from a fourth-order polynomial regression:

$$\overline{\tau}(\phi) = \overline{\tau}_0 + \overline{\tau}_1 \cos(\phi) + \overline{\tau}_2 \cos^2(\phi) + \overline{\tau}_3 \cos^3(\phi) + \overline{\tau}_4 \cos^4(\phi)$$

and

$$\overline{\rho}(\phi) = \overline{\rho}_0 + \overline{\rho}_1 \cos(\phi) + \overline{\rho}_2 \cos^2(\phi) + \overline{\rho}_3 \cos^3(\phi) + \overline{\rho}_4 \cos^4(\phi) - \overline{\tau}(\phi)$$

The polynomial coefficients are given in Table 28.

Table 28: Polynomial coefficients used to determine angular properties of coated glass.

	0	1	2	3	4
$\overline{\tau}_{clr}$	-0.0015	3.355	-3.840	1.460	0.0288
$\overline{\rho}_{clr}$	0.999	-0.563	2.043	-2.532	1.054
$\overline{\tau}_{bnz}$	-0.002	2.813	-2.341	-0.05725	0.599
$\overline{\rho}_{bnz}$	0.997	-1.868	6.513	-7.862	3.225

These factors are used as follows to calculate the angular transmittance and reflectance:

For $T(0) > 0.645$:

$$T(\phi) = T(0)\overline{\tau}_{clr}(\phi)$$

$$R(\phi) = R(0)(1 - \overline{\rho}_{clr}(\phi)) + \overline{\rho}_{clr}(\phi)$$

For $T(0) \le 0.645$:

$$T(\phi) = T(0)\overline{\tau}_{bnz}(\phi)$$

$$R(\phi) = R(0)(1 - \overline{\rho}_{bnz}(\phi)) + \overline{\rho}_{bnz}(\phi)$$

Angular Properties for Simple Glazing Systems

When the glazing system is modeled using the simplified method, an alternate method is used to determine the angular properties. The equation for solar transmittance as a function of incidence angle, $T(\phi)$, is,

$$T(\phi)=T(\phi=0)\cos(\phi)\left(1+(0.768+0.817\,SHGC^4)\sin^3(\phi)\right)$$

where,

$T(\phi=0)$ is the normal incidence solar transmittance, T_{Sol}.

The equation for solar reflectance as a function of incidence angle, $R(\phi)$, is,

$$R(\phi)=\frac{R(\phi=0)\left(f_1(\phi)+f_2(\phi)\sqrt{SHGC}\right)}{R_{fit,o}}$$

where,

$$f_1(\phi)=\left(\left(\left(2.403\cos(\phi)-6.192\right)\cos(\phi)+5.625\right)\cos(\phi)-2.095\right)\cos(\phi)+1$$

$$f_2(\phi)=\left(\left(\left(-1.188\cos(\phi)+2.022\right)\cos(\phi)+0.137\right)\cos(\phi)-1.720\right)\cos(\phi)$$

$$R_{fit,o}=0.7413-\left(0.7396\sqrt{SHGC}\right)$$

Calculation of Hemispherical Values

The hemispherical value of a property is determined from the following integral:

$$P_{hemispherical}=2\int_0^{\frac{\pi}{2}}P(\phi)\cos(\phi)\sin(\phi)d\phi$$

The integral is evaluated by Simpson's rule for property values at angles of incidence from 0 to 90 degrees in 10-degree increments.

Optical Properties of Window Shading Devices

Shading devices affect the system transmittance and glass layer absorptance for short-wave radiation and for long-wave (thermal) radiation. The effect depends on the shade position (interior, exterior or between-glass), its transmittance, and the amount of inter-reflection between the shading device and the glazing. Also of interest is the amount of radiation absorbed by the shading device.

In EnergyPlus, shading devices are divided into four categories, "shades," "blinds," "screens," and "switchable glazing." "Shades" are assumed to be perfect diffusers. This means that direct radiation incident on the shade is reflected and transmitted as hemispherically uniform diffuse radiation: there is no direct component of transmitted radiation. It is also assumed that the transmittance, τ_{sh}, reflectance, ρ_{sh}, and absorptance, α_{sh}, are the same for the front and back of the shade and are independent of angle of incidence. Many types of drapery and pull-down roller devices are close to being perfect diffusers and can be categorized as "shades."

"Blinds" in EnergyPlus are slat-type devices such as venetian blinds. Unlike shades, the optical properties of blinds are strongly dependent on angle of incidence. Also, depending on slat angle and the profile angle of incident direct radiation, some of the direct radiation may pass between the slats, giving a direct component of transmitted radiation.

"Screens" are debris or insect protection devices made up of metallic or non-metallic materials. Screens may also be used as shading devices for large glazing areas where excessive solar gain is an issue. The EnergyPlus window screen model assumes the screen is composed of intersecting orthogonally-crossed cylinders, with the surface of the cylinders assumed to be diffusely reflecting. Screens may only be used on the exterior surface of a window construction. As with blinds, the optical properties affecting the direct component of transmitted radiation are dependent on the angle of incident direct radiation.

With "Switchable glazing," shading is achieved making the glazing more absorbing or more reflecting, usually by an electrical or chemical mechanism. An example is electrochromic glazing where the application of an electrical voltage or current causes the glazing to switch from light to dark.

Shades and blinds can be either fixed or moveable. If moveable, they can be deployed according to a schedule or according to a trigger variable, such as solar radiation incident on the window. Screens can be either fixed or moveable according to a schedule.

Shades

Shade/Glazing System Properties for Short-Wave Radiation

Short-wave radiation includes

1) Beam solar radiation from the sun and diffuse solar radiation from the sky and ground incident on the outside of the window,
2) Beam and/or diffuse radiation reflected from exterior obstructions or the building itself,
3) Solar radiation reflected from the inside zone surfaces and incident as diffuse radiation on the inside of the window,
4) Beam solar radiation from one exterior window incident on the inside of another window in the same zone, and
5) Short-wave radiation from electric lights incident as diffuse radiation on the inside of the window.

Exterior Shade

For an exterior shade we have the following expressions for the system transmittance, the effective system glass layer absorptance, and the system shade absorptance, taking inter-reflection between shade and glazing into account. Here, "system" refers to the combination of glazing and shade. The system properties are given in terms of the isolated shade properties (i.e., shade properties in the absence of the glazing) and the isolated glazing properties (i.e., glazing properties in the absence of the shade).

$$T_{sys}(\phi) = T_{1,N}^{dif} \frac{\tau_{sh}}{1 - R_f^{dif} \rho_{sh}}$$

$$T_{sys}^{dif} = T_{1,N}^{dif} \frac{\tau_{sh}}{1 - R_f^{dif} \rho_{sh}}$$

$$A_{j,f}^{sys}(\phi) = A_{j,f}^{dif} \frac{\tau_{sh}}{1 - R_f \rho_{sh}}, \qquad j = 1 \text{ to } N$$

$$A_{j,f}^{dif,sys} = A_{j,f}^{dif} \frac{\tau_{sh}}{1-R_f \rho_{sh}}, \qquad j = 1 \text{ to } N$$

$$A_{j,b}^{dif,sys} = A_{j,b}^{dif} \frac{T_{1,N}^{dif} \rho_{sh}}{1-R_f \rho_{sh}}, \qquad j = 1 \text{ to } N$$

$$\alpha_{sh}^{sys} = \alpha_{sh} \left(1 + \frac{\tau_{sh} R_f}{1-R_f \rho_{sh}} \right)$$

Interior Shade

The system properties when an interior shade is in place are the following.

$$T_{sys}(\phi) = T_{1,N}(\phi) \frac{\tau_{sh}}{1-R_b^{dif} \rho_{sh}}$$

$$T_{sys}^{dif} = T_{1,N}^{dif} \frac{\tau_{sh}}{1-R_b^{dif} \rho_{sh}}$$

$$A_{j,f}^{sys}(\phi) = A_{j,f}(\phi) + T_{1,N}(\phi) \frac{\rho_{sh}}{1-R_b^{dif} \rho_{sh}} A_{j,b}^{dif}, \qquad j = 1 \text{ to } N$$

$$A_{j,f}^{dif,sys} = A_{j,f}^{dif} + T_{1,N}^{dif} \frac{\rho_{sh}}{1-R_b^{dif} \rho_{sh}} A_{j,b}^{dif}, \qquad j = 1 \text{ to } N$$

$$A_{j,b}^{dif,sys} = \frac{\tau_{sh}}{1-R_b^{dif} \rho_{sh}} A_{j,b}^{dif}, \qquad j = 1 \text{ to } N$$

$$\alpha_{sh}^{sys}(\phi) = T_{1,N}(\phi) \frac{\alpha_{sh}}{1-R_b^{dif} \rho_{sh}}$$

$$\alpha_{sh}^{dif,sys} = T_{1,N}^{dif} \frac{\alpha_{sh}}{1-R_b^{dif} \rho_{sh}}$$

Long-Wave Radiation Properties of Window Shades

Long-wave radiation includes

- Thermal radiation from the sky, ground and exterior obstructions incident on the outside of the window,
- Thermal radiation from other room surfaces incident on the inside of the window, and
- Thermal radiation from internal sources, such as equipment and electric lights, incident on the inside of the window.

The program calculates how much long-wave radiation is absorbed by the shade and by the adjacent glass surface. The system emissivity (thermal absorptance) for an interior or exterior shade, taking into account reflection of long-wave radiation between the glass and shade, is given by

$$\varepsilon_{sh}^{lw,sys} = \varepsilon_{sh}^{lw}\left(1+\frac{\tau_{sh}^{lw}\rho_{gl}^{lw}}{1-\rho_{sh}^{lw}\rho_{gl}^{lw}}\right)$$

where ρ_{gl}^{lw} is the long-wave reflectance of the outermost glass surface for an exterior shade or the innermost glass surface for an interior shade, and it is assumed that the long-wave transmittance of the glass is zero.

The innermost (for interior shade) or outermost (for exterior shade) glass surface emissivity when the shade is present is

$$\varepsilon_{gl}^{lw,sys} = \varepsilon_{gl}^{lw}\frac{\tau_{sh}^{lw}}{1-\rho_{sh}^{lw}\rho_{gl}^{lw}}$$

Switchable Glazing

For switchable glazing, such as electrochromics, the solar and visible optical properties of the glazing can switch from a light state to a dark state. The switching factor, f_{switch}, determines what state the glazing is in. An optical property, p, such as transmittance or glass layer absorptance, for this state is given by

$$p = (1-f_{switch})p_{light} + f_{switch}p_{dark}$$

where

p_{light} is the property value for the unswitched, or light state, and p_{dark} is the property value for the fully switched, or dark state.

The value of the switching factor in a particular time step depends on what type of switching control has been specified: "schedule," "trigger," or "daylighting." If "schedule," f_{switch} = schedule value, which can be 0 or 1.

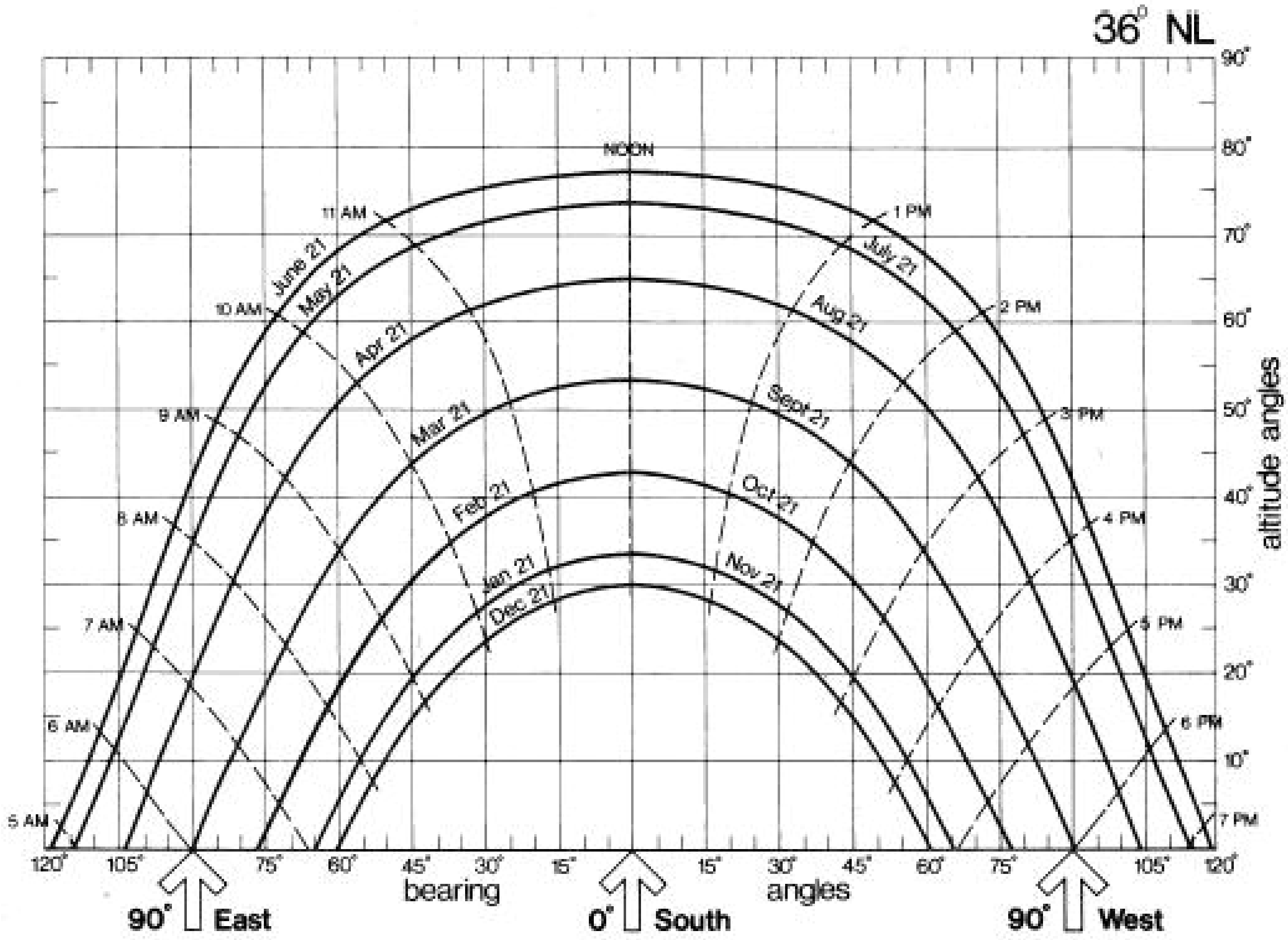
Thermochromic Windows

Thermochromic (TC) materials have active, reversible optical properties that vary with temperature. Thermochromic windows are adaptive window systems for incorporation into building envelopes. Thermochromic windows respond by absorbing sunlight and turning the sunlight energy into heat. As the thermochromic film warms it changes its light transmission level from less absorbing to more absorbing. The more sunlight it absorbs the lower the light level going through it. Figure 75 shows the variations of window properties with the temperature of the thermochromic glazing layer. By using the suns own energy the window adapts based solely on the directness and amount of sunlight. Thermochromic materials will normally reduce optical transparency by absorption and/or reflection, and are specular (maintaining vision).

Weather Data for the city of Chania

Station Longitude-latitude height							Chania, Crete 24° 02′ / 35° 3′ 62					
month	Solar hours	barometric pressure	Mean air temperature	Absolute maximum temperature	Absolute minimum temperature	relative Humidity	Average Cloudiness	rainfall	Wind direction	Total solar radiation on horizontal planes.	Diffuse solar radiation on horizontal planes	wind speed
	h	mm Hg	°C	°C	°C	%	8	mm				m/sec
1	111,7	1016,8	11,6	25,6	0,5	71,7	5,1	122,9	SW	62,1	33,1	3,2
2	128,9	1015,3	11,8	29,4	0	69,3	5	108,6	N	78,2	38,3	2,8
3	174,4	1015,1	13,2	34	0,4	68,4	4,4	71,9	SW	120,0	54,9	3
4	228,5	1013,3	16,3	35,8	5	65,4	3,5	31,9	NW	153,4	61,4	2,6
5	314,2	1014,1	20,1	38,6	8,5	62,2	2,8	13,9	NW	206,8	61,3	2,3
6	357,8	1013,3	24,5	40	13	55,8	1,3	6,6	NW	224,2	56,6	2,3
7	391,7	1012	26,5	42,5	16,6	55,3	0,6	0,5	NW	237,6	60,6	2,3
8	368,4	1012,4	26,1	41,2	12,5	57,7	0,6	2,7	NW	218,1	50,4	2,1
9	276,3	1015,3	23,3	39,6	10,5	63,9	1,6	18,2	N	163,2	43,8	2,1
10	183,8	1016,9	19,4	35,6	9,2	70,4	3,5	82,1	N	104,7	43,9	2
11	157,7	1018	16,1	35	2	72,2	4,2	70,9	N	75,1	32,7	2
12	115,4	1016,3	13,1	28,8	3,6	72,1	4,8	91,3	SW	57,4	29,7	2,6
total	2809							621,5		1700,6	566,9	

Sun path diagram for the latitude of Crete



Daylight glare probability (DGI)

Daylight glare probability (DGP) is a recently proposed discomfort glare index. This was proposed by Wienold and Christoffersen from laboratory studies in day lit spaces using 72 test subjects in Denmark and Germany. It is defined as:

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-5} \log\left(1 + \sum_i \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} P_i^2}\right)$$

Where:
E_v is the vertical illuminance at the eye level (lux)
L_s is the glare source luminance (cd/m2)
ω_s is the solid angle of the source
P_i is the position index

«*The validity of the equation is within the range of the tests, which means a DGP value between 0.2 and 0.8. In the author's point of view, calculated values higher than 0.8 could be trusted to some extent, since the comparison of 10 cases with the highest DGP-values also gave reasonable results (average DGP was 80% by having 100% disturbed persons). DGP values lower than 0.2 should not be used unless additional experiments confirm the validity of the equation in that region*» (Weinold & Christoffersen, 2006).

Dependence of the transmittance to the angle of incidence

The dependence of the transmittance to the angle of incidence can be seen in the following equations.

For example the **visible transmittance** at incident angle ϑ is defined as:
$\tau_{vis} (\vartheta) = \int D_{65} (\lambda) V (\lambda) \tau (\lambda,\theta) d\lambda$ where:

τ_{vis} it is the visible transmittance
$D_{65}(\lambda)$ is the spectral relative power distribution of the Commission Internationale de l' Eclairage (CIE) Standard illuminant and
$V (\lambda)$ it is the standard photopic luminous efficiency function

And the **solar transmittance** at incident angle ϑ is defined as:
$T_{sol} (\vartheta) = \int E_s(\lambda)\tau (\lambda,\vartheta) d\lambda$ where:
$E_s(\lambda)$ is the normalized spectral power distribution of solar radiation (Tzempelikos, 2008).

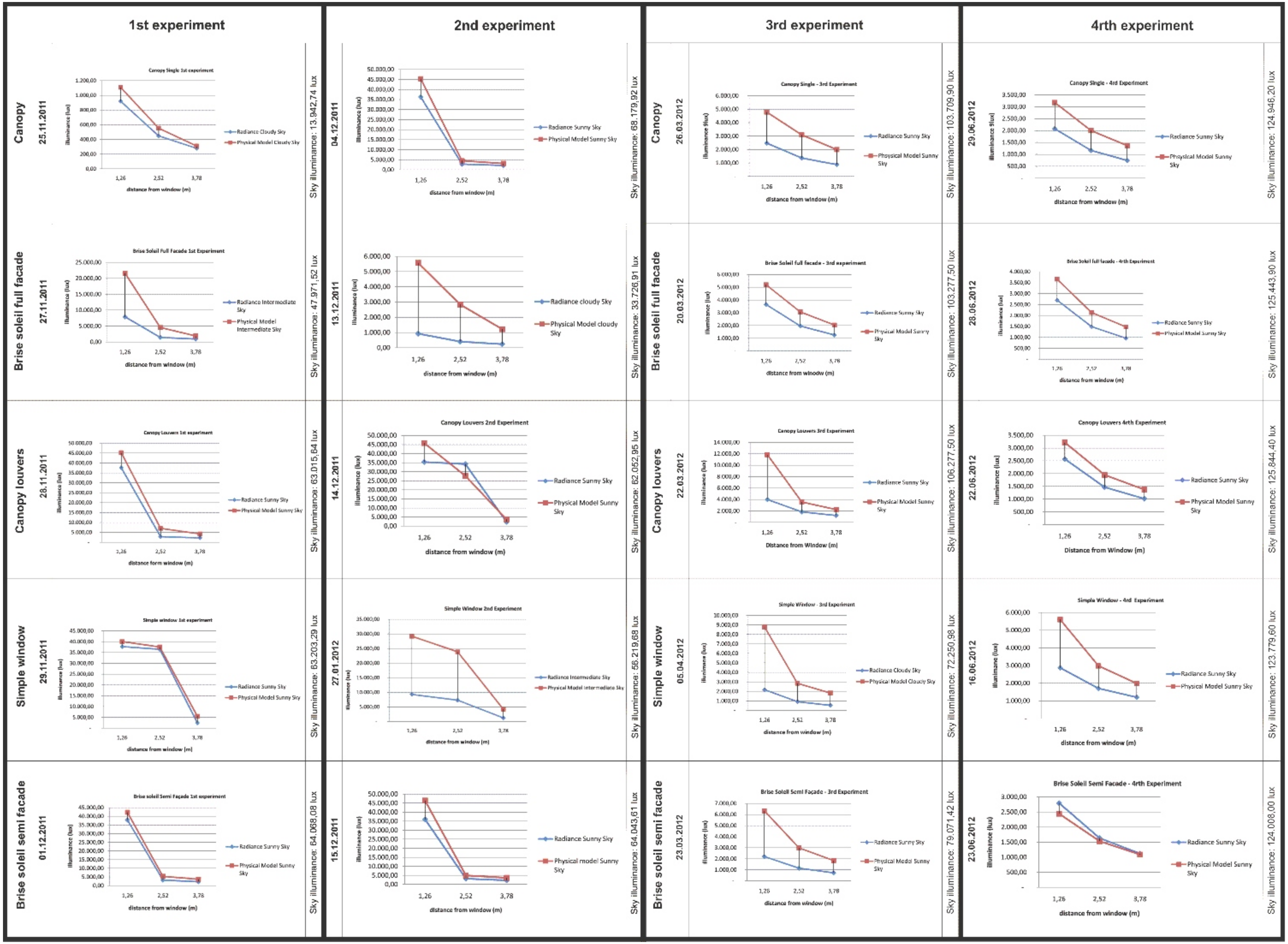
Solar thermal gain factor

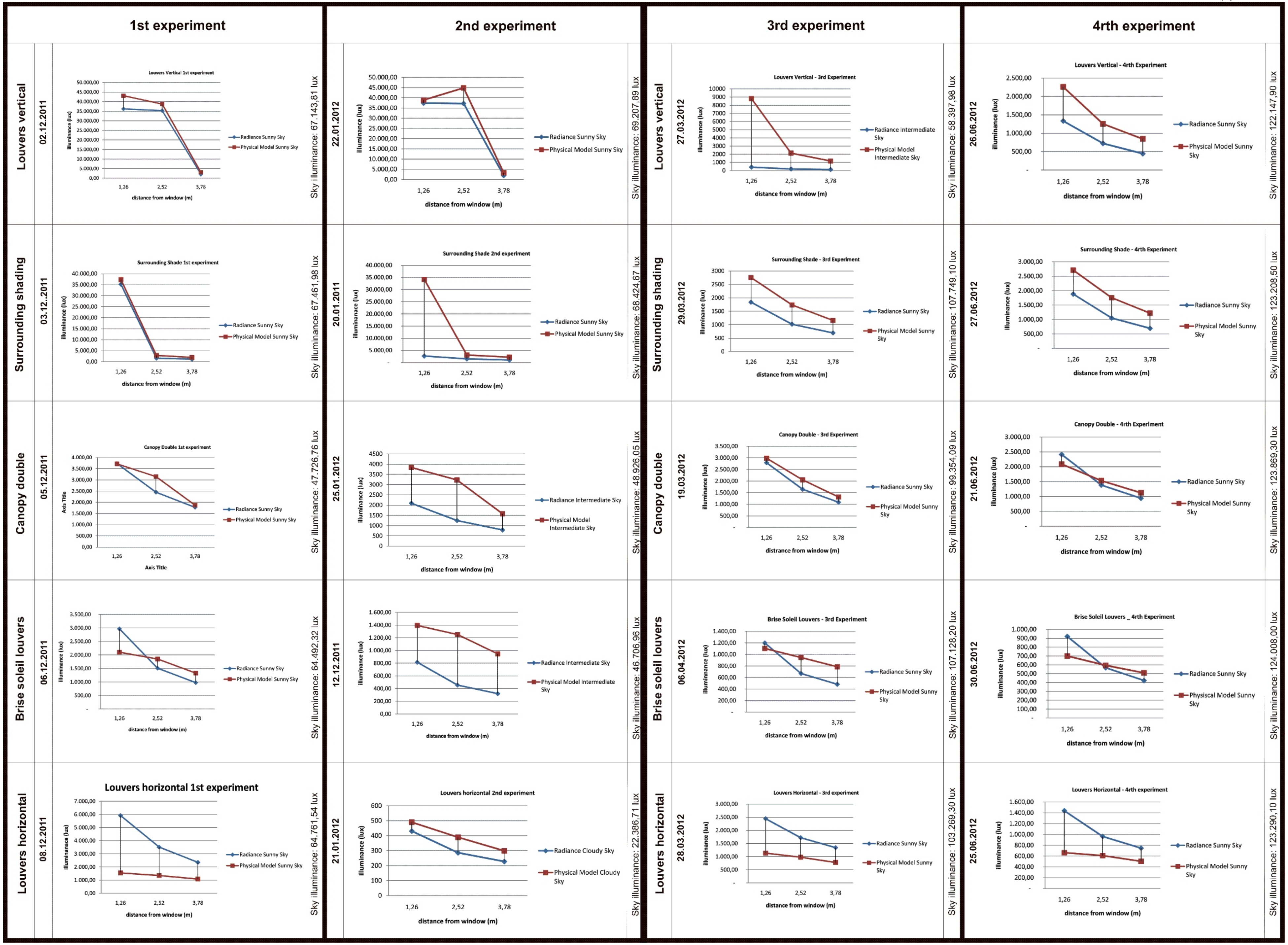
According to Greek legislation (Law 3661/2008, that followed the EU Directive 2002/91/EC on the Energy Performance of Buildings and the ISO (13790, 2008)) the **solar thermal gain factor (g_w)** is defined as:

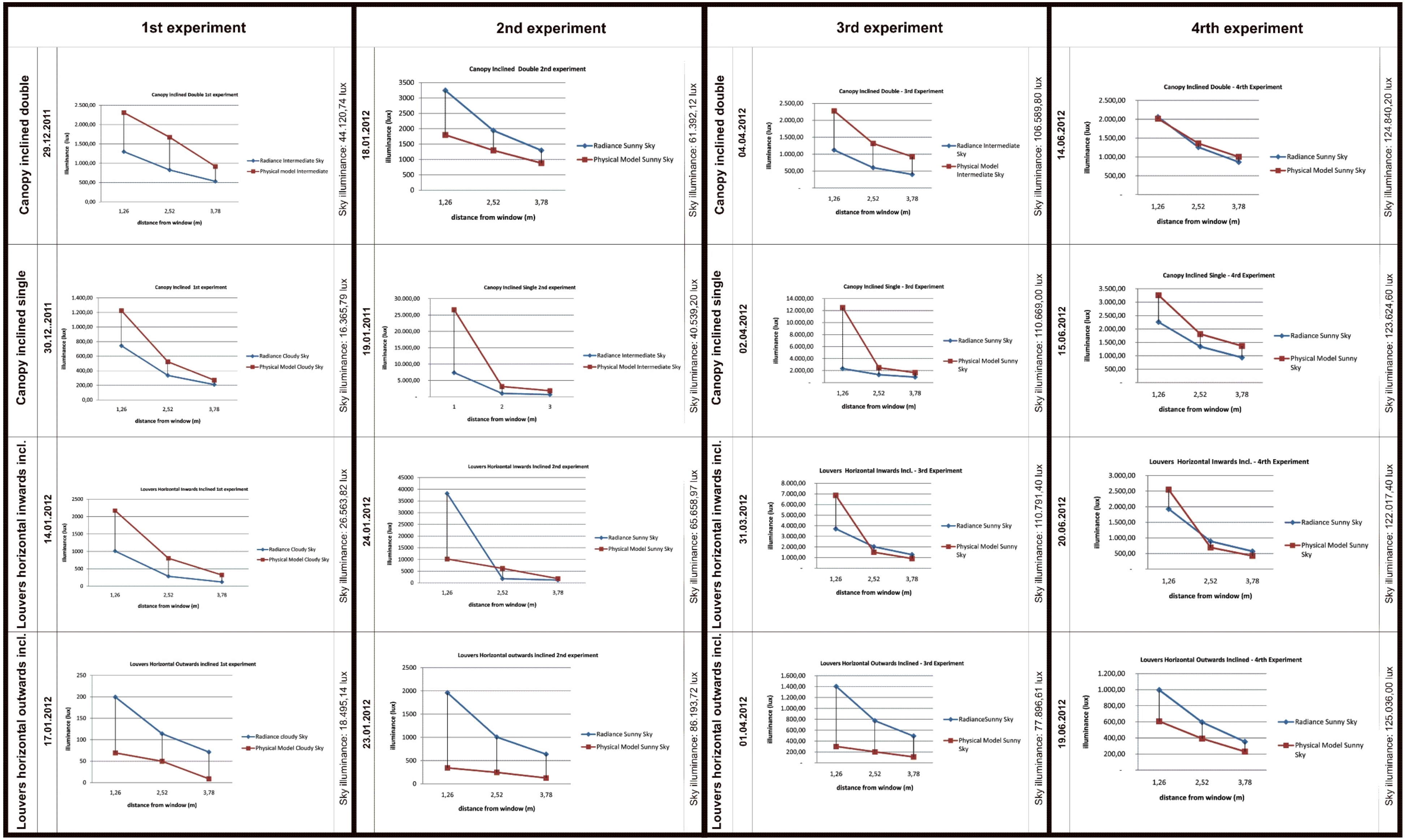
$g_w = g_{gl} (1 – F_f)$, where:

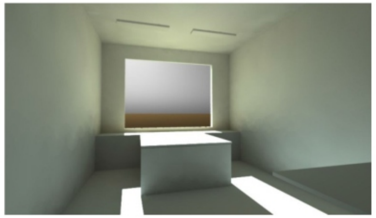
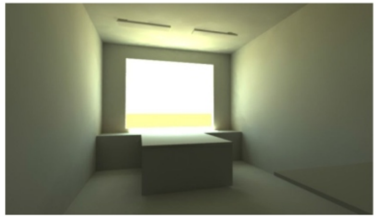
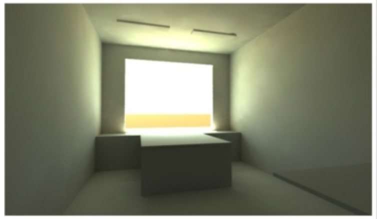
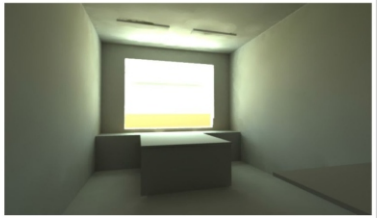
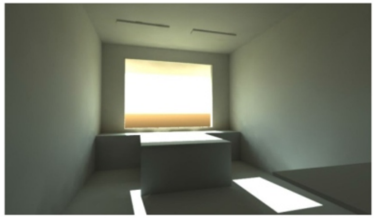
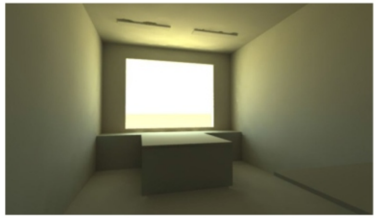
g_{gl} is the solar heat gain coefficient of the glazing and the
F_f is the percentage of the glazing in the opening
(Technical Chamber of Greece and Ministry of Environment, Energy and Climate Change, Technical Report, 2010, p. 1_66)

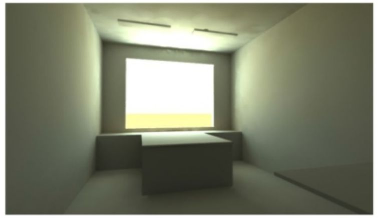
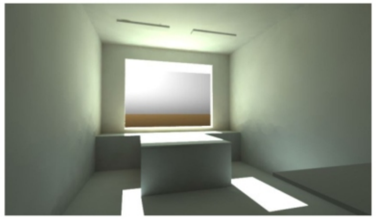
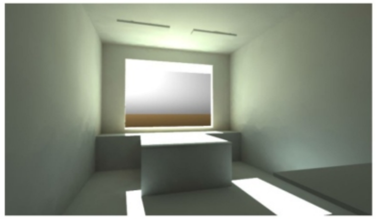
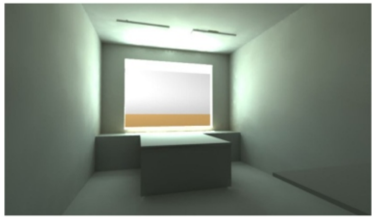
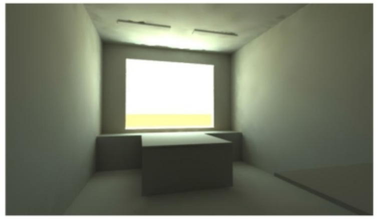
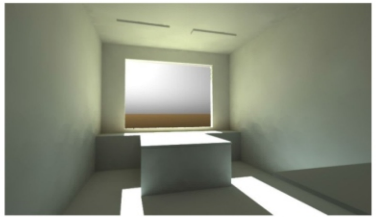
Appendix B

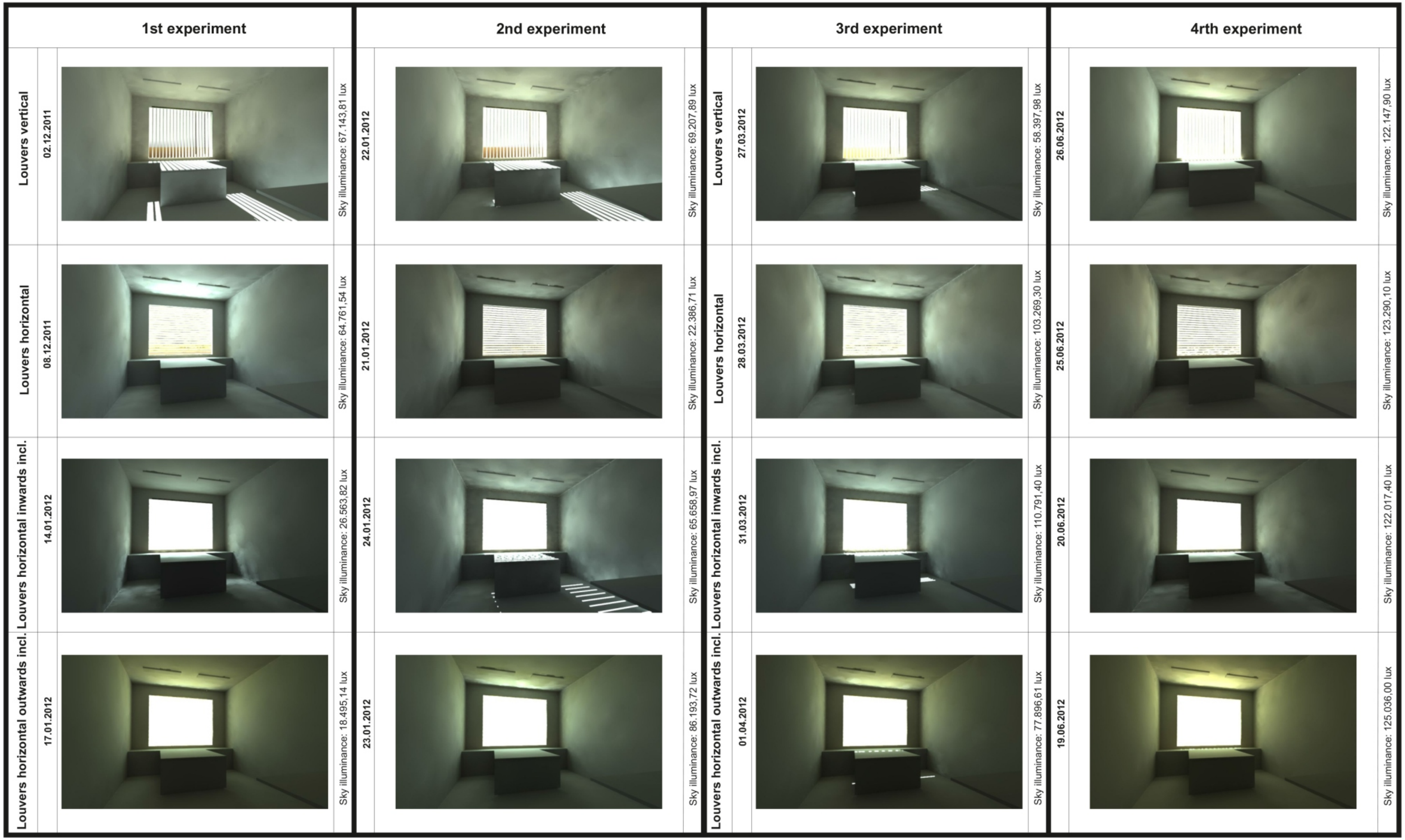

1st experiment
2nd experiment
3rd experiment
4rth experiment
Canopy
Brise soleil full facade
Canopy louvers
Simple window
Brise soleil semi facade
25.11.2011
Sky illuminance: 13.942,74 lux
04.12.2011
Sky illuminance: 68.179,92 lux
26.03.2012
Sky illuminance: 103.709,90 lux
29.06.2012
Sky illuminance: 124.946,20 lux
27.11.2011
Sky illuminance: 47.971,52 lux
13.12.2011
Sky illuminance: 33.726,91 lux
20.03.2012
Sky illuminance: 103.277,50 lux
28.06.2012
Sky illuminance: 125.443,90 lux
28.11.2011
Sky illuminance: 63.015,64 lux
14.12.2011
Sky illuminance: 62.052,95 lux
22.03.2012
Sky illuminance: 106.277,50 lux
22.06.2012
Sky illuminance: 125.844,40 lux
29.11.2011
Sky illuminance: 63.203,29 lux
27.01.2012
Sky illuminance: 56.219,68 lux
05.04.2012
Sky illuminance: 72.250,98 lux
16.06.2012
Sky illuminance: 123.779,60 lux
01.12.2011
Sky illuminance: 64.068,08 lux
15.12.2011
Sky illuminance: 64.043,61 lux
23.03.2012
Sky illuminance: 79.071,42 lux
23.06.2012
Sky illuminance: 124.008,00 lux
Canopy Louvers 2nd Experiment
Canopy Louvers 4rth Experiment
Brise Soleil Semi Facade - 4rth Experiment
distance from window (m)
Radiance Sunny Sky
Physical Model Sunny Sky
Radiance cloudy Sky
Physical Model cloudy Sky

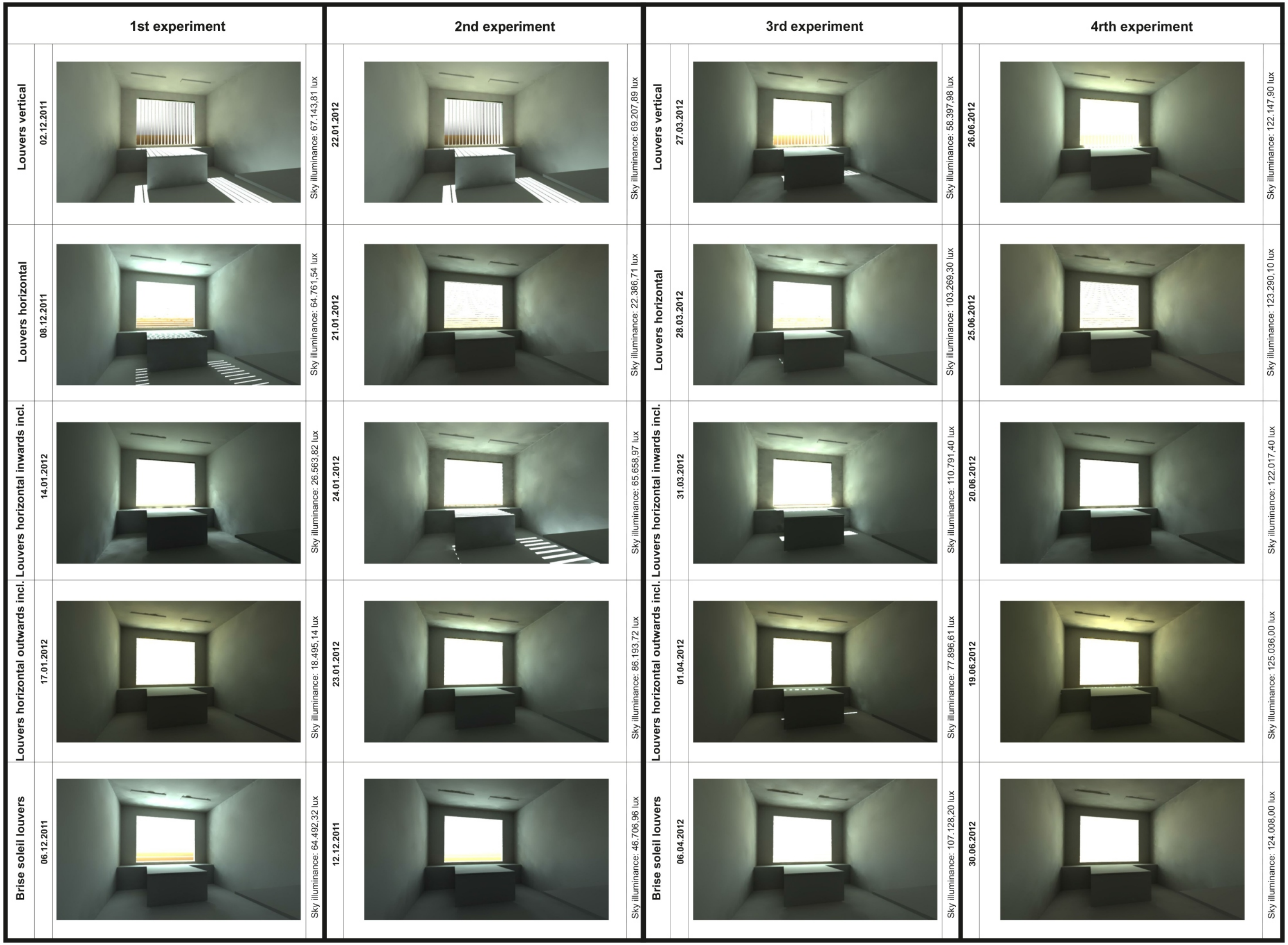

1st experiment
2nd experiment
3rd experiment
4rth experiment
Louvers vertical
02.12.2011
Louvers Vertical 1st experiment
Sky illuminance: 67.143,81 lux
22.01.2012
Sky illuminance: 69.207,89 lux
27.03.2012
Louvers Vertical - 3rd Experiment
Sky illuminance: 58.397,98 lux
26.06.2012
Louvers Vertical - 4rth Experiment
Sky illuminance: 122.147,90 lux
Surrounding shading
03.12..2011
Surrounding Shade 1st experiment
Sky illuminance: 67.461,98 lux
20.01.2011
Surrounding Shade 2nd experiment
Sky illuminance: 68.424,67 lux
29.03.2012
Surrounding Shade - 3rd Experiment
Sky illuminance: 107.749,10 lux
27.06.2012
Surrounding Shade - 4rth Experiment
Sky illuminance: 123.208,50 lux
Canopy double
05.12.2011
Canopy Double 1st experiment
Axis Title
Sky illuminance: 47.726,76 lux
25.01.2012
Sky illuminance: 48.926,05 lux
19.03.2012
Canopy Double - 3rd Experiment
Sky illuminance: 99.354,09 lux
21.06.2012
Canopy Double - 4rth Experiment
Sky illuminance: 123.869,30 lux
Brise soleil louvers
06.12.2011
Sky illuminance: 64.492,32 lux
12.12.2011
Sky illuminance: 46.706,96 lux
06.04.2012
Brise Soleil Louvers - 3rd Experiment
Sky illuminance: 107.128,20 lux
30.06.2012
Brise Soleil Louvers _ 4rth Experiment
Sky illuminance: 124.008,00 lux
Louvers horizontal
08.12.2011
Louvers horizontal 1st experiment
Sky illuminance: 64.761,54 lux
21.01.2012
Louvers horizontal 2nd experiment
Sky illuminance: 22.386,71 lux
28.03.2012
Louvers Horizontal - 3rd experiment
Sky illuminance: 103.269,30 lux
25.06.2012
Louvers Horizontal - 4rth experiment
Sky illuminance: 123.290,10 lux
Illuminance (lux)
distance from window (m)
1,26
2,52
3,78
Radiance Sunny Sky
Physical Model Sunny Sky
Radiance Intermediate Sky
Physical Model Intermediate Sky
Radiance Cloudy Sky
Physical Model Cloudy Sky


1st experiment
2nd experiment
3rd experiment
4rth experiment
Canopy inclined double
Canopy inclined single
Louvers horizontal inwards incl.
Louvers horizontal outwards incl.
29.12.2011
Canopy Inclined Double 1st experiment
Radiance Intermediate Sky
Physical model Intermediate
Sky illuminance: 44.120,74 lux
18.01.2012
Canopy Inclined Double 2nd experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 61.392,12 lux
04.04.2012
Canopy Inclined Double - 3rd Experiment
Radiance Intermediate Sky
Physical Model Intermediate Sky
Sky illuminance: 106.589,80 lux
14.06.2012
Canopy Inclined Double - 4rth Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 124.840,20 lux
30.12.2011
Canopy Inclined 1st experiment
Radiance Cloudy Sky
Physical Model Cloudy Sky
Sky illuminance: 16.365,79 lux
19.01.2011
Canopy Inclined Single 2nd experiment
Radiance Intermediate Sky
Physical Model Intermediate Sky
Sky illuminance: 40.539,20 lux
02.04.2012
Canopy Inclined Single - 3rd Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 110.669,00 lux
15.06.2012
Canopy Inclined Single - 4rd Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 123.624,60 lux
14.01.2012
Louvers Horizontal Inwards Inclined 1st experiment
Radiance Cloudy Sky
Physical Model Cloudy Sky
Sky illuminance: 26.563,82 lux
24.01.2012
Louvers Horizontal Inwards Inclined 2nd experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 65.658,97 lux
31.03.2012
Louvers Horizontal Inwards Incl. - 3rd Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 110.791,40 lux
20.06.2012
Louvers Horizontal Inwards Incl. - 4rth Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 122.017,40 lux
17.01.2012
Louvers Horizontal Outwards inclined 1st experiment
Radiance cloudy Sky
Physical Model Cloudy Sky
Sky illuminance: 18.495,14 lux
23.01.2012
Louvers Horizontal outwards Inclined 2nd experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 86.193,72 lux
01.04.2012
Louvers Horizontal Outwards Inclined - 3rd Experiment
RadianceSunny Sky
Physical Model Sunny Sky
Sky illuminance: 77.896,61 lux
19.06.2012
Louvers Horizontal Outwards Inclined - 4rth Experiment
Radiance Sunny Sky
Physical Model Sunny Sky
Sky illuminance: 125.036,00 lux
illuminance (lux)
distance from window (m)

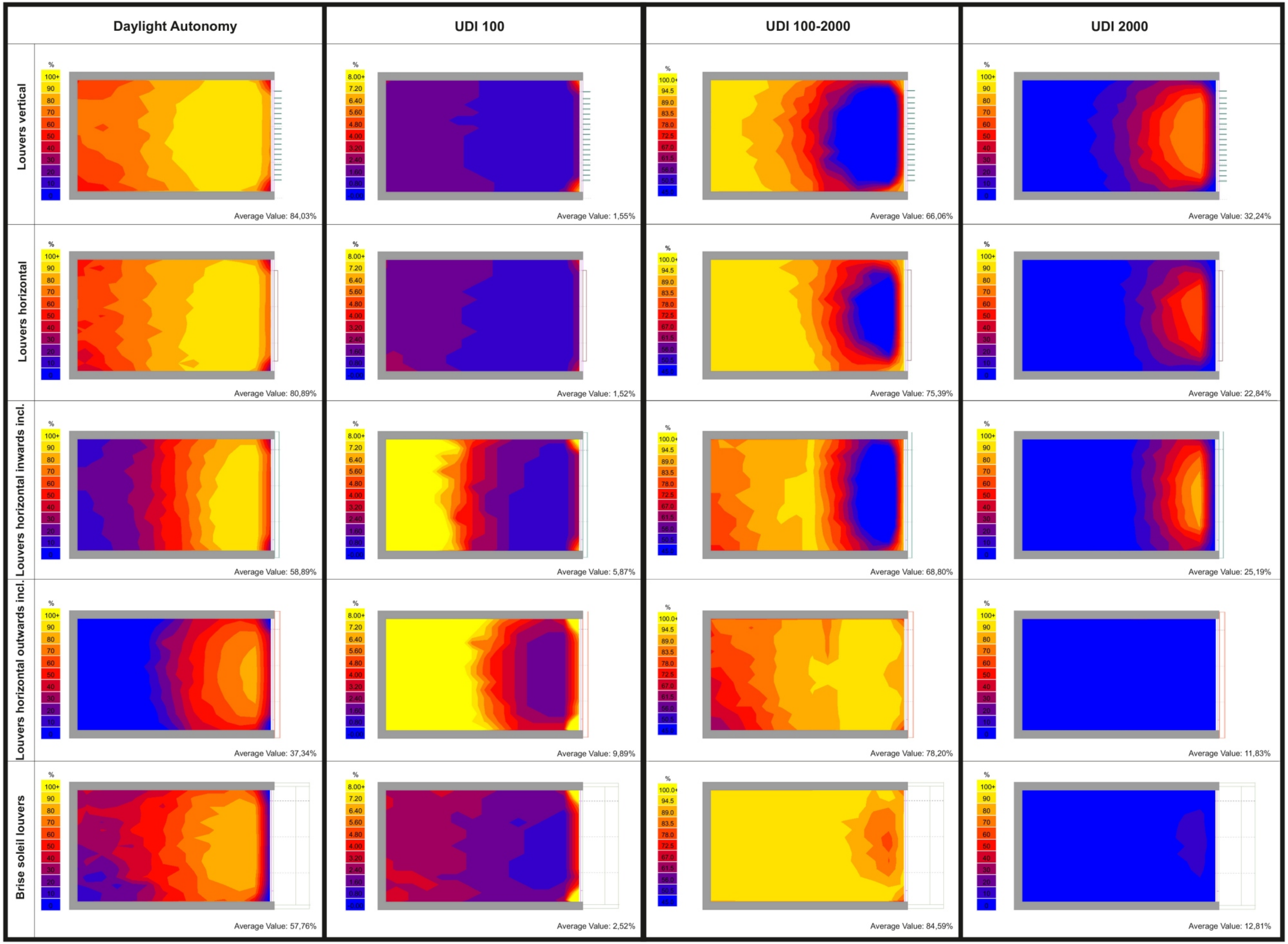
	1st experiment	2nd experiment	3rd experiment	4rth experiment
Simple Window	**29.11.2011**  Sky illuminance: 63.203,29 lux	**27.01.2012**  Sky illuminance: 56.219,68 lux	**05.04.2012**  Sky illuminance: 72.250,98 lux	**16.06.2012**  Sky illuminance: 123.779,60 lux
Canopy	**25.11.2011**  Sky illuminance: 13.942,74 lux	**04.12.2011**  Sky illuminance: 68.179,92 lux	**26.03.2012**  Sky illuminance: 103.709,90 lux	**29.06.2012**  Sky illuminance: 124.946,20 lux
Canopy Double	**05.12.2011**  Sky illuminance: 47.726,76 lux	**25.01.2012**  Sky illuminance: 48.926,05 lux	**19.03.2012**  Sky illuminance: 99.354,09 lux	**21.06.2012**  Sky illuminance: 123.869,30 lux
Canopy inclined single	**30.12.2011**  Sky illuminance: 16.365,79 lux	**19.01.2012**  Sky illuminance: 40.539,20 lux	**02.04.2012**  Sky illuminance: 110.669,00 lux	**15.06.2012**  Sky illuminance: 123.624,60 lux
Canopy inclined double	**29.12.2011**  Sky illuminance: 44.120,74 lux	**18.01.2012**  Sky illuminance: 61.392,12 lux	**04.04.2012**  Sky illuminance: 106.589,30 lux	**14.06.2012**  Sky illuminance: 124.840,20 lux

	1st experiment	2nd experiment	3rd experiment	4rth experiment
Brise soleil full facade	27.11.2011  Sky illuminance: 47.971,52 lux	13.12.2011  Sky illuminance: 33.726,91 lux	20.03.2012  Sky illuminance: 103.277,50 lux	28.06.2012  Sky illuminance: 125.443,90 lux
Brise soleil semi facade	01.12.2011  Sky illuminance: 64.068,08 lux	15.12.2011  Sky illuminance: 64.043,61 lux	23.03.2012  Sky illuminance: 79.071,42 lux	23.06.2012  Sky illuminance: 124.008,00 lux
Surrounding shading	03.12..2011  Sky illuminance: 67.461,98 lux	20.01.2011  Sky illuminance: 68.424,67 lux	29.03.2012  Sky illuminance: 107.749,10 lux	27.06.2012  Sky illuminance: 123.208,50 lux
Canopy louvers	28.11.2011  Sky illuminance: 63.015,64 lux	14.12.2011  Sky illuminance: 62.052,95 lux	22.03.2012  Sky illuminance: 106.277,50 lux	22.06.2012  Sky illuminance: 125.844,40 lux
Brise soleil louvers	06.12.2011  Sky illuminance: 64.492,32 lux	12.12.2011  Sky illuminance: 46.706,96 lux	06.04.2012  Sky illuminance: 107.128,20 lux	30.06.2012  Sky illuminance: 124.008,00 lux

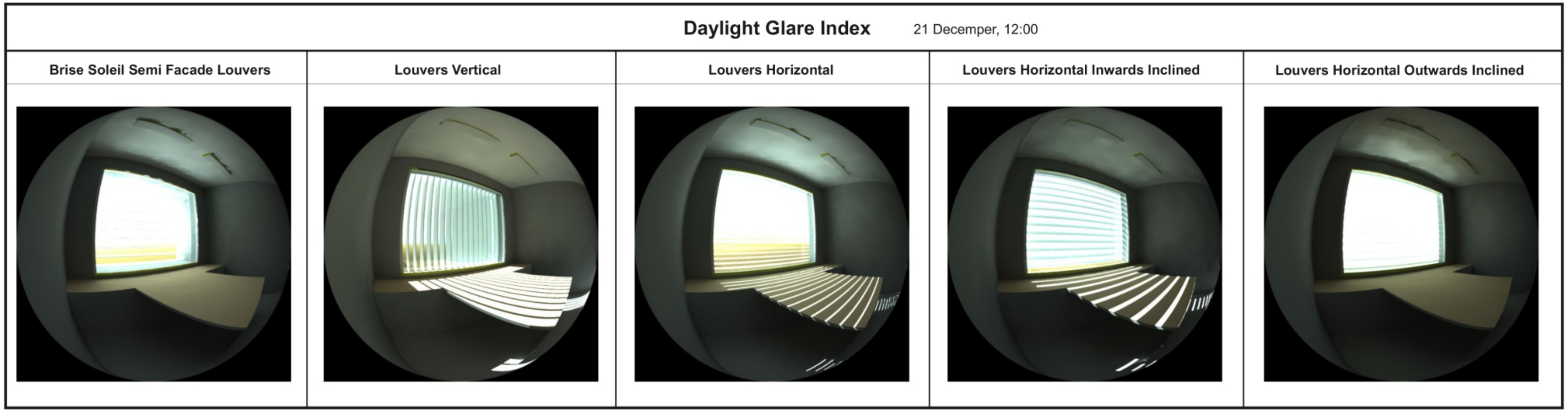

1st experiment
2nd experiment
3rd experiment
4rth experiment
Louvers vertical
02.12.2011
Sky illuminance: 67.143,81 lux
22.01.2012
Sky illuminance: 69.207,89 lux
27.03.2012
Sky illuminance: 58.397,98 lux
26.06.2012
Sky illuminance: 122.147,90 lux
Louvers horizontal
08.12.2011
Sky illuminance: 64.761,54 lux
21.01.2012
Sky illuminance: 22.386,71 lux
28.03.2012
Sky illuminance: 103.269,30 lux
25.06.2012
Sky illuminance: 123.290,10 lux
Louvers horizontal inwards incl.
14.01.2012
Sky illuminance: 26.563,82 lux
24.01.2012
Sky illuminance: 65.658,97 lux
31.03.2012
Sky illuminance: 110.791,40 lux
20.06.2012
Sky illuminance: 122.017,40 lux
Louvers horizontal outwards incl.
17.01.2012
Sky illuminance: 18.495,14 lux
23.01.2012
Sky illuminance: 86.193,72 lux
01.04.2012
Sky illuminance: 77.896,61 lux
19.06.2012
Sky illuminance: 125.036,00 lux



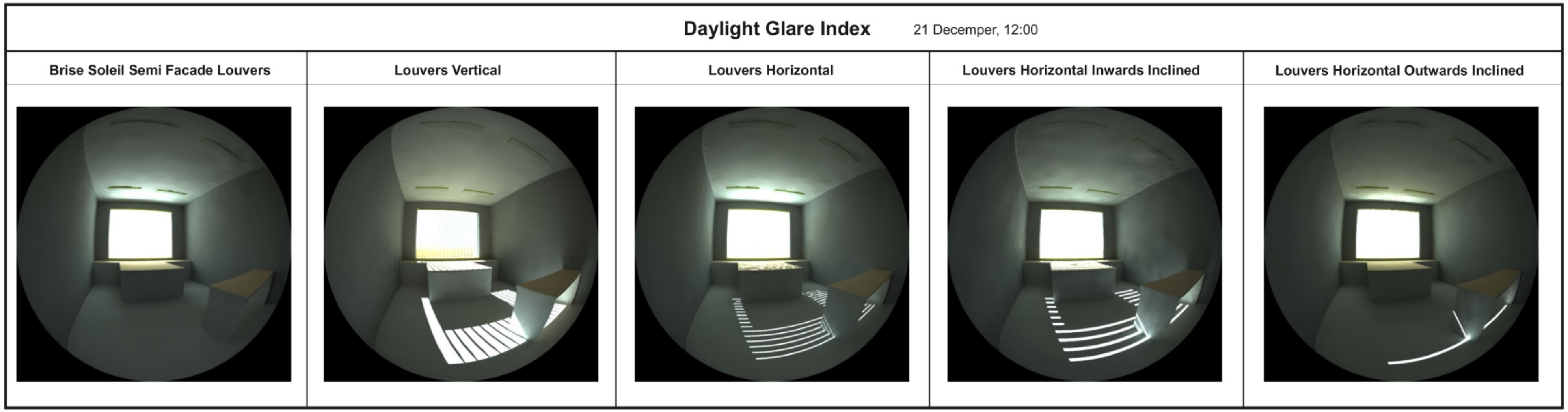
Simulations with radiance for louver systems of 1.5 cm thick



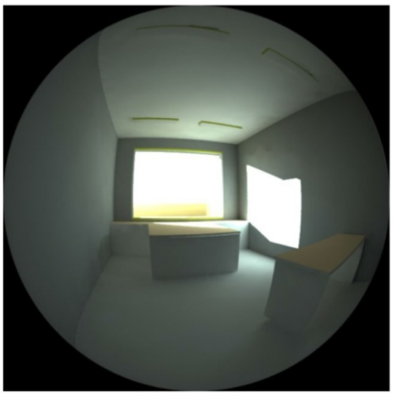
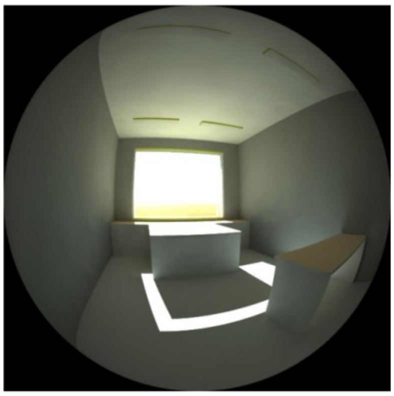
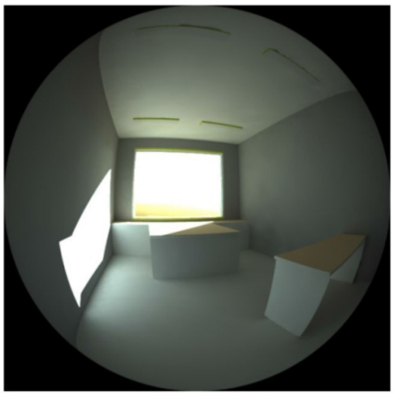
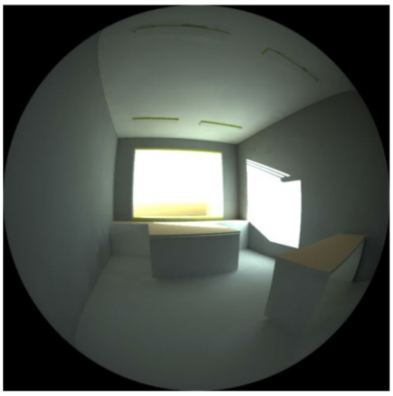
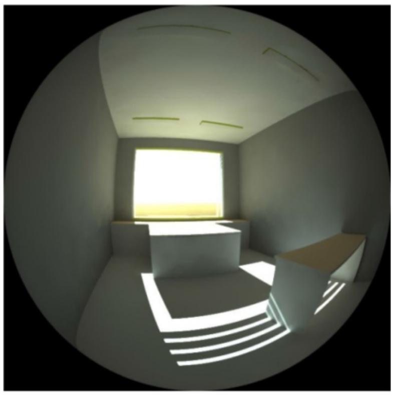
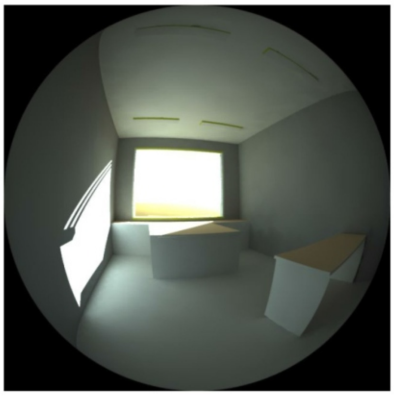
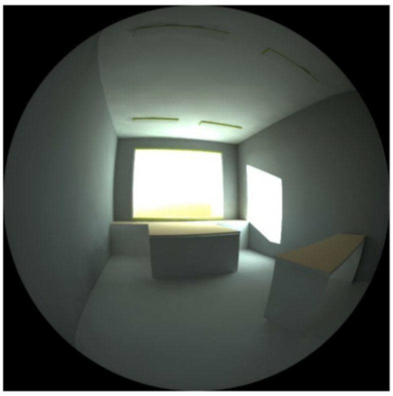
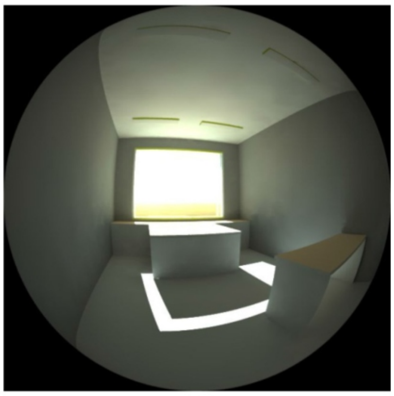
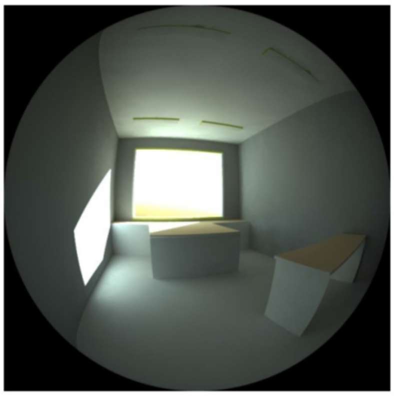
Simulations with Daysim for louver systems of 1.5 cm thick

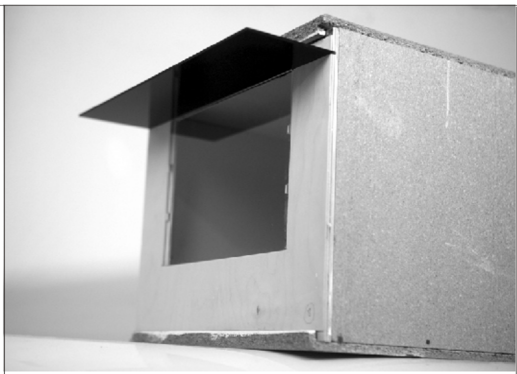
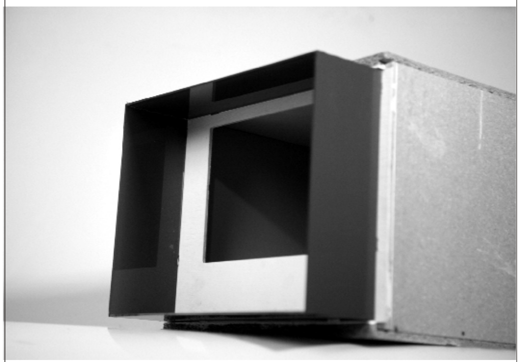
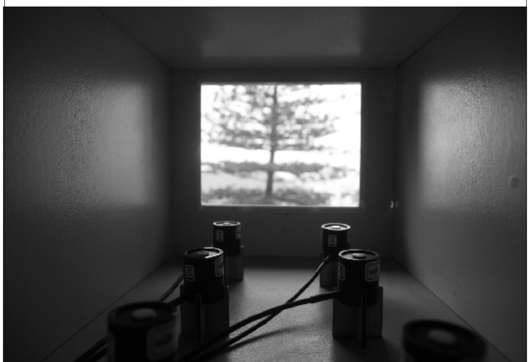
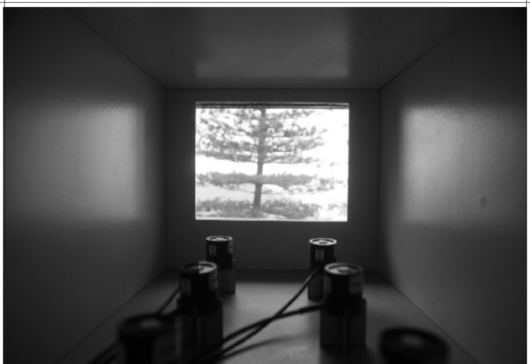
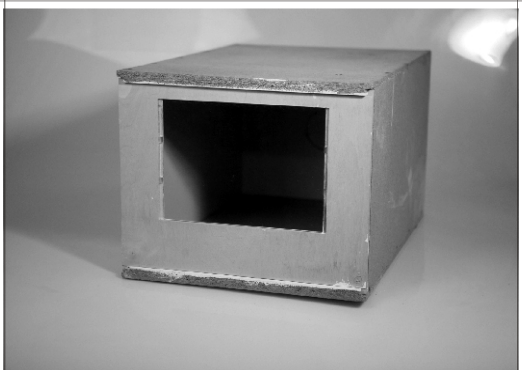
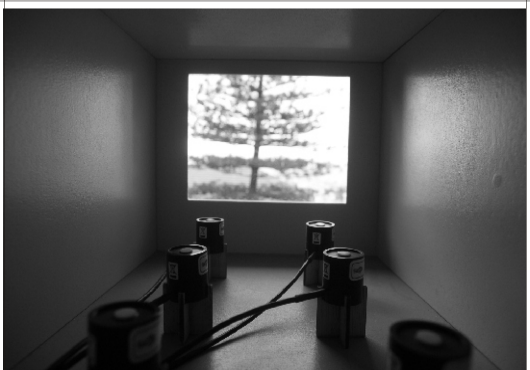
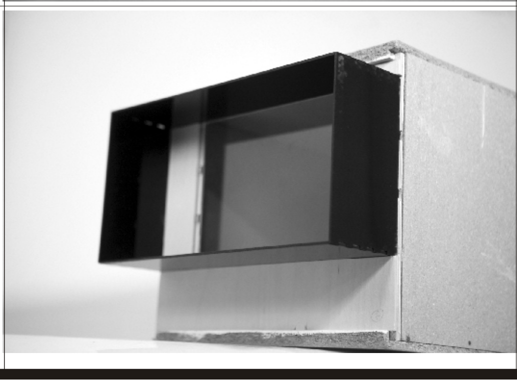


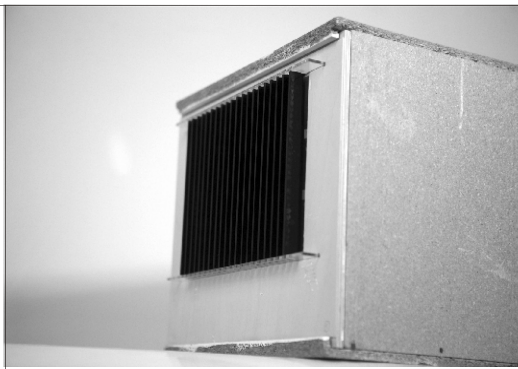
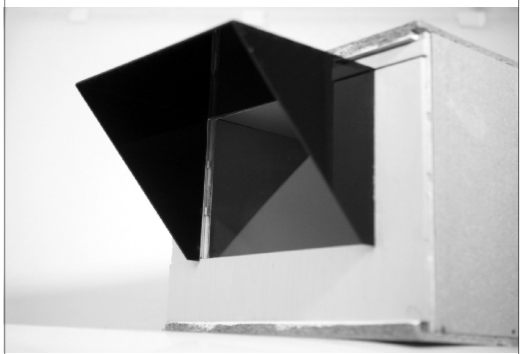
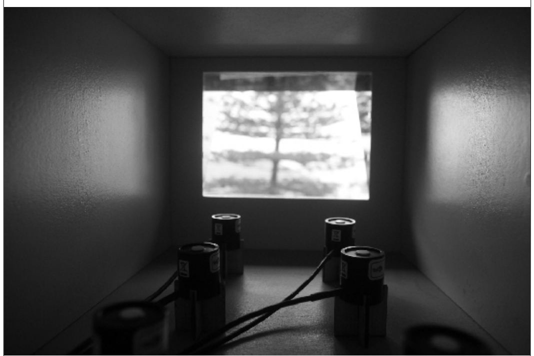
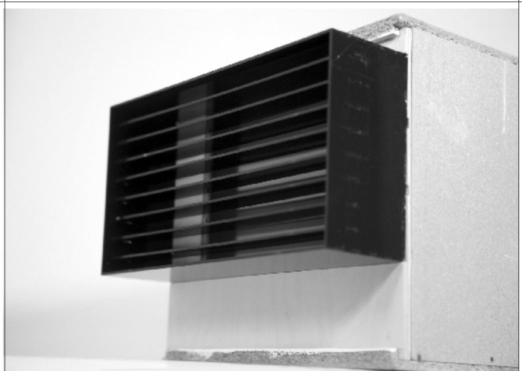
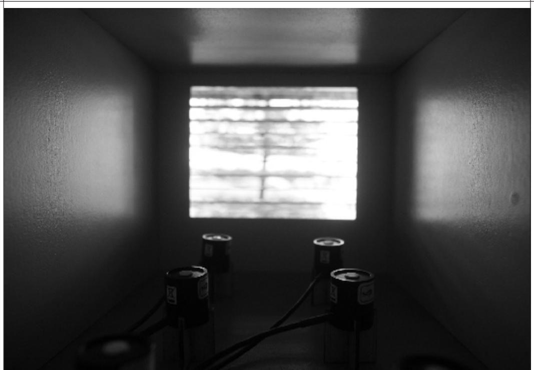
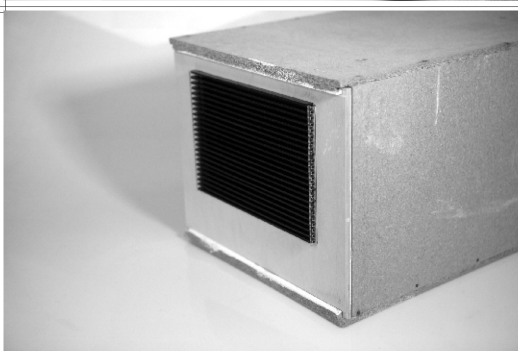
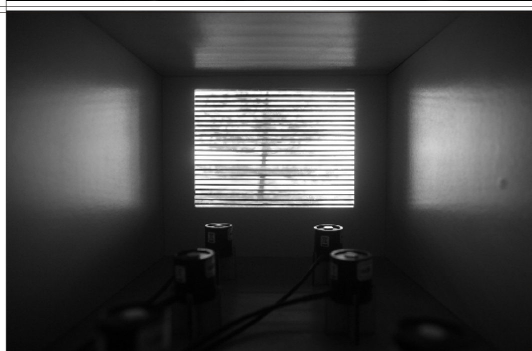
Simulations with Radiance for louver systems of 1.5 cm thick for positions near the window

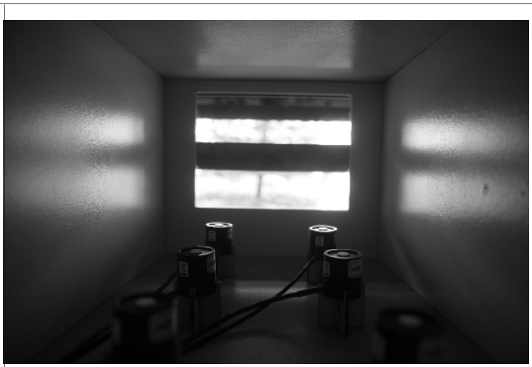
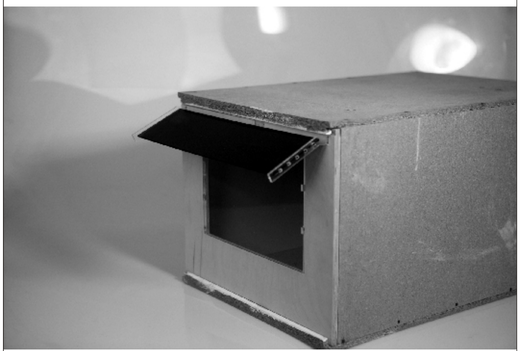
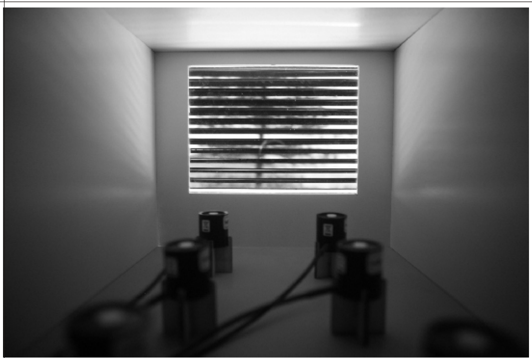
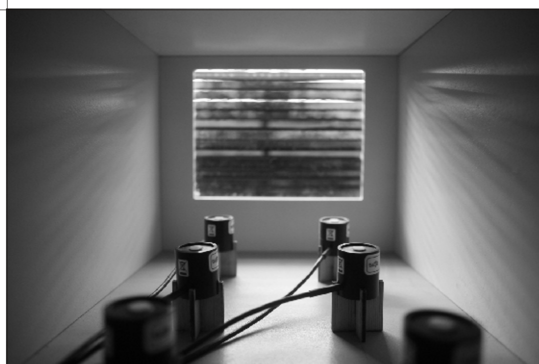


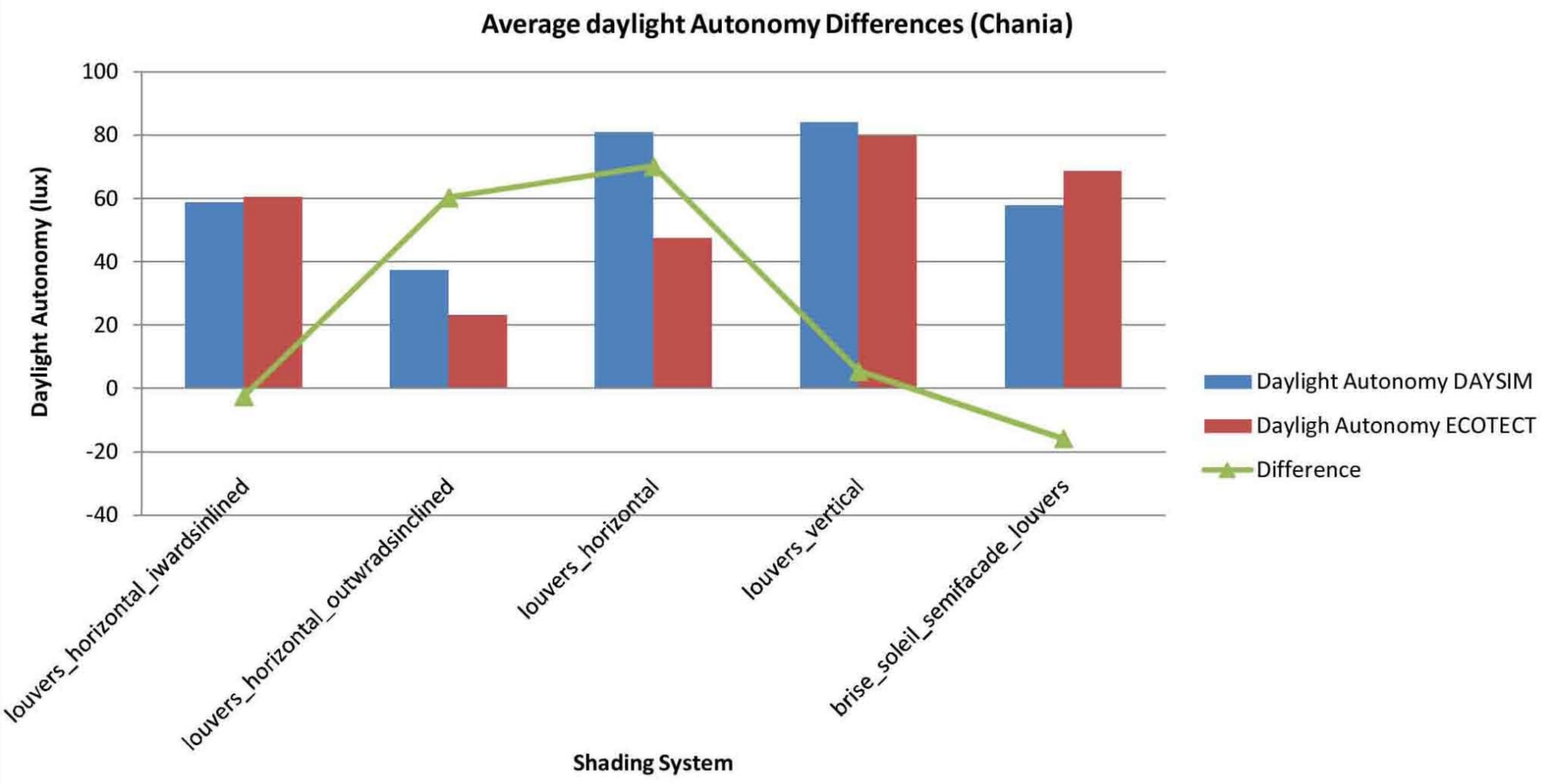
Simulations with Radiance for louver systems of 1.5 cm thick for positions away from the window

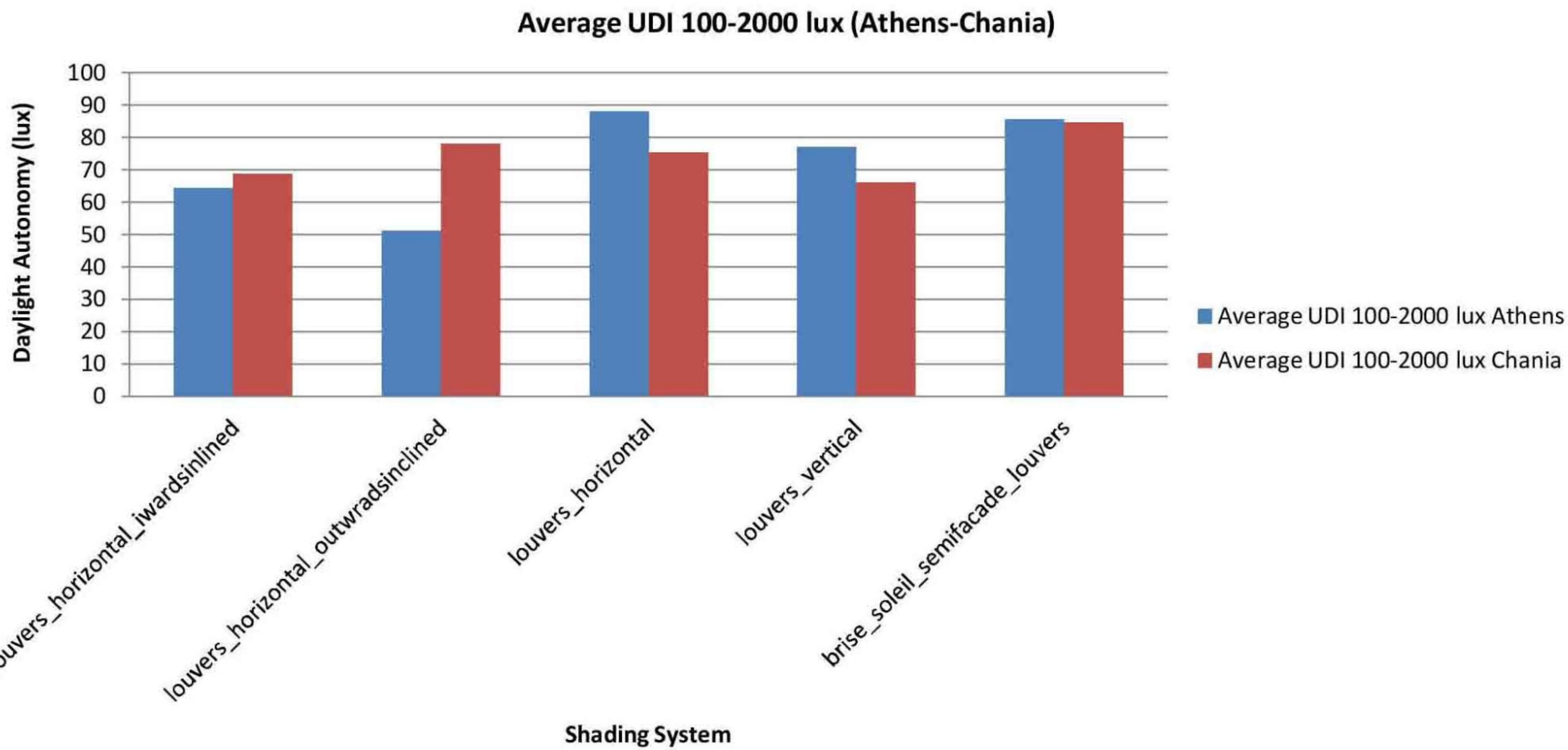
Daylight Glare Index 21 Decemper			
	09:00	12:00	15:00
Canopy Horizontal Single			
Canopy Horizontal Louvers			
Brise Soleil Full Facade			
Louvers Vertical			

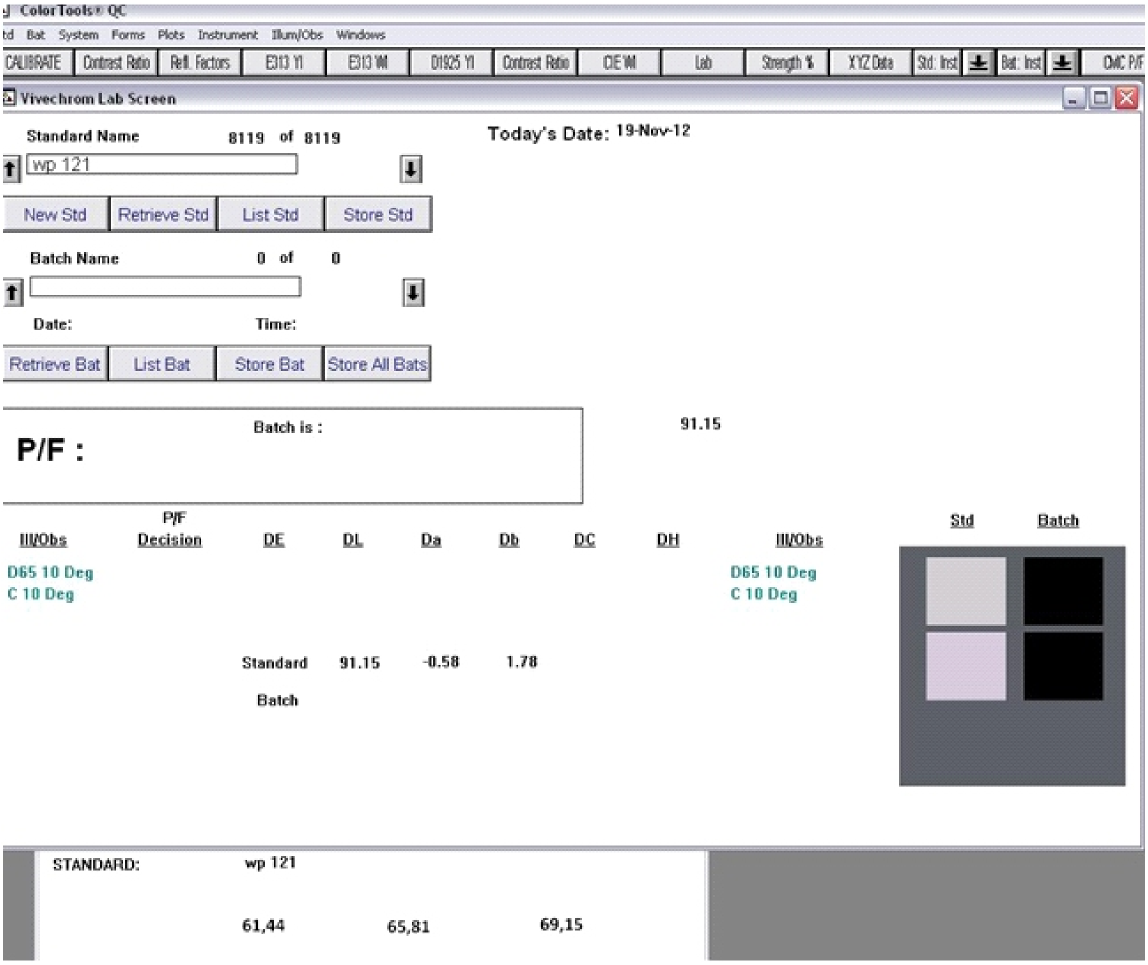
		External View	Interior View
Canopy	**24.12.2012**		
Brise soleil full facade	**27.11.2011**		
Canopy louvers	**28.11.2011**		
Simple window	**29.11.2011**		
Brise soleil semi facade	**01.12.2011**		

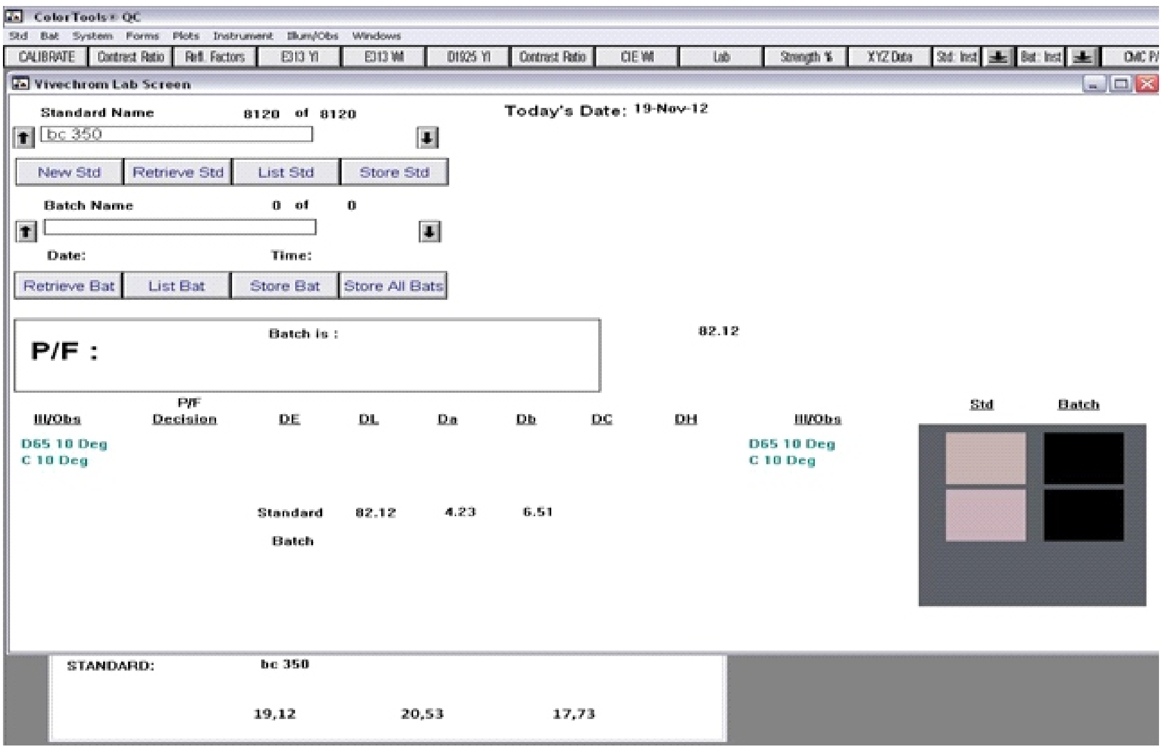
		External View	Interior View
Louvers vertical	02.12.2011		
Surrounding shading	03.12.2011		
Canopy double	05.12.2011		
Brise soleil louvers	06.12.2011		
Louvers horizontal	08.12.2011		

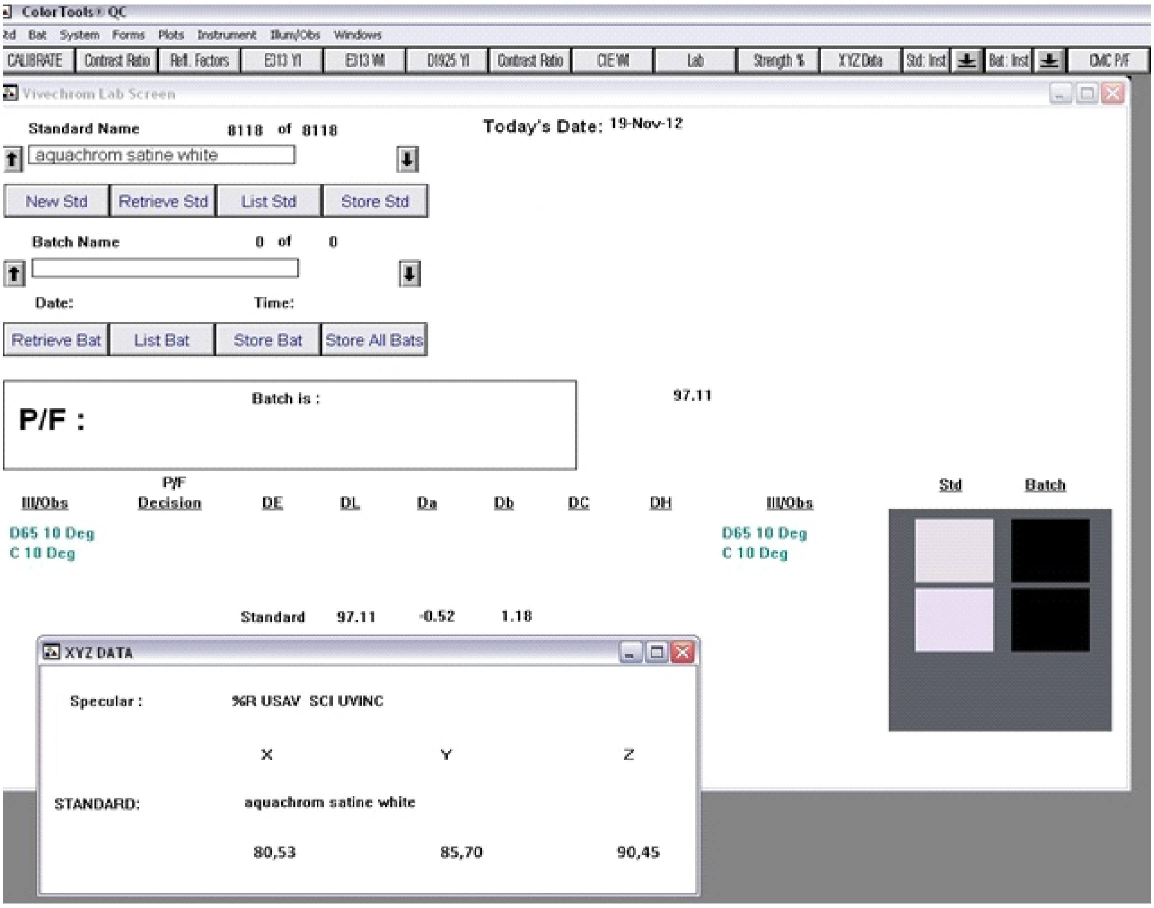
		External View	Interior View
Canopy inclined double	**29.12.2011**		
Canopy inclined single	**30.12.2011**		
Louvers horizontal inwards incl.	**14.01.2012**		
Louvers horizontal outwards incl.	**17.01.2012**		


Average daylight Autonomy Differences (Chania)
Daylight Autonomy (lux)
100
80
60
40
20
0
-20
-40
louvers_horizontal_iwardsinlined
louvers_horizontal_outwradsinclined
louvers_horizontal
louvers_vertical
brise_soleil_semifacade_louvers
Shading System
Daylight Autonomy DAYSIM
Dayligh Autonomy ECOTECT
Difference


Average UDI 100-2000 lux (Athens-Chania)
Daylight Autonomy (lux)
100
90
80
70
60
50
40
30
20
10
0
louvers_horizontal_iwardsinlined
louvers_horizontal_outwradsinclined
louvers_horizontal
louvers_vertical
brise_soleil_semifacade_louvers
Shading System
Average UDI 100-2000 lux Athens
Average UDI 100-2000 lux Chania


ColorTools® QC
Std Bat System Forms Plots Instrument Illum/Obs Windows
CALIBRATE Contrast Ratio Refl. Factors E313 YI E313 WI D1925 YI Contrast Ratio CIE WI Lab Strength % XYZ Data Std: Inst Bat: Inst CMC P/F
Vivechrom Lab Screen
Standard Name 8119 of 8119
wp 121
Today's Date: 19-Nov-12
New Std Retrieve Std List Std Store Std
Batch Name 0 of 0
Date: Time:
Retrieve Bat List Bat Store Bat Store All Bats
P/F :
Batch is :
91.15
Ill/Obs P/F Decision DE DL Da Db DC DH Ill/Obs
D65 10 Deg
C 10 Deg
D65 10 Deg
C 10 Deg
Std Batch
Standard 91.15 -0.58 1.78
Batch
STANDARD: wp 121
61,44 65,81 69,15


ColorTools® QC
Std Bat System Forms Plots Instrument Illum/Obs Windows
CALIBRATE Contrast Ratio Refl. Factors E313 YI E313 WI D1925 YI Contrast Ratio CIE WI Lab Strength % XYZ Data Std: Inst Bat: Inst CMC P/F
Vivechrom Lab Screen
Standard Name 8120 of 8120
bc 350
Today's Date: 19-Nov-12
New Std Retrieve Std List Std Store Std
Batch Name 0 of 0
Date: Time:
Retrieve Bat List Bat Store Bat Store All Bats
P/F :
Batch is :
82.12
Ill/Obs P/F Decision DE DL Da Db DC DH Ill/Obs
D65 10 Deg
C 10 Deg
D65 10 Deg
C 10 Deg
Std Batch
Standard 82.12 4.23 6.51
Batch
STANDARD: bc 350
19,12 20,53 17,73



Light Reflectance value	**VIVEXROM**
WP121	65,81
BC350	20,53
AQUACHROM SATINE WHITE	85,70

Application Characteristics of PLEXIGLAS®

PLEXIGLAS® GS	PLEXIGLAS® XT
cast	extruded
absolutely colorless and clear	
break-resistant to impact-resistant (PLEXIGLAS RESIST® HP)	break-resistant to impact-resistant (PLEXIGLAS RESIST® 45 ... 100)
unequalled resistance to weathering and aging	
high-quality surface and planarity; high-gloss, textured or satin (PLEXIGLAS SATINICE® DC/SC)	very good surface; high-gloss, textured or satin (PLEXIGLAS® Crystal Ice)
solid sheets, blocks, tubes, round and square rods	solid sheets, tubes, round rods, multi-skin sheets, corrugated sheets, mirror sheets
2 mm to 160 mm solid sheet/block thickness	1.5 to 25 mm solid sheet thickness, multi-skin sheets 8, 16 and 32 mm thick
tandard sizes up to 3050 x 2030 mm	standard size 3050 x 2050 mm, extra lengths and special sizes on request
over 50 standard color	over 25 standard colors
good resistance to dilute acids and to alkalis limited resistance to organic solvents	
very easy to work, similar to hardwood	easy to work, similar to hardwood
easy to thermoform over a wide range of conditions	very easy to thermoform under optimal, constant conditions
easily and firmly bonded, e.g. with reaction adhesives (e.g. ACRIFIX® 1R 0190, 1R 0192)	very easily bonded, also with solvent adhesives (e.g. ACRIFIX® 1S 0116, 1S 0117)
burns more or less like hardwood; very little smoke generation; combustion gases are non-toxic and non-corrosive	
max. service temperature approx. 80 °C	max. service temperature approx. 70 °C

Optical properties (of clear grades, at 3 mm thickness)

	PLEXIGLAS® GS 233; 222; 209; (0F00; 0F00; 0Z09)	PLEXIGLAS® XT 20070; 29070 (0A000; 0A070)	PLEXIGLAS RESIST® 45; 65; 75; 100	Unit	Teststandard
Transmittance τ_{D65}	~ 92	~ 92	~ 91	%	DIN 5036, Part 3
UV transmission	no; no; no	no; yes	no; no; no; no	–	–
Reflecion loss the visible range (for each surface)	4	4	4	%	–
Total energy transmittance *g*	85	85	85	%	DIN EN 410
Adsorption in the visible range	< 0,05	< 0,05	< 0,05	%	–
Refractive index n_D^{20}	1,491	1,491	1,491	–	ISO 489

Electrical properties

	PLEXIGLAS® GS 233; 222; 209; (0F00; 0F00; 0Z09)	PLEXIGLAS® XT 20070; 29070 (0A000; 0A070)	PLEXIGLAS RESIST® 45; 65; 75; 100	Unit	Teststandard
Volume resistivity ρ_D	> 10^{15}	> 10^{15}	> 10^{14}	Ohm · cm	DIN VDE 0303, Part 3
Surface resistivity σ R_{OA}	$5 \cdot 10^{13}$	$5 \cdot 10^{13}$	> 10^{14}	Ohm	DIN VDE 0303, Part 3
Dielectric strength E_d (1 mm specimen thickness)	~ 30	~ 30	–	kV/mm	DIN VDE 0303, Part 2
Dielectric constant ε at 50 Hz at 0,1 MHz	3,6 2,7	3,7 2,8	– –	– –	DIN VDE 0303, Part 4
Dissipation factor tan δ at 50 H at 0,1 MHz	0,06 0,02	0,06 0,03	– –	– –	DIN VDE 0303, Part 4
Tracking, CTI-Value	600	600	–	–	DIN VDE 0303, Part 1

Behavior towards water

	PLEXIGLAS® GS 233; 222; 209; (0F00; 0F00; 0Z09)	PLEXIGLAS® XT 20070; 29070 (0A000; 0A070)	PLEXIGLAS RESIST® 45; 65; 75; 100	Unit	Teststandard
Water absorption (24 hrs, 23 °C) from dry state; specimen 60 x 60 x 2 mm³	41	38	41; 45; 46; 49	mg	ISO 62, Method 1
Max. weight gain during immersion	2,1	2,1	2,1	%	ISO 62, Method 1
Permeability to water vapour	$2{,}3 \cdot 10^{-10}$	$2{,}3 \cdot 10^{-10}$	–		
N_2	$4{,}5 \cdot 10^{-15}$	$4{,}5 \cdot 10^{-15}$	–		
O_2	$2{,}0 \cdot 10^{-14}$	$2{,}0 \cdot 10^{-14}$	–		
CO_2	$1{,}1 \cdot 10^{-13}$	$1{,}1 \cdot 10^{-13}$	–		
air	$8{,}3 \cdot 10^{-15}$	$8{,}3 \cdot 10^{-15}$	–	$\frac{\text{g cm}}{\text{cm}^2\text{ h Pa}}$	–

Technical Data

Module sizes:
Min. 19.7" x 19.7"
(500 x 500 mm)
Max. 78.7" x 118.1"
(2000 x 3000 mm)
*Curves also possible

Cell types:
Monocrystalline
Polycrystalline
Amorphous

Cell colors:
Polycrystalline – Blue, bronze, grey, other colors on request.
Monocrystalline – Blue, bronze, grey, black, other colors on request.
Amorphous – Brown, black.

Configuration of reverse side:
Transparent, translucent or a choice of colored, structural glazes

Cell efficiency:
Polycrystalline – 13-15%
Monocrystalline – 15-21%
Amorphous – 6-9%

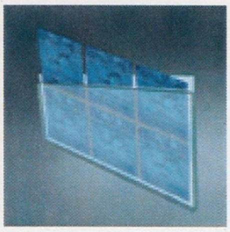
Type of connection:
Socket
Edge connector

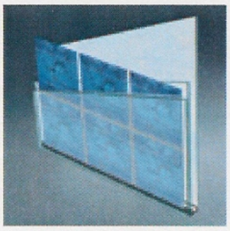
System voltage:
Max. 600 V
Protection class II
EN 61215 certificate
U value: Min. 0.9 W/m²K,
Max. 5.7 W/m²K
G value: Min. 15%,
Max. 50%

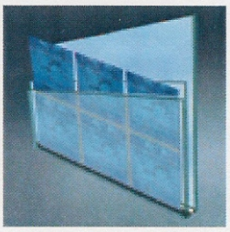
Additional functions:
Overhead glazing
Noise reduction
Anti-glare protection
Solar shading
Weather protection

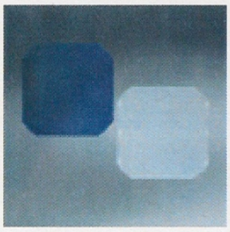
Product guarantee: 5 years
Performance guarantee:
10 years at 90% initial power

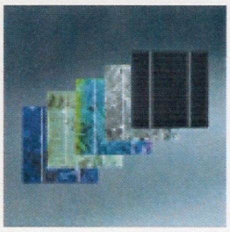

Glass / Tedlar


Glass / Glass


Glass / Glass – insulating glass


Glass / Glass – insulating glass – laminated safety glass


Cell Structure


Colors

Schüco USA L.P.
www.schuco-usa.com

P3124/USA/08.07/Printed in the USA

DATALOGGERS

DataHog2

- Dedicated, accurate and reliable systems, which are easy to use, completely weatherproof, robust, durable and low cost
- User selectable logging and integration intervals, plus a 24 hour summary
- Multi-channel with a choice of voltage, current or digital count inputs
- Optional electrical relay outputs for switching or alarm facilities
- Battery operated with a choice of additional power supplies - solar and mains
- Optional SkyeLynx Software Packages
- Access via a portable PC, permanent cable link or GSM mobile phone remote data link
- Real-time clock for synchronization with other installations

The Skye DataHog loggers have been available for several years as small easy to use devices suitable for many applications.

The DataHog2 has a large storage memory and extended battery life to allow long term projects to be monitored at remote sites, or short term logging at frequent intervals. The range of input types is varied - customers can use their own sensors or choose from Skye's range of precision sensors. Choose combinations of single ended or differential voltage, current inputs or digital count.

Channels can be individually programmed with logging interval and gain to suit each sensor type. Units for scaling are defined by the user for easy and straightforward operation. At user-set levels, the DataHog2 will give an electrical relay or alarm output from up to two different channels. There is also a timed start/stop function.

Supplied with a 'ready-to-go' package of batteries, datalead, USB serial converter & Windows communication software

Softwares Available

SkyeLynx Standard software supplied free of charge with all DataHog2 and MiniMet2 dataloggers. Allows logger setup, configuration and data download.

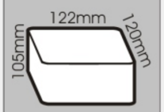
SkyeLynx Auto software allows the automatic data download from a logger connected by a hard wire link, standard telephone line or cellular modem.

SkyeLynx Deluxe software contains all logger set up and download functions plus data tabulating, summarising and graphing with a special windrose feature.

Skye

updated 14/03/11

SPECIFICATIONS DATALOGGER

operating temperature	Housing	Mounting	Weight Dimensions	Connections	Memory	Resolution Units
-20 to + 70°C standard range (units for extended temperature range available)	Grey ABS-sealed to IP65.	Can be mounted in any position	1100g 	Binder sub-miniature type 8 & 5 pin Sealed to IP65 when mated with plug or blanking cap	Battery backed RAM, 1 Mbit. e.g. 2-channels, 8068 recordings of each channel plus date and time	15 bits resolution User definable scaling and units

Communications	Power	Inputs	Outputs	Modes	Clock
RS232C, ASCII output will communicate with any PC. All units are supplied with a datalead, USB serial converter and software for an IBM compatible PC. Data offload at a baud rate of 9600 Binary offload option Instant 'wake up'	Standard: 6 x 'C' batteries (4-6 months) Internal 10 year lithium battery for data memory and channel configurations Optional: Mains Hog (mains power - 240 or 110V) Solar Hog (solar power)	Voltage - single ended or differential ±2mV to ±2V Current 0-200nA to 0-400 A Digital count RH 10k thermistor Wind direction	4 optional independent electrical relay switches open/close contact on user set conditions	Each channel configured individually Logging intervals - 10, 20, 30 secs, 1,2, 5, 10, 20, 30 mins, 1, 2, 3, 4, 6, 12 hours. Integration intervals- as for logging intervals above. Transmit data at above intervals to RS232 whilst logging Transmit data on demand from signal via RS232. Stop/start logging time	Real time year, month, date, time clock enabling synchronisation of several units. Clock backed by lithium battery

ORDERING INFORMATION

A comprehensive list of part numbers with descriptions for the many DataHog datalogger options can be found in the price list. The following give some examples:

SDL 5050	1 channel DataHog2
SDL 5250	5 channel DataHog2
SDL 5800	16 channel DataHog2

Accessories

SKM 225	Pole mount for DataHog
SKLS 940/SKLS 950	SkyeLynx Auto and Deluxe Communications Software Package

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Skye

LIGHT

Lux Sensor

- The design of buildings including all types of architectural models. Variations in levels of lighting are obviously a very important criterion when considering design
- Specific lighting conditions under which animal experiments are carried out
- Design of lighting levels in psychological experiments
- Lighting for animal housing, e.g. poultry houses

Visible light can be defined as the part of the wavelength spectrum perceived by the human vision in a manner similar to the eye. This response to the human eye to light can be expressed as a spectral reponse curve which has the form shown on reverse. There is a peak sensitivity at 555nm for the light adapted eye. This curve is known as the photopic curve or CIE Standard Observer Curve. The response curve for this filtered sensor is almost indistinguishable from the Photopic curve shown on the reverse. Light falling within the curve is measured in Lux units.

Appropriate levels of light measured in Lux units are important in many areas of human activity such as close field work, general reading, relaxation and can have important psychological effects.

SKL 310 SPECIFICATIONS

Dimensions	Weight	Construction	Cable	Sensor	Detector	Filters	Sensitivity -current (1)	Sensitivity -voltage	Working range (2)
34mm, 38mm	130g. (with 3m cable)	Material Dupont 'Delrin' fully sealed to IP68	2 core screened DEF std 61-12/4.5	Cosine corrected head	Silicon photocell. Low fatigue character-istics	Optical Glass	1.4µA/ 10kLux	1mV/ 10kLux	0-500 kLux
Linearity error-to above level	**Absolute calibration error (3)**	**Cosine error (4)**	**Azimuth error (5)**	**Temperature coefficient**	**Longterm stability (6)**	**Response time (7) - voltage output**	**Internal resistance - voltage output**	**Operating range**	**Humidity range**
<0.2%	typ. <3% 5% max.	3%	<1%	±0.1%/°C	±2%	10ns	c.650 ohms	-35 to +75°C	0-100% RH

NOTES ON SPECIFICATIONS

(1) Current output varies from sensor to sensor. Each individual unit will have a slightly different output. A calibration certificate is supplied with each sensor

(2) All Skye sensors will work at levels of irradiance well above that found in terrestrial sunlight conditions, room or growth chamber lighting

(3) Main source of this error is uncertainty of calibration of Reference Lamp. Skye calibration standards are directly traceable to N.P.L. standard references.

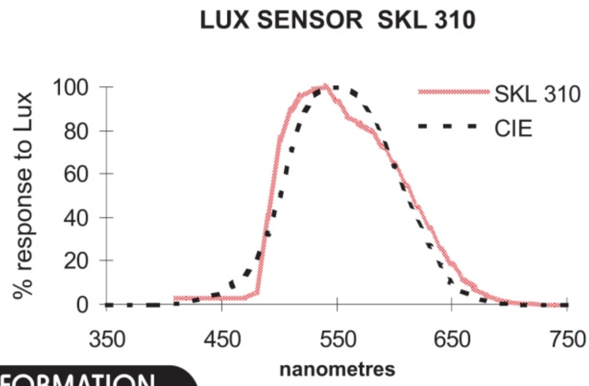
(4) Cosine error to 80° is typically 5% max. Figures shown are for normal use sources, e.g., sun plus sky, diffuse sun, growth chambers, etc.

(5) Measured at 45° elevation over 360°

(6) Maximum change in one year. Calibration check recommended at least every two years. Experience has shown that changes are typically much less than figures quoted

(7) Times are generally less than the figure quoted, which is in nanoseconds. They may be slightly increased if long leads are fitted, or those of a higher capacity cable

GRAPH



ORDERING INFORMATION

Sensor

SKL 310	Photometric or Lux sensor

Accessories

SKM 221	Levelling unit
SKM 226	Long arm pole/wall mount

Meters and dataloggers

SKL 300	Display meter
SKL 904	SpectroSense2
SKL 908	SpectroSense2+
SDL 5000 series	DataHog datalogger

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Abbreviations

ASHRAE: American Society of Heating Refrigerating and Air Conditioning Engineers

CDC: Charge-Couple Device Camera

DF: Daylight Factor

DA: Daylight Autonomy

UDI: Useful daylight Illuminance

DGI: Daylight glare index

HF: High Frequency Tubes

SD: Shading Device

PV: Photovoltaic panel

WWA: Window to Wall area

WWR: Window to Wall ratio

U- value: thermal transmittance (W/m^2 K), U-value = 1/ R-value

g - value: total solar energy transmittance

R - value: insulation (m^2 k/ W)

K - value: thermal conductivity (W/m k)