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Daylight Performance Assessment of an Innovative Energy Efficient Building Envelope

DOCTORAL THESIS

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to my Godfather...

J'ai des amis à descouvrir,
et beaucoup de choses à connaître...
(Antoine de Saint-Exupéry)

I had the opportunity to follow my curiosity...
(Randy Schekman, Nobelist, UC Berkeley)

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SUMMARY

Buildings are considered to be one of the primary contributors to the socioeconomic development of a country. However, they use a large portion of energy and available natural resources. With the industrialization leading to an increase in urban population, the number of urban buildings which has major effects on energy consumption, has significantly increased. Even with the implementation of energy efficient policies, energy consumption in buildings has regularly grown over the last decades affecting the building's operating cost. For this reason, the construction industry seeks to create a model of sustainable development in buildings which has low environmental impact and high economic and social gains. This requires the adoption of an integrated approach covering a number of features such as energy reduction, improved use of materials including water, reuse and recycling of materials, and emissions control.

More than ever, there is an increasing concern for depletion today's world resources. Therefore, development and implementation of renewable energy technologies have become increasingly important and necessary for the society. Since the earth constantly receives a supply of solar radiation which is the cleanest and the most abundant renewable free energy source available, use of solar energy in buildings is gaining momentum. Nowadays, with new solar technologies, the sunlight can be harnessed for a variety of uses such as electricity generation, daylighting, heating water, and so on. In addition, currently new buildings integrate solar systems into its exterior envelope, which are capable of collecting large amounts of solar energy. Moreover, humans have evolved under the influence of daylight and the light-dark cycle while developing a variety of psychological advantages e.g. affecting people's health and mood, less absence at work and higher productivity. After the introduction of electric lighting, people started spending most of their time inside buildings. Consequently, thermal comfort became a significant factor for humans in order to perform an activity within a building. Thus, an improve of the energy efficiency of the building contributes to the interior comfort and health of the occupants. Therefore, multifunctional façades and roofs are gaining the attention of the construction market due to its versatility on energy savings while improving the interior comfort.

The present research covers the aforementioned issues with regards to improving the buildings' energy efficiency by achieving a reduction in energy consumption with innovative technologies that utilize solar energy resources while creating a comfortable living environment. For this objective, this Thesis has been divided into two lines of work. The first line of research describes and illustrates the most common construction problems during the life cycle of façades and roofs of buildings built with a poor energy performance solution. Therefore, a building envelope energy retrofit undertaken on an existing affordable multifamily building has been used as a case study. This work is intended to understand the complexity and requirements of the building envelope in terms of energy efficiency together with the occupants' interior comfort. Through this case study, significant improvements in thermal energy savings were observed after undertaking the energy retrofit of the assessed envelope, which resulted in an increase of interior thermal comfort. This demonstrates the need to urge the construction industry to design and develop novel energy efficient building envelopes for newly constructed buildings and retrofitted ones such as the Translucent Concrete Panel (TCP). The TCP presents a new alternative passive solution which reduces the energy consumption of the building by optimizing the entrance of natural sunlight into the building's interior through the traditionally opaque parts of the exterior walls by allowing sunlight permeability through these panels while improving occupants' interior daylight and thermal comfort.

Based on the results obtained from the first line of research, the second study only assesses the daylight performance of the TCP construction solution. In the last decades, the science and industry have created different passive and active daylighting systems which try to provide solutions in terms of reducing and alleviating the energy inefficiency of buildings. The TCP is viewed as an advanced energy efficient wall technology with the property to subsidize the energy liability related to opaque walls by providing daylight transmission. However, currently the TCP's daylight performance cannot be computer modeled because there is no software in the market that can simulate and assess the daylight properties of both of the TCP's main components, i.e. the Compound Parabolic Concentrators (CPCs) and the Optical Fibers (OFs). Therefore, new experimental studies had to be designed following theoretical development. The tests were conducted outdoors under real sky conditions as a way to further create and validate computational codes which will allow easy adoption of the novel construction solution by the industry. Nevertheless, all the tests were divided into two categories. The first one sought to demonstrate and confirm that TCP, with a proper design of its components and orientation, can scatter sunlight into the building's interior during the hours of the day. Several TCP panels, embedded with different OF diameters and volumetric ratios, were tested outdoors and aligned with panels outfitted with CPCs of different geometries. As the obtained preliminary results were positive, this helped to move the research to the second step that was mainly focused on improving the amount of sunlight captured with the CPCs and the daylight scattered with the OFs into the building's interior. For this purpose, the research proposed to geometrically modify the embedded OFs tips interfaced with the TCPs, and test them independently or aligned with CPCs of different geometries. This was an important milestone for the study since the OF tips were able to improve the daylight performance of the multifunctional building envelope case study while also improving the interior daylighting.

Interestingly, there exists a number of different daylight metrics used by professionals for daylight performance. For this reason, all the daylight tests were designed to fulfill the intended objectives. However, in the present Thesis, it was decided to design and build a Small Portable Test Bed (SPTB) to be used outdoors which has an integrated control system with wireless sensors that actively respond to the changing climatic conditions during the conducted test duration. The SPTB is a cuboid-like element whose design can simulate a real building envelope with four façades and a roof. This specific design allows to test the façades under the four basic compass orientations at the same time including the roof. Accordingly, the SPTB comes up as a tool for testing under real outdoor conditions. In addition, the versatility of the structure allows that the dimensions of SPTB to be changed if required. For this research, the first objective of this portable test bed was to give a fair assessment of the daylight performance of the TCP from the conducted dynamic daylight tests. Secondly, the SPTB design sought to develop a physical tool which could be used beyond the needs of the current research for other future tests and projects. For the multifunctional building envelope case study, the SPTB was placed outdoors and a variety of small non-scaled TCP specimens were tested to assess its daylight performance under real sky conditions by collecting data and transmitting them wirelessly to be stored in a central database over the Internet.

The final results obtained in this Thesis state that by using the technology discussed herein, it is possible to achieve energy efficiency measures with the potential of improving the occupants comfort and health. This is demonstrated by the energy retrofitted façade case study leading to about 12% of energy savings. On the other hand, the TCP outfitted with CPCs, is shown to scatter (direct and diffuse) sunlight thereby improving the illumination distribution in the building interior. Moreover, the research has improved the daylight captured and scattered by the OFs with geometrical modification of the tips of the OFs. In

addition, the use of the designed SPTB, facilitated the assessment of the daylight performance of the TCPs by using dynamic daylight metrics. However, more experimental research together with new computer simulations, should be performed in the future in order to acquire more conclusive results in terms of energy savings and building interior thermal comfort.

RESUM

Els edificis estan considerats els primers contribuïdors del desenvolupament socioeconòmic d'un país. No obstant, utilitzen una gran quantitat d'energia i recursos naturals disponibles. Amb la industrialització, que va donar lloc a un increment de la població urbana, aquest resulta un factor que ha fet augmentar el nombre d'edificis urbans i ha creat un major efecte en el consum energètic. Tot i la implementació de polítiques d'eficiència energètica, el consum energètic ha augmentat durant les ultimes dècades afectant a la despesa operacional de l'edifici. Per aquesta raó, la indústria de la construcció cerca crear models de desenvolupament sostenible en edificis i que tinguin un baix impacte mediambiental i un alt impacte econòmic i guanys socials. Això requereix l'adopció d'un sistema integrat que cobreixi un nombre de característiques tals com reducció energètica, millora de l'ús de materials, la qual cosa inclou l'aigua, reutilització i reciclatge de materials, i emissions de control.

Més que mai, a dia d'avui hi ha una creixent preocupació per l'esgotament dels recursos naturals. Per tant, desenvolupament i implementació de noves tecnologies d'energia renovable s'han tornat importants i necessàries per la societat. Des de que la terra rep constantment radiació solar, la qual resulta una font d'energia gratuïta neta i abundant, la utilització de la energia solar en edificis esta agafant força. A dia d'avui, amb les noves tecnologies, la llum solar pot ser emprada per una varietat d'usos, tals com generadora d'electricitat, llum interior natural, escalfadora d'aigua, entre altres. Actualment els nous edificis acostumen a integrar sistemes solars dintre de la part exterior de la envolvent, els quals poden col·lectar grans quantitat d'energia solar. A més a més, els humans hem evolucionat sota la influència de la llum del sol i el cicle llum-foscor mitjançant el desenvolupament d'una varietat d'avantatges psicològics, la qual cosa afecta al caràcter i salut de la gent, així com menor absència del lloc de treball i més alta productivitat. Després de la introducció de la llum elèctrica, la gent va començar a passar més temps dins de l'interior dels edificis. Conseqüentment, el confort tèrmic es va tornar un factor significatiu pels humans amb vistes a desenvolupar una activitat dintre de l'edifici. Així que, una millora en la eficiència energètica dels edificis contribueix al confort interior i la salut dels ocupants. Per aquest motiu, façanes i cobertes multifuncionals estan darrerament guanyant l'atenció del mercat de la construcció a causa de la seva versatilitat en l'estalvi d'energia i la millora en el confort interior de l'edifici.

La present recerca pretén cobrir les qüestions comentades amb anterioritat referents a la millora de l'eficiència energètica dels edificis i obtenir, d'aquesta manera, una reducció en consum energètic amb tecnologies innovadores que utilitzen fonts d'energia solar per crear un ambient interior confortable. Per aquest objectiu, la present Tesis s'ha dividit en dos línies de treball. La primera línia de recerca descriu i il·lustra els problemes constructius més habituals durant el cicle de vida de les façanes i cobertes dels edificis construïts amb una solució constructiva de baix rendiment energètic. Per tant, s'ha estudiat un cas real on s'ha rehabilitat energèticament la envolvent exterior d'un edifici plurifamiliar d'habitatge social. Aquesta feina te la intenció entendre la complexitat i els requeriments de la envolvent exterior de l'edifici en termes d'eficiència energètica, juntament amb el confort interior dels ocupants. A través del cas real estudiat, s'ha observat millores significatives en l'estalvi energètic després de la rehabilitació energètica de les façanes i cobertes que dóna lloc a un augment del confort tèrmic interior. El resultat demostra la necessitat que hi ha d'empènyer a la indústria de la construcció de dissenyar i desenvolupar noves envolvents exteriors energèticament eficients tant per noves construccions com per edificis rehabilitats. Una de les solucions novells és el cas del Panell de Formigó Translúcid (Translucent Concrete Panel – TCP). El TCP presenta una nova alternativa passiva el qual redueix el consum energètic tot optimitzant l'entrada de llum solar natural a dintre de l'edifici a través de la tradicional part opaca de les parets

exterior de façana i coberta. Això permet la permeabilitat de la llum natural a través de les parets tot millorant el confort tèrmic i lumínic interior.

Basada en els resultats obtinguts en la primera línia de recerca, la segona línia només estudia i analitza el comportament de la llum del TCP. Durant les darreres dècades, ciència i indústria han creat diferents sistemes lumínics actius i passius els quals intenten proveir solucions per reduir i alleugerir la ineficiència energètica dels edificis. El TCP es veu com una nova tecnologia constructiva, energèticament eficient, dissenyada per envolvents exteriors, i que té la propietat de resoldre la càrrega energètica de la part opaca de les parets i permetre l'entrada de llum natural. No obstant això, actualment el comportament de la llum dels TCPs no es pot simular per ordinador degut a que no hi ha cap software en el mercat que pugui simular i analitzar les propietats de transmissió de llum dels dos components principals del TCP i que són: Concentrador Solar (Compound Parabolic Concentrator – CPC) i la Fibra Òptica (Optical Fiber – OF). Per tant, nous estudis experimentals han hagut de ser dissenyats amb procediments teòrics. Els tests van tenir lloc a l'exterior sota condicions reals de cel i d'aquesta manera en un futur poder crear i validar programes els quals permetran una fàcil adopció del TCP per part de la indústria. No obstant això, tots els tests van ser dividits en dos categories. El primer buscava demostrar i confirmar que el TCP, amb un disseny apropiat dels seus components i orientació, pot distribuir la llum natural dintre del edifici durant les hores solars. Diferents panells de TCP amb diferents diàmetres i rati de les OF, van ser assajats a l'exterior junt amb panells amb CPCs de diferents geometries. Com els primers resultats van ser òptims, això va ajudar poder moure la recerca a un segon nivell el qual estava principalment centrat en la millora de la quantitat de llum solar capturada amb els CPCs i la quantitat de llum distribuïda amb les OFs dintre de l'edifici. Amb aquest objectiu, la present recerca va proposar modificar els extrems de les OFs amb diferent geometries, i així analitzar-les independentment i alinear-les amb CPCs de diferent geometries. Aquest ha sigut un punt important per l'estudi, degut a que els extrems modificats de la OF són capaços de millorar l'entrada de llum natural a l'interior de l'edifici

Per una altra banda, hi ha un gran nombre de diferents sistemes mètrics utilitzats per professionals per avaluar les propietats de la llum dintre d'un espai. Per aquest motiu, tots els tests van ser dissenyat seguint els objectius de la recerca. No obstant això, la present Tesis va decidir dissenyar i construir un Petit Portable Banc de Proves (Small Portable Test Bed – SPTB) per ser utilitzat a l'exterior i el qual té un sistema integrat de control de sensors sense cables i que activament respon als canvis exteriors climàtics durant els tests. El SPTB es una mena de cub el qual vol simular la envolvent exterior de l'edifici amb quatre façanes i coberta. Aquest disseny específic pot permetre analitzar a la vegada les façanes sota les quatre orientacions, juntament amb la coberta. Així que el SPTB va ser concebut com una eina per fer assajos sota condicions reals exteriors. A més a més, gràcies a la versatilitat de la seva estructura, les dimensions del SPTB poden ser canviades en cas necessari. Per la present recerca, el primer objectiu d'aquest banc de proves portable era fer una avaluació justa del comportament de la llum del TCP basat en tests de llum dinàmics. I en segon lloc, el SPTB buscava desenvolupar una eina física per ser utilitzada més enllà de les necessitats de la present recerca, així com en altres projectes i assajos. Pel novell TCP cas d'estudi, el SPTB va ser ubicat a l'exterior i una varietat de petites mostres a escala real de TCPs van ser assajades per analitzar el comportament de la llum sota condicions de cel reals, així com una recopilació de dades les quals eren enviades wireless i emmagatzemades a una base de dades centrals ubicada a internet.

Els resultats finals obtinguts en la present Tesis confirmen que utilitzant la tecnologia comentada en aquesta recerca, es demostra que les mesures preses en eficiència energètica, pot millorar el confort

interior i la salut dels ocupants. Aquest és el cas de la rehabilitació energètica de la façana utilitzada com a cas d'estudi tot obtenint aproximadament un 12% d'estalvi energètic. Per un altre costat, el TCP equipat amb CPCs, es capaç de dispersar (directa i difusa) llum solar, i d'aquesta manera millorar la distribució lumínica en el interior de l'edifici. La recerca ha millorar la llum capturada i dispersada per les OFs tot modificant la geometria dels extrems de la OF. Amb l'ús del SPTB, ha sigut possible avaluar el comportament de la llum del TCP tot utilitzant sistemes mètrics lumínics dinàmics. No obstant, més recerca experimentals junt amb noves simulacions per ordinador, s'haurien de fer en un futur a fi d'obtenir resultats més concloents en termes d'estalvi energètic i confort tèrmic interior.

RESUMEN

Los edificios son considerados los primeros contribuyentes al desarrollo socioeconómico de un país. No obstante, utilizan una gran cantidad de la energía y de recursos naturales disponibles. Con la industrialización tuvo lugar un importante incremento de la población urbana y este hecho provocó un aumento del número de edificios urbanos, los cuales provocaron un mayor incremento del consumo energético. A pesar de que se han implementado políticas de eficiencia energética, el consumo energético ha seguido aumentando durante las últimas décadas y ha afectado al gasto operacional del edificio. Por este motivo, la industria de la construcción busca crear modelos de desarrollo sostenible en edificios que tengan un bajo impacto medioambiental, y un alto impacto económico y beneficios sociales. Esto requiere la adopción de un sistema integrado que cubra un número de características, así como reducción energética, mejora del uso de los materiales, incluyendo el agua, reutilización y reciclaje de materiales, y emisiones de control.

Más que nunca, a día de hoy, hay una creciente preocupación por el agotamiento de los recursos naturales. Por tanto, desarrollo e implementación de nuevas tecnologías de energía renovable resultan tan importantes y necesarias para la sociedad. Desde que la tierra recibe constantemente radiación solar, la cual es una fuente de energía gratuita, limpia y abundante, el uso de la energía solar en edificios está ganando fuerza. A día de hoy, con las nuevas tecnologías, la luz solar puede ser empleada para una amplia variedad de usos, así como generadora de electricidad, luz interior natural, calentadora de agua, entre otras utilidades. Actualmente, los nuevos edificios acostumbran a integrar sistemas solares dentro de la parte exterior de la envolvente del edificio, los cuales pueden captar gran cantidad de energía solar. Además, los humanos hemos evolucionado bajo la influencia de la luz solar y el ciclo luz-oscuridad. Este hecho ha permitido el desarrollo de una variedad de ventajas psicológicas que afectan al carácter y a la salud de las personas, así como a una menor ausencia del lugar de trabajo y una alta productividad. Tras la aparición de la luz eléctrica, la gente comenzó a pasar más tiempo dentro de los edificios. Consecuentemente, el confort térmico resultó un factor significativo para los humanos en vistas a poder desarrollar una actividad dentro del edificio. Así pues, vemos que una mejora en la eficiencia energética de los edificios contribuye al confort interior y a la salud de los ocupantes. Por este motivo, últimamente, fachadas y cubiertas multifuncionales están ganando la atención del mercado de la construcción debido a su versatilidad en el ahorro de energía y en la mejora del confort interior del edificio.

La presente investigación cubre las cuestiones comentadas con anterioridad referentes a la mejora de la eficiencia energética de los edificios, y así obtener una reducción en el consumo energético mediante tecnologías innovadoras que utilizan fuentes de energía solar para crear un ambiente interior confortable. Por este motivo, la presente Tesis está dividida en dos líneas de trabajo. La primera línea de investigación describe e ilustra los problemas constructivos más habituales durante el ciclo de vida de las fachadas y cubiertas de los edificios construidos con una solución constructiva de bajo rendimiento energético. De tal manera, se ha estudiado un caso real en donde se ha rehabilitado energéticamente la envolvente exterior de un edificio plurifamiliar de vivienda social. Este trabajo tiene la intención de ser utilizado como una herramienta para entender la complejidad y los requisitos de la envolvente exterior del edificio en temas de eficiencia energética, junto al confort interior de los ocupantes. A través del caso real estudiado, se han observado mejoras significativas en el ahorro energético después de la rehabilitación energética de las fachadas y cubierta, dando lugar a un aumento del confort térmico interior. El resultado demuestra la necesidad de incitar a la industria de la construcción para que sea capaz de diseñar y desarrollar nuevas envolventes exteriores energéticamente eficientes, tanto en el caso de nuevas construcciones como en el de edificios rehabilitados. Una de las soluciones noveles es el caso del Panel de Hormigón Translucido

(Translucent Concrete Panel – TCP). El TCP presenta una nueva alternativa pasiva capaz de reducir el consumo energético del edificio, con la optimización de la entrada de luz solar natural dentro del mismo, a través de la tradicional parte opaca de las paredes exteriores de fachada y cubierta, permitiendo así la permeabilidad de la luz solar a través de las paredes y mejorando el confort térmico y lumínico interior.

Basada en los resultados obtenidos en la primera línea de investigación, la segunda línea solamente estudia y analiza el comportamiento de la luz del TCP. Durante las últimas décadas, ciencia e industria han creado diferentes sistemas lumínicos activos y pasivos los cuales intentan proveer soluciones para reducir y aligerar la ineficiencia energética de los edificios. El TCP está considerado como una nueva tecnología constructiva energéticamente eficiente diseñada para envolventes exteriores, y que tiene la propiedad de resolver la carga energética de la parte opaca de las paredes permitiendo así la entrada de luz natural. No obstante, actualmente el comportamiento de la luz de los TCPs no se puede simular por ordenador debido a que no hay ningún software en el mercado que pueda simular y analizar las propiedades de transmisión de luz de los dos componentes principales del TCP que son Concentrador Solar (Compound Parabolic Concentrator – CPC) y la Fibra Óptica (Optical Fiber – OF). Por tanto, los nuevos estudios experimentales han tenido que ser diseñados siguiendo procedimientos teóricos. Los test tuvieron lugar en el exterior bajo condiciones reales de cielo y de esta manera en un futuro poder crear y validar programas los cuales permiten una fácil adopción del TCP por parte de la industria. No obstante, todos los test se dividieron en dos categorías. El primero buscaba demostrar y confirmar que el TCP, con un diseño apropiado de sus componentes y orientación, puede distribuir la luz natural dentro del edificio durante las horas solares. Diferentes paneles de TCP, con diferentes diámetros y ratios de OFs, fueron ensayados en el exterior junto con paneles con CPCs de diferentes geometrías. Dado que los primeros resultados fueron óptimos, se pudo dirigir la investigación a un segundo nivel, principalmente centrado en la mejora de la cantidad de luz solar capturada con los CPCs y la cantidad de luz distribuida con las OFs dentro del edificio. Con este objetivo, la presente investigación propuso modificar geométricamente los extremos de las OFs con diferentes geometrías, y así analizarlas independientemente y alinearlas con CPCs de diferentes geometrías. Este ha sido un punto importante del estudio, debido a que los extremos modificados de las OFs son capaces de mejorar la entrada de luz natural en el interior del edificio.

Por otro lado, existe una gran diferencia entre los diferentes sistemas métricos utilizados por los profesionales para evaluar las propiedades de la luz dentro de un espacio. Por este motivo, todos los ensayos fueron diseñados siguiendo los objetivos de la investigación. No obstante, la presente Tesis decidió diseñar y construir un Pequeño Portable Banco de Pruebas (Small Portable Test Bed – SPTB) para ser utilizado en el exterior, el cual tiene un sistema integrado de control de sensores sin cables y que activamente responden a los cambios exteriores climáticos durante los ensayos. El SPTB es una especie de cubo que pretende simular la envolvente exterior del edificio con cuatro fachadas y cubierta. Este diseño específico permite analizar a la vez las fachadas bajo las cuatro orientaciones junto con la cubierta. De hecho, el SPTB fue concebido como una herramienta versátil para realizar ensayos bajo condiciones reales exteriores. Además, gracias a la versatilidad de su estructura, las dimensiones del SPTB pueden ser cambiadas en caso necesario. Para la presente investigación, el primer objetivo de este banco de pruebas era realizar una evaluación justa del comportamiento de la luz del TCP basado en ensayos de luz dinámicos. Y en segundo lugar, el SPTB buscaba desarrollar una herramienta física para ser utilizada más allá de las necesidades de la presente investigación, así como en otros proyectos y ensayos. Para el novel TCP caso de estudio, el SPTB fue ubicado en el exterior y una variedad de pequeñas muestras a escala real de TCPs fueron ensayadas para analizar el comportamiento de la luz bajo condiciones reales del cielo, así como una

recopilación de datos los cuales eran enviados Wireless i guardadas a una base de datos centrales ubicado en internet.

Los resultados finales obtenidos en la presente Tesis confirman que, utilizando la tecnología comentada en ésta investigación, se demuestra que las medidas tomadas en eficiencia energética pueden mejorar el confort interior y la salud de los ocupantes. Éste es el caso de la rehabilitación energética de la fachada utilizada como casa de estudio donde se obtuvo aproximadamente un 12% de ahorro energético. Por otro lado, el TCP equipado con CPCs, es capaz de dispersar (directa y difusa) luz solar, i de esta manera mejorar la distribución lumínica del interior del edificio. La investigación ha mejorado la luz capturada y dispersada por las OFs gracias a la modificación de los extremos de la OF. Con el uso del SPTB, ha sido posible evaluar el comportamiento de la luz del TCP con la utilización de sistemas métricos lumínicos dinámicos. No obstante, más investigación experimental junto con nuevas simulaciones por ordenador, se tendrían que hacer en un futuro a fin de obtener resultados más concluyentes en términos de ahorro energético y confort térmico interior.

INDEX

INDEX OF TABLES

Chapter 2 __ Energy Retrofit Of An Existing Affordable Building Envelope in Spain

Chapter 3 __ Experimental Investigation of Sunlight Permeability by Translucent Concrete Panels as an Energy Efficient Building Envelope

Chapter 4 __ Optical Fiber Light Scattering Outdoor Tests For Interior Daylighting

Chapter 5 __ A Portable Test Bed For Daylight Performance Assessment Of Translucent Concrete Panel

INDEX OF FIGURES

Chapter 1 __ Introduction

Chapter 2 __ Energy Retrofit Of An Existing Affordable Building Envelope in Spain

Chapter 3 __ Experimental Investigation of Sunlight Permeability by Translucent Concrete Panels as an Energy Efficient Building Envelope

Chapter 4 __ Optical Fiber Light Scattering Outdoor Tests For Interior Daylighting

Chapter 5 __ A Portable Test Bed For Daylight Performance Assessment Of Translucent Concrete Panel

ANNEX - Chapter 2 Results

ANNEX - Chapter 4 Results

ANNEX - Chapter 5 Results

SYMBOLS

°C	Degree Celsius
Ø	Optical fiber diameter
d_1	Compound Parabolic Concentrator larger diameter
d_2	Compound Parabolic Concentrator smaller diameter
E_i	Internal diffuse illuminance
E_o	External diffuse illuminance
°F	Degree Fahrenheit
k	Thermal conductivity coefficient
L	Compound Parabolic Concentrator length
m	Meter
m^2	Squared meter
m^3	Cubic meter
mL	Milliliter
mm	Millimeter
mm^2	Squared millimeter
mm^3	Cubic millimeter
m/s	Wind speed
$n_{cladding}$	Refractive index for the OF cladding material.
n_{core}	Refractive index for the OF core material.
R	Resistivity
R1	The sum of all the resistances
R_{so}	Thermal resistance of the outside surface of the element
R_{si}	Thermal resistance of the internal surface of the element
R-Value	Thermal resistance
U-Value	Thermal transmittance
θ_{max}	Compound Parabolic Concentrator half acceptance angle.
ρ	The radial distance to a point on the CPC parabola.
ϕ	The angle between the tangent to the CPC parabola at its focus and the radial distance.

ABBREVIATIONS

AR	Acrylic Rods
BiB	Building-in-Briefcase sensor
CABS	Climate Adaptive Building Shell
CIE	Commission Internationale de l'Éclairage
CNC	Computer Numerical Controlled
CPC	Compound Parabolic Concentrator
CTE	Spanish Building Code
DA	Daylight Autonomy
DA_{con}	Continuous Daylight Autonomy
DBE	Dynamic Building Envelope
DDP	Dynamic Daylight Performance
DF	Daylight Factor
DOE	Department Of Energy (USA)
DSI	Daylight Saturation Illuminance
DSP	Daylight Saturation Percentage
EM	Electromagnetic
EPS	Expanded Polystyrene
EU	European Union
HVAC	Heat, Ventilation and Air Conditioning
IR	Infrared light
MDF	Medium Density Fiberboard
NA	Numerical Aperture
OF	Optical Fiber
PLA	Polylactic acid polymer
RC	Reinforced Concrete
RH	Relative Humidity (%)
SC	Straight Cones
SCENIHR	Scientific Committee on Emerging a Newly Identified Health Risks
SPTB	Small Portable Test Bed
TCP	Translucent Concrete Panel
TIR	Total Internal Reflection
UDI	Useful Daylight Illuminance
UNPD	United Nations Population Division
UV	Ultraviolet spectrum
XPS	Extruded Polystyrene
WHO	World Health Organization
WWR	Window-to-Wall Ratio

GLOSSARY

Active System	uses mechanical components which work with electricity or fuel to achieve indoor comfort.
Anidolic	non-imaging optics, also called anidolic optics, is the branch of optics concerned with the optimal transfer of light radiation between a source and a target.
Building Envelope	is a collective term which includes all the façade and roof components that limit the minimum energy demand to obtain thermal comfort in the building's interior.
Climate Adaptive Building Shell	is a dynamic envelope placed on the outermost of the building envelope which has the ability to change some of its functions, features or behavior throughout the day.
Daylight	is the combination of direct sunlight and diffuse sky radiation.
Daylighting Harnessing	is a passive design strategy in buildings that improves the occupants' visual comfort and the building's energy performance with an affordable cost of installation.
Daylight Illuminance Level	is a dynamic parameter which is constantly changing both in intensity and in spatial distribution due to the sun track and the sky conditions.
Daylight Factor	is the ratio of internal illuminance to the external horizontal illuminance under overcast sky (diffuse light).
Dynamic Building Envelope	which attempts to achieve a near optimum energy efficient environment meeting occupant needs throughout the year by adapting to dynamic meteorological conditions and changing occupant preferences in real time.
Dynamic Daylight Performance	is based on time series of illuminances or luminances obtained in an interior space, which are based on external and annual solar radiation data for the building site
Energy Consumption	Amount of energy consumed in a process or system, or by an organization or society.
Energy Efficiency	is a generic term which refers to using less energy to produce the same amount of services or useful output.
Energy Intensity	is the measure of energy efficiency of a country's economy and is usually related to income, urbanization and industrialization.
Energy Poverty	is lack of access to modern energy services. It is referred to the situation of people from developed countries whose well-being is negatively affected by very low consumption of energy.

Energy Retrofit	reduces energy demand by replacing outdated and inefficient sub-systems with the latest in energy efficient technology.
Energy Savings	is the process of monitoring, controlling, and conserving energy in a building.
Fenestration	exterior windows and/or doors placed on the building envelope.
Glare	is difficulty seeing in the presence of bright light such as direct or reflected sunlight or artificial light such as car headlamps at night. Glare is caused by a significant ratio of luminance between the task (which is being looked at) and the glare source.
Hygrometry	is the branch of physics that deals with the measurement of the humidity of air and gases.
Illuminance	is the amount of light energy reaching a given point on a defined surface area, namely the luminous flux (i.e. lumens) per square meter.
Light Scattering	Almost all objects scatter light, that means they reflect the light that illuminates them in all directions.
Luminance	is the amount of light energy emitted or reflected from an object in a specific direction and this is the only form of light we can see. It is measured in candela per square meter.
Multifunctional Building Envelope	is a term which describes a building façade or roof that performs a number of energetic tasks.
Net Zero	indicates a building connected to the energy grids, which is balanced between weighted demand and supply.
Opaque Wall	is a solid wall constructed with a construction material that provides 100 percent screening.
Passive System	does not involve mechanical components and it takes advantage of nature to achieve indoor comfort.
Prototype	is the original model, like a sample on which to base future designs.
Renewable Energy	is generally defined as energy that comes from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, etc.
Retrofit	Is to add a component or accessory to an existing old sub-system and/or systems for the purpose of improving and/or fixing the performance.

Smart Building Envelope	is a term which describes a building façade or roof that performs a number of energetic tasks. The systems may also be separated or not used at all.
Solar Noon	when the sun crosses the meridian and is at its highest elevation in the sky.
Solar Radiation	is radiant energy emitted by the sun, particularly electromagnetic energy.
Sub-system	refers to the collection of construction elements that work together for the same objective in a building system.
Sunlight Collector	collects heat by absorbing sunlight. A collector is a device for capturing solar radiation.
Sustainability	refers to the endurance of systems and processes, focusing on how to keep the systems diverse and productive indefinitely or for a long time.
System	in architecture is synonym of the word "building".
Test Bed	is an experimental platform which is outfitted with instruments and is used for testing, getting feedback, making revisions and studying selected properties under working conditions.
Thermal Comfort	means interpreting the human energy balance equation, the resulting energy fluxes and physiological parameters.
Transparent / Translucent	medium allows the transport of light while a transparent medium not only allows the transport of light but also allows for image formation.
Window-to-wall ratio	is the ratio of the window area to the total external wall area, including the window itself.

CHAPTER 1

Introduction

1. THE ORIGIN OF THE IDEA

"Cities are increasingly expanding their boundaries and populations, and from the climatological point of view, human history is defined as the history of urbanization" **[1].**

Today, research lines are focused on how urbanization is destroying the planet. Patrick Brown, a photojournalist, recently stated the following: *"Now it is not just about saving the planet and the nature, we are reaching the point that is about saving the human race too".* And probably this is the clue. Today's society needs to struggle to make this planet a good place for humans to live within the climate consequences. New technological innovations and urban solutions are pushing cities into a new wave where they are becoming cosmopolitan spaces. As a consequence, in few years the earth will be converted to a planet full of cities. So what can we do to save the human race?

Buildings are designed and built for residential, public, office and commercial purposes. They are considered contributors to the socioeconomic development of a nation at the expense of consuming a large proportion of energy and available natural resources **[2]**. The United Nations Population Division (UNPD) according to

their data source in 2007, indicated that the most developed countries of the world have higher urbanization compared to less developed countries. However, both will keep rising but the less developed countries will rise faster. In fact, 2010 was the year when the world urbanization passed 50% **[3]**. With the increase of industrialization and the consequences with an increase of urban population, both factors have affected drastically the number of urban buildings with major effects on the energy consumption **[1]**. There are several parameters where urbanization affects energy use, and one of them is the relationship between urbanization and economic development. Once the homeowners become wealthier, then as a consequence, they change their consumption patterns with more energy consumption **[3]**. In economy, the term that identifies this behavior is called energy intensity, i.e. the measure of energy efficiency of a country's economy and is usually related to income, urbanization and industrialization. In general, high income countries are most efficient at using energy compared to low and middle income countries **[3]**. Nevertheless, the impact of the urbanization on energy intensity is hard to prognosticate. This is due to the fact that urbanization increases the economy through a higher concentration of consumption and production but it also provides the opportunity for increases in energy efficiency **[3].**

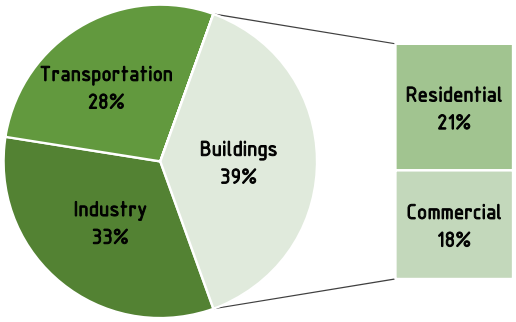
"Efficient-at what? Overly efficient buildings can also be dangerous. [...] Which the "eco-efficiency" movement provides in abundance, with its exhortations to consume and produce less by minimizing, avoiding, reducing, and sacrificing. [...] The goal is Zero: Zero waste, zero emissions, zero "ecological footprint" **[4].**

Figure 1. Concept of sustainability. (Artwork by Antoni Batllori©).

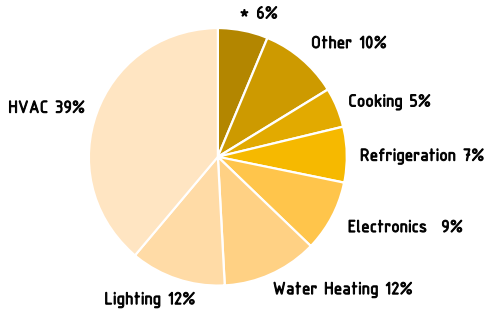
With the increasing development of world energy use because of the world urbanization, energy resources are decreasing and produce major detrimental environmental impacts, e.g. Ozone layer depletion, global warming, climate change, etc. However, some of the most important causes of energy consumption, CO_2 emission and waste generation are due to construction, maintenance and use of buildings, **Figure 1**. A large part of the total primary energy is consumed by buildings located throughout developed countries. According to the U.S. Department Of Energy (DOE) **[5]**, they consume about 39% of the total US primary energy, as seen in **Figure 2a**. This is due to the occupant demand for interior comfort levels and increased time spent inside the buildings which increases the energy demand. Therefore, energy efficiency in buildings is a primary goal of energy policies in many countries **[6]**. Thus, innovation should facilitate minimizing these issues while supporting development at the same time.

On the other side, the issue of physical discomfort in buildings directly affects people with health problems. During the 80s, the World Health Organization (WHO) reported that over 70% of respiratory illnesses are

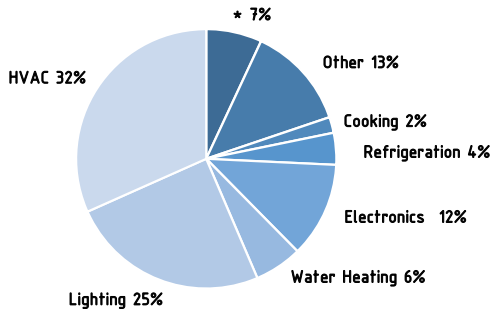
due to badly designed spaces. It is common to find health problems in children and elderly people, who may be living in hot, cold or humid housing conditions. Moreover, areas with poor lighting quality can cause visual problems and noisy spaces can cause hearing problems or stress, for instance. Under these types of negative health conditions, people's efficiency and productivity may be reduced. Therefore, it is necessary to work with an efficient architectural design which aims to harmonize the spaces and create conditions of comfort for their occupants. There is a need to create habitable spaces that suit the functional use and at the same time must be psychologically suitable to develop specific activities.



a. Buildings share of U.S. primary energy consumption (2006)



b. Residential buildings total energy end use (2006)



c. Commercial sector buildings energy end use (2006)

Figure 2. Building energy data source: U.S DOE (2008 Buildings Energy Data Book)

Nevertheless, as it is observed in **Figure 2b** and **Figure 2c**, HVAC followed by electric lighting are the factors that consume the most energy in both residential and commercial buildings. These data clearly indicate the necessity of creating efficient buildings with the aim of saving energy and this is possible by adding passive or active efficient energy strategies **[7]**. However, the first step is to implement an energy efficient building design approach. This can be achieved by simply reducing the use of some existing mechanical building systems which compensate for the additional cost of energy savings features **[7]**. However, an excessive use of passive and active features in a building may be counterproductive. It is observed that low energy buildings perform better than self-sufficient (zero operating energy) buildings in the life cycle context **[2]**. Summarizing, for the building construction industry, it is important to be able to create a sustainable development in the society which is viewed as development with low environmental impact, and high economic and social gains. This requires adoption of a multi-disciplinary approach covering a number of features such as energy saving, improved use of materials including water, reuse and recycling of materials, and emissions control **[2]**.

1.1 Motivation

"All of nature's industries relies on energy from the sun, which can be viewed as a form of current, constantly renewing income. [...] For the majority of our simple energy need, humans could be accruing a great deal of current solar income, of which there is plenty: Thousands of times the amount of energy needed to fuel human activities hits the surface of the planet every day in the form of sunlight." **[4]**.

Solar radiation or sunlight is a universal free source of renewable energy. The survival of life and maintaining of health as conditions of environmental comfort and prosperity are dependent on the effective use of this resource **[8]**. Sunlight is the most abundant renewable energy source available. Many countries, due to their locations into the hemisphere, have a surplus of sunlight. Nevertheless, the solar energy can be harnessed with the help of new solar technologies in order to generate electricity, utilize daylight, heat water, and so on. Nowadays, it is common to find solar systems integrated in buildings in different ways from before **[9]**. In fact, the façades and roofs of a building can collect large amounts of solar energy. For this reason, multifunctional building envelopes that supply energy, are gaining the attention of the construction market **[9]**.

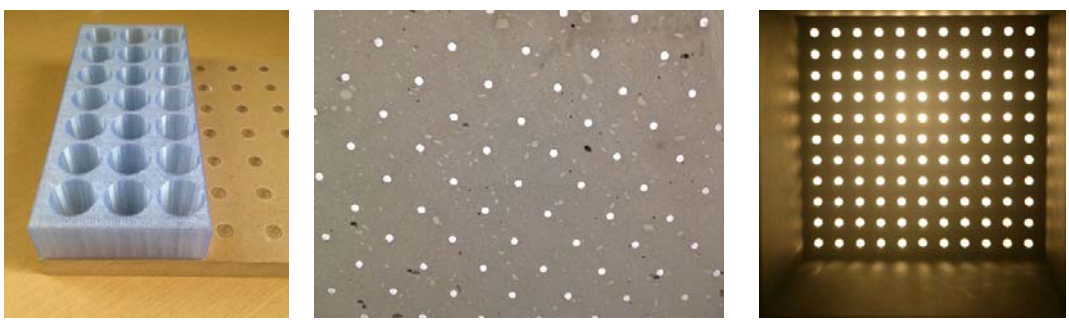


Figure 3. Overall views of the Translucent Concrete Panel (TCP).

On the other side, most of the existing buildings are badly constructed without or with unsuitable insulation on the building envelope and without any heating or cooling systems. As a consequence, occupants suffer from unacceptable interior thermal comfort due to an inappropriate envelope which causes energy losses through the façades and roofs. The building envelope can be compared to human skin behavior regarding its reaction towards the exterior thermal conditions. Basically, to its complexity is based on its needs to prevent water and air infiltration in order to avoid moisture and gain and/or lose heat through it. However, occupants can increase the energy savings by energy retrofitting the existing façades and roofs of a building while improving the occupants' interior thermal comfort.

As aforementioned, HVAC followed by electric lighting are the factors that consume more energy in both residential and commercial buildings **[5]**. Furthermore, daylight has an important effect on alertness and mood of individuals **[10]**, offering health and psychological advantages, e.g. less absence at work **[11]** and higher productivity. Accordingly, to design an energy efficient building envelope is presented as a solution to alleviate and reduce the energy inefficiency into the buildings, especially in terms of interior daylighting. However, the existing solutions for building envelopes are mainly based on external shading components, smart windows, climate adaptive building shells (CABS), among others, which mainly work with electric systems. Therefore, the Translucent Concrete Panel (TCP), **Figure 3 [12]**, comes up as an alternative passive solution for façades and roofs, which is able to intelligently reduce the energy consumption of the building

and improving the comfort of the occupant's by optimizing the entrance of natural sunlight and heat into the building's interior through the design, construction and maintenance phases. However, this novel multifunctional construction solution has not common daylight transmission properties due to its design configuration and materials. It is made up of existing components, i.e. Compound Parabolic Concentrators (CPCs) aligned with Optical Fibers (OFs). Commonly, the CPCs are used in the solar energy industry as solar collectors, and OFs are mainly used for data transmission in telecommunications. In addition, the TCP has to deal with the fact that it cannot be computationally modeled on a practical commercial scale because there is not open software in the market able to simulate the daylight performance of the CPCs and OFs **[13]**. For this reason, before disseminating the TCP into the construction market, it is necessary to assess and improve its daylight performance as a way to validate it as a feasible energy efficient solution for daylighting in buildings. Summarizing, the TCP is a novel multifunctional building envelope that might alleviate part of the existing problems of energy consumption in new and existing buildings while improving the occupants' interior comfort. Therefore, the proposal of improving the buildings' energy efficiency by achieving a reduction in energy consumption with innovative technologies while creating a comfortable living environment, is considered innovative. In fact, these are key factors in moving forward with the research on novel multifunctional building envelopes and later implementation into the building's market.

2. OBJECTIVES

2.1 General Objectives

a. Residential building designed by Richard Neutra (1940) (San Francisco-USA)

b. Commercial Building designed by Frank Lloyd Wright (1948) (San Francisco-USA)

Figure 4. Overall view of two different façades typologies.

After stating some of the existing problems on energy efficiency through the building envelope and the importance for occupants of having sufficient interior comfort, the present research first seeks to understand how to save on energy consumption through the building envelope, i.e. façades and roofs, while improving the occupants' interior thermal comfort based on an existing residential building used as a single case study. And the second issue of this Thesis is to assess and improve the daylight performance of the novel multifunctional building envelope called TCP, in order to be used in the future as an energy efficient solution for daylighting for façades and roofs. The thermal properties and energy savings of the TCP are out of the scope of the present research.

The objective of this Thesis is to resolve and answer some of the general issues previously mentioned in this chapter. For this reason, it is important to state some of the basic common problems on a building envelope as a way to understand its behavior and from this point to be able to improve on energy efficiency. In fact, the building case study shows how is possible to energy retrofit existing façades and roofs while improving the interior living environment and also reducing the energy consumption of the heating and/or cooling systems. This confirm the need to urge the construction industry to design and develop novel energy efficient construction solutions, e.g. Translucent Concrete Panel (TCP). The TCP has the capability of daylight permeability in an anidolic way through the opaque parts of the exterior façades and roofs. Due to the nature of traditional building materials blocking the passage of natural light, **Figure 4**, there is a constant requirement of artificial lighting into the building, even during daytime. On the other side, some of the most commonly used daylight metrics are not precise enough in order to assess the daylight performance of a prototype. In addition, there are not open software able to simulate the daylight performance of the CPCs and OFs **[13]**. For this reason, there is a need to design new daylight tests adapted to the TCP characteristics in order to evaluate its daylight performance. In fact, this is the first required step for future research lines that will be based on computer simulations that to rapidly assess influential parameters of the novel building envelope in several building sub-systems and systems.

2.2 Specific Objectives

In order to achieve the aforementioned general objectives, specific objectives are proposed as follow:

SUBJECT	SPECIFIC OBJECTIVES
Building Envelope	__ Identification of the basic construction problems that were found in an existing building envelope of a residential building in a developed country used as a case study. The target is to illustrate the construction problems that the envelope case study generates after several years into use. __ Assessment and improvement of the thermal properties of the building envelope of the building case study. The objective is to highlight the energy savings that can be achieved for façades and roofs of the building case study by conducting energy improvements for to the insulation of the envelope while improving the occupant's interior thermal comfort. __ Introduction of the novel smart energy efficient dynamic building envelope called TCP, considering its construction components, geometry and daylight behavior. The thermal properties are out of the scope of this research.
Daylight Performance	__ Basic demonstration of the daylight permeability of the TCP innovation. Thus, preliminary daylight tests have been designed and later conducted outdoors. __ Improving the amount of sunlight captured and daylight scattered from the exterior to the building's interior of the TCP. In this study, different OFs aligned with CPCs of different geometries have been tested outdoors throughout January to July 2015 under real sky conditions. __ Design, construction and implementation of a small portable test bed (SPTB) whose design physically simulates the building envelope, i.e. façades and roofs, and is able to test outdoor construction solutions. __ Assessment of the daylight scattered and diffused by the TCP under real sky conditions using a dynamic daylight performance method.

All the aforementioned specific objectives are consequentially explained throughout the different chapters of the present research, with the objective to disseminate:

- The importance of designing an energy efficient building envelope for energy savings and interior comfort and health of occupants.
- The TCP as a novel multifunctional building envelope solution into the building construction market.

2.3 Methodology

The present Thesis is mainly based on theory combined with experimental outdoors and indoors tests designed specifically to assess the energy savings after the energy retrofit of an existing building envelope and to evaluate the daylight performance of the TCP innovation. It is noted that the glare assessment of the TCP together with the thermal analysis, are out of the scope of this Thesis. On the other hand, all the daylight tests have been fully developed at the University California, Berkeley (USA) within the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) project.

The present Thesis has been developed thorough **6 Chapters**, where four of them contain specifically the conducted research. Each of the four chapters will be published in a scientific international journal catalogued within the Journal Citation Reports (JCR). All the communications, abstracts and posters for international congresses, have been intentionally left out. All those works are considered previous or partial parts of the Thesis. In **Figure 5**, the outline of the research is schematically illustrated. The Thesis is divided into the following chapters:

Chapter 1 explains in a global context the philosophy, motivation, and main idea of the present research. It is followed by an explanation of the origin of the needs for energy savings and an introduction of the lines of the research of the present Thesis by specifying the main and specific objectives. In addition, it also describes the used methodology throughout the Thesis.

Chapter 2 introduces the basic concept of energy savings and interior thermal comfort through the building envelope. Therefore, the research assess an energy retrofitted building envelope of an existing residential building used as a case study. The objective is to explain the current basic common problems on façades and roofs in existing constructions. The building envelope case study was energy inefficient due to the poor construction solution used for façades and roofs. For this reason, it was required to improve the thermal properties of the entire exterior of the building. The study of the assessed building is based on a pre-diagnosis of the envelope which shows their existing problems and also suggests construction solution improvements. For the energy assessment of the building case study, four apartments were monitored with sensors before and after the energy retrofit work. The main objective of this chapter is to highlight the importance of the building envelope and its viability in achieving energy savings by increasing the energy efficiency of the building envelope while improving the occupants' interior comfort.

Chapter 3 introduces the Translucent Concrete Panel (TCP) construction solution, and also justifies its daylight permeability with some preliminary experimental daylight tests conducted outdoors. Therefore, the present chapter theoretically describes all the different components of the TCP innovation, i.e. geometry and physical behavior, together with a state of knowledge of the CPCs and OFs. The common use of both materials together with their geometries are explained separately in this chapter. Afterwards, TCP daylight

behavior when the solar concentrators and optical fibers are aligned according to the TCP design, is discussed in details. The conducted outdoor tests individually assess different CPCs or OFs in panel configurations. Later, these panels are assessed together in order to simulate the TCP technology. The obtained preliminary results define the objectives of the following chapters.

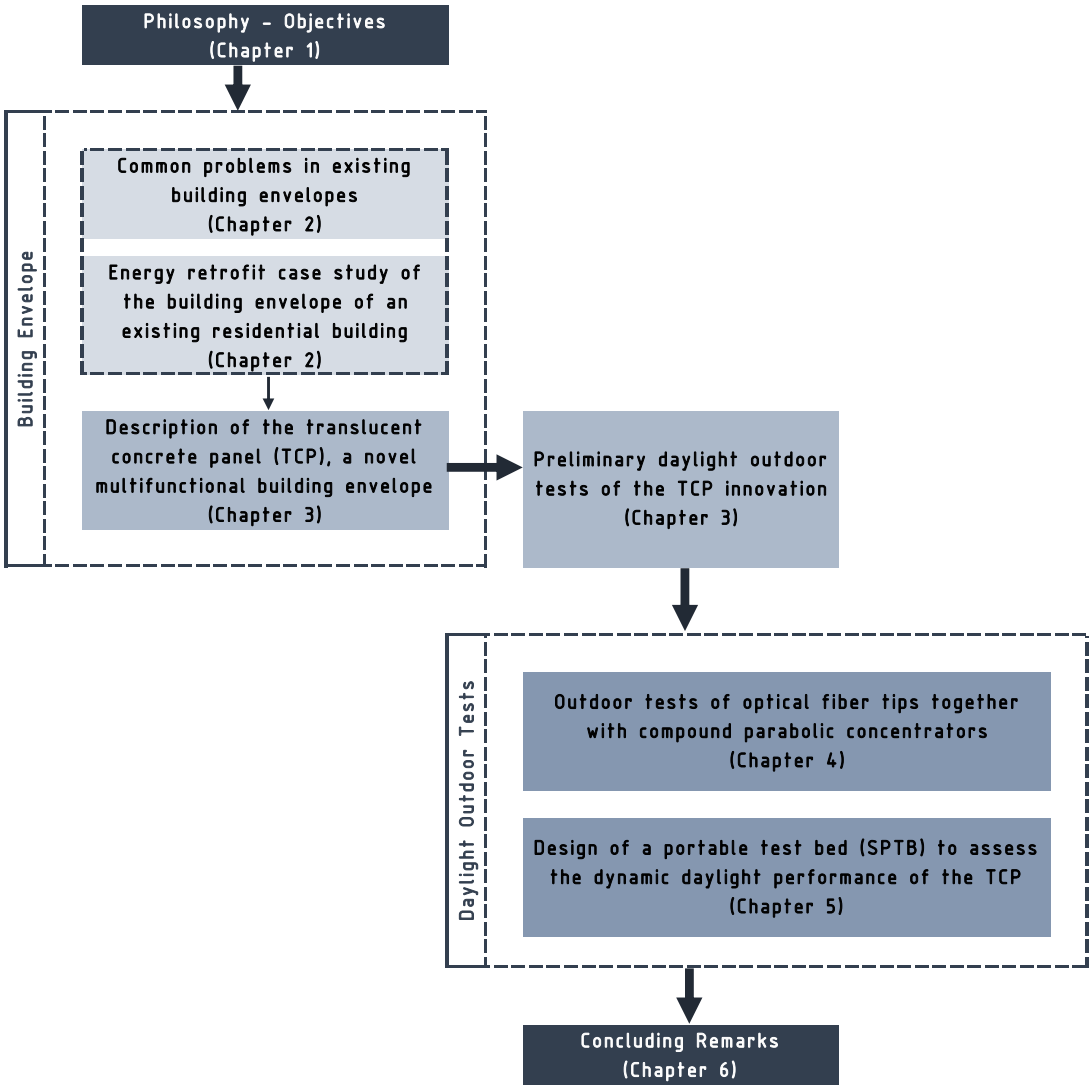


Figure 5. Outline of the research.

Chapter 4 explains a series of new outdoor daylight tests specifically designed in order to improve the amount of sunlight captured and daylight scattered through the TCP from the exterior to the interior of the building. As the TCP is designed with an unusual geometry and materials, i.e. solar concentrators and optical fibers, there is a need to design new tests for its daylight performance assessment which are tailored to the TCP components. Therefore, several optical fibers tips are tested individually and together with different solar concentrators as a way to improve the daylight permeability of this novel construction solution. The obtained results and final conclusions will help in future research lines to create new computer programs which are able to simulate all the daylight properties and thermal improvements of the TCP.

Chapter 5 describes the design, construction and implementation of a small portable test bed (SPTB) which is able to test outdoors the daylight performance of a small non-scaled portion of the TCP technology. The TCP is an unusual solution for building envelopes, and currently there are not standard tests to assess and improve its daylight performance. The objective of this chapter is to assess the dynamic daylight performance of the OFs of the TCP, and also to corroborate the design of the SPTB with some outdoor tests. The presented SPTB aims to be versatile enough as to simulate the whole building envelope, i.e. façades and roof. It also seeks to test specimens at the same time under the four compass orientations. The obtained results and final conclusions will help in future research lines to create new computer programs which are able to simulate and assess the daylight performance of the TCP.

Chapter 6 summarizes the content of the Thesis with a statement of the conclusions obtained from the previous chapters divided into general and specific conclusions. Moreover, this chapter presents and suggests the future lines of research.

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CHAPTER 2

Energy Retrofit of an Existing Affordable Building Envelope in Spain

1. ABSTRACT

In the last few years, the European Union has been concerned with how to achieve a significant reduction in the energy consumption from existing buildings. Many of these buildings located in developed countries do not reach the minimum energy required for comfortable environment within the dwellings. The present research describes a real case of a building envelope energy retrofit undertaken on an existing affordable multifamily building in Montcada i Reixac, Barcelona. With the economic support from the Catalan Government together with the local Building Department, it was possible to energy retrofit the main façades and roof of the building in this case study. Moreover, the Building Laboratory at Universitat Politècnica de Catalunya carried out the energy retrofit project and its construction. Finally, the Construction Technologic Center iMat, together with the Building Department of this municipality, conducted the monitoring of the building before and after the energy retrofit effort. The paper summarizes all the conducted work where it was observed that the energy retrofit of the building envelope resulted in about 12% savings in energy consumption.

KEYWORDS
Affordable Housing, Building Envelope, Energy Poverty, Energy Retrofit, Energy Savings.

2. INTRODUCTION

The European Union (EU) sheltered about 196 million dwellings in 2004. Over 50% of them were built before 1970 and about 1/3 were built between 1970 and 1990. The total energy consumption in Europe from the existing dwelling stock is around 63% in the building sector **[1]**. Currently, most of these buildings are over 50 years old and they were built according to the socioeconomics prevailing at that time, revealing poor energy performance nowadays. After the Second World War, Europe was war-torn. Therefore, a new migratory wave of population moved to the continent for its reconstruction **[2]**. This led to the construction of new residential buildings in a fast and economical way in order to shelter the new immigrants. This fact was also observed in Spain through the Spanish Stabilization Plan that took place during the 60s. In that case, the emigration helped to resolve the Spanish unemployment caused by the Spanish Civil War **[2]**. Nevertheless, between 1950 and 1970, there was no territorial immigration homogeneity in Spain. Accordingly, population concentration took place in the largest Spanish cities, i.e. Barcelona and Madrid **[3]**, where most of the buildings erected in these cities during those decades were in response to the migratory movement. Unfortunately, such buildings were badly constructed without or with unsuitable insulation on the building envelope and without any heating systems. These new urban areas were settled in non-urban zones, but over the years they have turned into marginal neighborhoods surrounding the big cities with low income population. As a result, nowadays in Spain most of the buildings in these marginal neighborhoods have severe construction problems easily observable on the façades and roofs. At present, these dwellings suffer from unacceptable interior thermal comfort due to inappropriate building envelope solutions. This causes energy losses through the façades and roofs creating low thermal comfort inside the buildings.

It is important to improve people household's energy situation. Kammen and Kirubi **[4]** specify that energy poverty affects poor communities and poor nations far more severely and more directly than in developed nations. Improving energy services for poor households in developing countries remains one of the most pressing challenges. Moreover, these households usually depend on traditional forms of energy leading to significant health impacts and there has been little progress in meeting this challenge. Nevertheless, according to Urge-Vorsatz and Tirado-Herrero **[5]**, the concept of energy poverty has become recently important recently in several developed countries, where general poverty has been eradicated while some inequalities in the living conditions of the population still prevail. This viewpoint argues for an "energy poverty alleviation" efforts to provide modern energy services to these households **[6]**. On the other hand, demands for energy are related to the economic development, but the energy supply is facing shortage **[7]**. Achieving energy efficiency in buildings is the first necessary step towards sustainable energy buildings **[8]**. Old and badly constructed buildings are difficult and expensive to heat where inadequate temperature within the dwellings can cause health problems to the occupants, especially during cold seasons. Consequently, a connection is observed between domestic energy and health. In addition, colder houses place more physiological stress on the elderly, babies, and sick people, who have less robust thermal control systems and are also likely to spend more time inside **[9]**. Therefore, the present research is based on a real case study of an energy retrofit of the building envelope of an energy inefficient existing affordable multifamily building in a developed European region. In this study, the retrofit of the building envelope focused on the opaque walls and roofs. The main objective in this case study was to insulate the

building on the exterior to increase the indoor temperatures as a way to reduce energy consumption and contribute to the improvement of comfort and health.

3. BACKGROUND

There is very little research about energy retrofit assessments on existing multifamily buildings and far less on affordable housing in developed countries. Most of the literature is focused on energy efficient building envelope design in residential high-rise apartments and office buildings in developed countries; assessments of the energy consumption of existing buildings; or studies about energy poverty in developing countries. However, some literature is focused on the building envelope thermal design for energy efficiency of residential buildings considering solar heat gains and losses, and natural ventilation. The heat transferred through the envelope varies in summers and winters, and the heat and mass transfer must be considered when providing natural ventilation. It is necessary during the design process to identify thermal design conditions that will provide maximum heat insulation and feasible thermal indices for building envelopes, making it a challenge to achieve an energy-efficient building design **[10]**. Some studies illustrate how in developed countries the energy consumption in residential and tertiary sectors is very high where there are many possibilities for energy savings. Energy conservation measures are developed for newly constructed buildings and for buildings under retrofit. However, to achieve a significant reduction in energy consumption apart from the standard energy-efficiency methods, innovative technologies should be implemented, including renewable energy sources **[8].** According to Magrini et al. **[11]**, the retrofit of the opaque part of the building envelope represents an important approach for the reduction in global European energy consumption as prescribed by the Directive 2010/31/EU. In fact, the improvement of the energy performance of existing buildings is one of the primary goals of the most recent European Directives, starting from 2002/91/EC. In the case of renovation or maintenance of building walls, the minimum requirements imposed at the national level usually indicate precise limits on the thermal transmittance values of walls.

The building envelope is an inclusive term which includes all the façade and roof components that limit the minimum energy demand to obtain the thermal comfort in the building interior. It separates the unconditioned environment of the building, i.e. the exterior weather changes of the geographical location of the building, from the conditioned one, i.e. the habitable spaces. In the present research, the building envelope refers to the following three components: External opaque walls, window areas, and roofs. The envelope is exposed to solar radiation and other environmental changes throughout the year. In addition, exterior fenestration, i.e. doors and windows, are placed on the envelope which usually have non-insulation properties, and opaque walls are outfitted with outdated or non-insulation layers. As a result, the energy in the building interior is usually lost through the envelope. Opaque walls are the predominant part of a building envelope expected to provide thermal and acoustic comfort in a building without compromising aesthetics. The thermal resistance (R-value) and the thermal transmittance (U-value) of the wall are crucial as they influence the building energy consumption **[12]**. Walls with thermal insulation can create condensation when the relative humidity of ambient air is greater than 80%, provided that the convective and radiative heat transfer coefficients of the exterior wall are small. This problem is especially significant during the cold seasons, when humidity levels are high **[12].** The exterior fenestration placed on the envelope provides thermal comfort and optimum illumination levels within the building and also plays an important role on aesthetics of the building design **[12]**. However, roofs are exposed to solar radiation and weather changes making them critical parts of the envelopes with large amounts of heat gain/loss influencing the indoor comfort

conditions for the occupants **[12]**. Some studies evaluated the wall insulation thickness influence according to its position on the building envelope **[13]**. Over the years, the Spanish Building Code (CTE) has reduced the recommended thermal transmittance (U-value) of the exterior fenestration and opaque elements placed on the building envelope as a way of increasing the thermal performance within the dwellings. However, thermal inertia is one of the most important parameters for improving thermal comfort conditions and reducing the heating and cooling building energy demands **[14]**.

The thermal transmittance (U-value) is the reciprocal of the sum of all the resistances (R) of the materials in an assessed construction element. The resistivity (R) is represented by **Equation 1**, where *k* is the thermal conductivity coefficient of the material and *d* is the material thickness. Whereby, the thermal transmittance (U-value) in [W/m^2/°K] is represented by **Equation 2**, where *Rso* is the thermal resistance of the outside surface of the element, *Rsi* is the thermal resistance of the internal surface of the element, and Ri, i =1, 2, … is the resistances of the i-th material in the element.

$$R = (1/k) \times d \qquad \textbf{Equation 1}$$

$$U\ (\text{element}) = 1 / (Rso + Rsi + R1 + R2 + \ldots) \qquad \textbf{Equation 2}$$

4. PRELIMINARY CONDITIONS

4.1 Climate Conditions

Montcada i Reixac is a small town that is part of the metropolitan area of Barcelona, Spain, and it is located at the confluence of two rivers: Ripoll and Besòs. According to the Statistical Institute of Catalonia, the town has an altitude of 36 m, and it is located at a latitude 41° 29' N and longitude 2° 11' E. Its climate is classified as Mediterranean, with very high humidity and hot summers. According to the weather records from the Cerdanyola Observatory, between 2008 and 2010, the winter period took place from the end of November through February and the average temperature was around 8°C. Occasionally, the minimum temperature was slightly lower than 0°C during these months. It is to be noted that the winter of 2010 was colder than usual. During the spring and fall seasons, the weather is warm and very rainy with showers and heavy thunderstorms with average temperature slightly lower than 20°C. In the summer, between June and September, the weather is very hot and humid with the maximum temperature sometimes reaching over 35°C. This high temperature causes a high population demand for air-conditioning. The average rainfall between 2008 and 2010 was about 601 mm and most of it took place during the spring and fall seasons. The location has an average exterior humidity of around 70%, which is slightly higher during the colder months of the year.

4.2 La Ribera Neighborhood

As shown in **Figure 1**, "La Ribera" is a small neighborhood in Montcada i Reixac which is located at the southern part of the town and was built during the 60s and 70s with affordable multifamily residential buildings. The original population came from the Spanish migratory movement of the 60s. However, nowadays this neighborhood shelters immigrants from different countries. According to the City Hall records, in 2005 La Ribera had a population of around 2,000 inhabitants, resulting in high urban density area. The neighborhood consists of a total of 41 attached residential buildings with an average of 6 floors in each

building. Usually, on the ground floor there are small commercial spaces, and the other floors comprise the apartments. Each building has at least two façades, one facing the main street and the other facing the interior courtyard. The living room and bedrooms are placed next to these façades. Furthermore, each building has two interior unroofed light wells that illuminate and ventilate kitchens, laundry rooms, and bathrooms. The roofs are basically flat and inaccessible.

4.3 Energy Retrofit Objectives

Between 2008 and 2012, the Montcada i Reixac Building Department together with the Catalan Government retrofitted the building envelope of different buildings from "La Ribera" neighborhood under the Catalan directive 2/2004 June 4th (a.k.a Pla de Barris). This directive required to improve the neighborhoods, urban areas, and locations that needed special attention. The aim of this energy retrofit was to improve the buildings energy efficiency by reducing energy consumption while creating a comfortable living environment. For this reason, the main work in all projects was to add an external thermal insulation in all the façades and roofs. This is a passive technique for cooling the indoor environments which depends on the weather conditions of the building location. At no time, the retrofit design project considered to replace the existing exterior fenestration.

The objective of this study is to summarize and assess a real case of energy retrofitting of a building envelope, namely the external opaque walls and roof, of an existing energy inefficient affordable building located in Montcada i Reixac, Barcelona, Spain. Therefore, the presented research investigates the thermal inertia properties of the building case study before and after retrofitting its envelope. From the data obtained of the monitored apartments and the weather station, some conclusions are derived about the energy savings after the energy retrofit work.

Figure 1. Location of "La Ribera" neighborhood. (Source: Google Maps).

5. BUILDING CASE STUDY

According to the Spanish Cadaster (a public register of property ownership including boundaries and tax assessments) records, the building being retrofitted was built in 1964. **Figure 2** shows the original footprint with a total area of about 350 m^2 and height between finished floors of 2,75 m. Each floor contains 5

apartments where all layouts include a living room, 3 bedrooms, a kitchen, a bathroom, a laundry room, and a hallway. Each apartment faces either the street or the interior courtyard. Most of the apartments have a balcony.

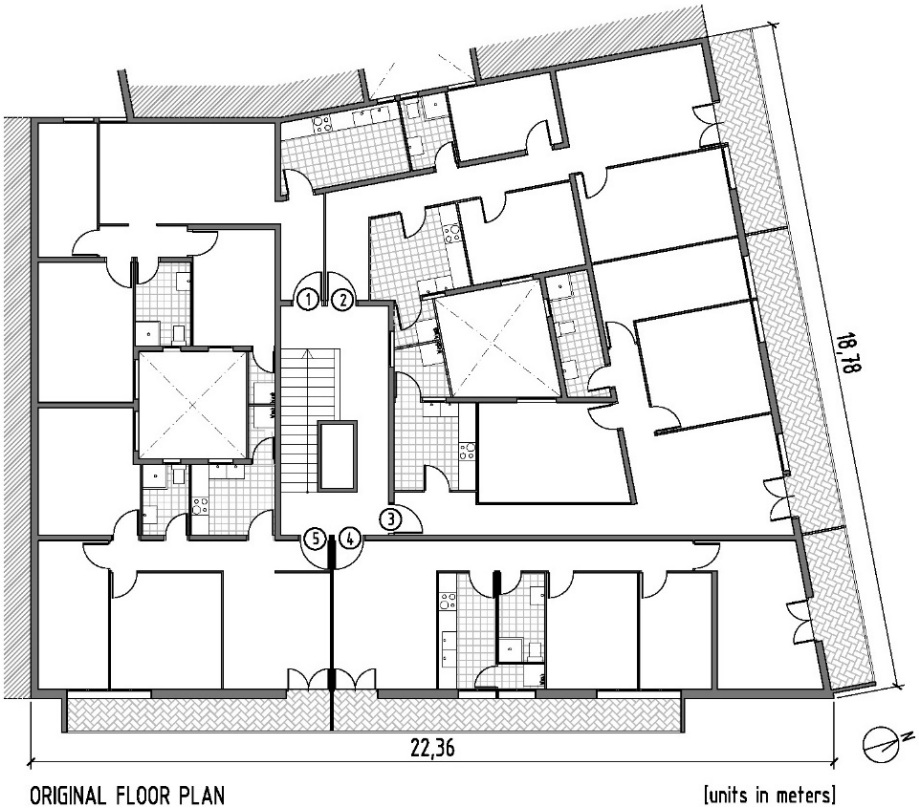


Figure 2. Building case study original floor plan [Units in meters].

As a typology, it is a common affordable multifamily building divided into 6 floors and adjacent to two buildings. On the ground floor, there are 2 commercial spaces. On the remaining 5 floors, there are a total of 21 apartments. From **Figure 3**, the building has 3 façades. The first and main façade, **Figure 3a**, is facing the main street and orientated towards the East. The second and side façade, **Figure 3b,** is orientated towards the North. The third façade, **Figure 3c**, is placed in the interior courtyard and faces the West. The building structure consists of bearing walls made of hollow brick masonry with thickness of 150 mm. This was a very common affordable construction method from the 50s through the 70s in Spain. Currently, according to CTE, that construction method is not allowed where nowadays walls must be made of perforated or solid brick masonry. The floors consist of reinforced concrete joists with high-alumina cement with precast concrete filler blocks. The façades were erected with a single layer of hollow concrete blocks with thickness of 150 mm without any insulation layer or air cavity. This is a very unusual construction solution in Catalonia even for an affordable building. Before the 80s, it was common to include an air cavity but it was not required to add an insulation layer into the façade. As shown **Figure 3b**, throughout the years, some owners have covered part of the balconies of the façade facing the North into envelope made of windows of aluminum framing creating a kind of Trombe Wall effect. The original exterior doors and windows of the building were made of wood with a single glass of about 3 mm thickness. According to the tenants, they had been replaced over the years with new ones made of aluminum without thermal break and with a single glass. However, the existing quality of the exterior openings was still low. As a shading technique, the openings have roll-up blinds. The window-to-wall ratio (WWR), i.e. the ratio of the window

area to the total external wall area, of the main façade facing the East is 24%. For the side façades facing the North and West, WWR are 25% and 40%, respectively. It is known that when the WWR increases, the solar heat gain and exchange increase because the heat transfer coefficient of a window is usually larger than that of a wall **[15]**. The roof of the case study building, **Figure 3d**, is flat and inaccessible. Originally, the roof consisted of sloped lightweight concrete under an asphaltic layer with a finishing pavement made of ceramic tiles. Over the years, the roof was finished with different layers. Before the retrofit construction work, there was a waterproof paint over the original pavement.

a. Main Façade b. Side Façade

c. Rear façade d. Roof

Figure 3. Overall view of the building case study façades and roof before energy retrofit work (2007).

Originally, the apartments in the case study building were not outfitted with any active cooling system. Over the years, some tenants adapted their own apartments with natural gas boiler with water radiators. Others apartments are using electric heating systems or domestic Butane gas. **Table 1** lists the layout of each monitored dwelling with its area, volume, and occupancy.

Table 1. Floor plan layout, area, volume and occupancy of the monitored apartments of the building case study.

Unit	Apartment	Occupancy	Layout	Area [m²]	Volume [m³]	Unit	Apartment	Occupancy	Layout	Area [m²]	Volume [m³]
AP1	**Apart. 1-5** Third Level Facing East	1 Elderly Person 1 Person >10 years A dog	Living room	9.75	24.38	AP3	**Apart. 4-4** Sixth Level (under roof) Facing East	2 Elderly Persons 1 Person >10 years No Animals	Living room	12.03	30.08
			Bedroom 1	10.07	25.18				Bedroom 1	8.28	20.70
			Bedroom 2	8.09	20.23				Bedroom 2	6.50	16.25
			Bedroom 3	9.80	24.50				Bedroom 3	11.23	28.08
			Bathroom	2.57	6.43				Bathroom	3.25	8.13
			Kitchen	4.64	11.60				Kitchen	5.20	13.00
			Laundry room	1.10	2.75				Laundry room	0.91	2.28
			Hallway	5.23	13.08				Hallway	6.06	15.15
			TOTAL	**51.25**	**128.13**				**TOTAL**	**53.46**	**133.65**
AP2	**Apart. 2-2** Fourth Level Facing North	2 Elderly Persons No Animals	Living room	12.03	30.08	AP4	**Apart. 4-5** Sixth Level (under roof) Facing East	1 Elderly Person 1 Person >10 years No Animals	Living room	12.45	31.13
			Bedroom 1	5.83	14.58				Bedroom 1	10.07	25.18
			Bedroom 2	10.37	25.93				Bedroom 2	8.09	20.23
			Bedroom 3	7.52	18.80				Bedroom 3	9.80	24.50
			Bathroom	2.60	6.50				Bathroom	2.57	6.43
			Kitchen	6.17	15.43				Kitchen	4.64	11.60
			Laundry room	1.39	3.48				Laundry room	1.10	2.75
			Hallway	8.79	21.98				Hallway	2.68	6.70
			TOTAL	**54.70**	**136.75**				**TOTAL**	**51.40**	**128.50**

6. ENERGY RETROFIT PROJECT

In June 2007, the Building Laboratory at Universitat Politècnica de Catalunya (UPC) developed a report about the condition of the building envelope of this case study. The diagnosis was described and used as a base for the design of the energy retrofit project. **Table 2** summarizes the diagnosis, indicating the main characteristics and problems of the building envelope components, observed in **Figure 4**.

Based on the diagnosis report, the Building Laboratory at UPC prepared the energy retrofit project during summer 2007. The design project resolved all the problems observed during the diagnosis, **Table 2**. The presented research focuses only on the energy retrofit of the opaque walls of the façades and roof. The other construction problems observed and later resolved during the construction process, e.g. structural problems on the cantilever beams, rusted railing, thermal breaking and so forth, are out of the scope of this paper. The project did not consider replacing the exterior existing fenestration, i.e. exterior doors and windows, or resolving the thermal break problem of those openings. It is necessary to clarify that this was a public project supported with a specific budget, and there was not enough public fund to assume all the required retrofit work. Thus, it was necessary to set priorities and the project ended up not proceeding with the exterior fenestration replacement in favor of resolving existing structural problems of the building.

During the design of the energy retrofit project, it was required by the Catalan Government and the Building Department of the municipality to consider construction specifications to achieve the minimum energy requirement for the envelope, i.e. the opaque walls and roofs in this study. Thus, the building case study was checked again to verify the diagnosis report. During this design process, the architects decided what energy solution led to better energy savings. During the process of retrofitting existing buildings, it is important to choose an appropriate solution that must be energy efficient and feasible from a technical and economical points of view. Actions on the existing building envelope are not always possible and they must be carefully evaluated. For example, higher thermal insulation can be achieved, causing worse hygrometrical behavior of the walls **[11]**. It was necessary to control the thermo-physical characteristics of the building envelope with the thermal transmittance (U-value) and inertia, **Figure 5**.

a. Details of existing façade

b. Rusted railing embedded into the façade

c. Cracks through the floor thickness

d. Moisture and water stains under the balconies

Figure 4. Overall view of the existing condition of the building case study before the retrofit work.

a. Main façade

b. Side façade

c. Rear façade d. Roof

Figure 5. Overall view of the building case study façades and roofs after the energy retrofit work (2010).

Table 2. Reported building case study diagnosis.

	PROBLEM DESCRIPTION	DIAGNOSIS	SOLUTION
Structure	**Horizontal Structure (Floors)** Joists made of concrete with aluminous cement and precast concrete filler blocks.	Without apparent problems.	-
	Vertical Structure (Walls) ▪ Bearing walls made of hollow brick masonry. ▪ 150 mm thickness.	Without apparent problems.	-
	Cantilever ▪ Same structure as the horizontal walls. ▪ Ceramic pavement.	▪ Horizontal cracks along the cantilever exposed edge due to the aluminous cement process. ▪ Owners removed original pavement or just added a new one over the original.	▪ Retrofit the cantilever beams against the aluminous cement process. ▪ Remove existing pavements and put a new one including an appropriate waterproof layer below it.
Façade	**Façade Envelope** ▪ One layer of hollow concrete block masonry. ▪ 150 mm thickness. ▪ No insulation layer.	▪ There are no external visible cracks on the building envelope walls. ▪ Moisture problems inside apartments.	▪ Remove the existing cladding. ▪ Observe and subsequently repair existing cracks on the façade walls. ▪ Insulate façades with a 60 mm thick external insulation layer. ▪ Final cladding and light color paint.
	Cladding Finishing plaster and paint.	Cladding full of hairline cracks, cracks, bulge, dust, water stains, etc.	
Roof	▪ Flat and inaccessible roof. ▪ Multiple outdated layers. ▪ Insulation layer. ▪ Pavement made of ceramic tiles. ▪ Waterproof painting over original pavement.	▪ Water filtration from the roof to the apartment interior. ▪ Heat gains/losses inside apartments during hot and cold seasons. ▪ Outdated insulation layer has lost its properties.	▪ Remove all roof layers except sloped lightweight concrete (pavements, thermal insulation, waterproof, etc.) ▪ Rebuild a new roof with a new construction method and add an 80 mm thick insulation layer.
External Elements	**Railing** ▪ Steel tubing with a final black color paint. ▪ Tubing embedded inside the structural (horizontal and vertical) elements.	Observed cracks around all the railing embedded into the envelope due to the rust of the railing.	▪ Remove all railings of the façades. ▪ Design and build new ones according the CTE (1.10 m high) ▪ In this project, exterior fenestration (doors and windows) were not changed for economic reasons.
	Carpentry Work Original external fenestration made of wood.	Over the years, owners have replaced the original units with new aluminum ones.	

6.1 Façades

The façades were erected with a single layer of hollow concrete blocks with a thickness of 150 mm without any insulation layer or air cavity. It was composed of the following layers: 1) On the outermost side, a 20 mm layer of cement and sand plaster with a final light color paint, and 2) On the innermost side, a 15 mm layer of gypsum plaster with a final light color paint. Thus, the total thickness of the façade before the energy retrofit work was 185 mm. The maximum overall U-value for the exterior opaque walls considering the thermal breaks was established at 1.89 W/m^2/^{o}K. The existing floors had a thickness 200 mm using reinforced concrete joists and precast concrete filler blocks. Over them, there was a 10 mm thick pavement placed on a 40 mm thick mortar layer. On the innermost side of the floor, there was a finish of 15 mm gypsum plaster with a final light color paint. The total thickness of the existing floor was 265 mm with a U-value of 2.99 W/m^2/^{o}K. The existing construction façade solution did not satisfy the CTE, which defined the building as C2 according to its location, with acceptable maximum overall U-value for the wall façade of 0.73 W/m^2/^{o}K. Thus, the energy retrofit project proposed adding an insulation layer on all the existing façades to reduce the existing U-value to be below the maximum allowed by the CTE, **Table 3**.

a. Existing cladding removal

b. EPS thermal insulation addion

c. Cement and sand plaster layer added over the EPS thermal isolation

Figure 6. Overall view of the energy façade retrofit construction process.

The energy retrofit façade project proceeded with the requirement that the interiors of the apartments are not altered due to the thermal insulation addition because of: a) The apartments were occupied and reducing the already small space of the dwellings by adding layers to its interior surface was not acceptable; b) The dwellings have experienced minor alterations throughout the years because of the tenants needs. For these reasons the new thermal layer was decided to be placed on the exterior side of the opaque walls, which is judged to be a better solution for the global energy behavior of the building

envelope. However, this insulation retrofit had to respect the shapes of all existing exterior openings of the building, including the shadings. Therefore, the architects designed the construction solutions of the façade with the aim to minimize the thermal break around those openings. The Montcada i Reixac Building Department required the addition of an external insulation layer of Expanded Polystyrene (EPS) foam with a minimum thickness of 60 mm. This is a closed-cell insulation resistant to moisture which is manufactured by expanding a polystyrene polymer. The EPS, which is usually white, is a material to be used over a vapor barrier and under the exterior cladding, as shown in **Figure 6**.

The final energy retrofit wall façade construction solution consisted of a 15 mm stucco layer with a final light green color on the exterior side of the existing façade wall placed over a 15 mm thick cement and sand plaster layer. Below the plaster layer was the 60 mm thick EPS foam thermal insulation panel. On the innermost side, the façade consisted of a 15 mm layer of gypsum plaster with a final light color paint. The total thickness of the energy retrofitted façade including the 150 mm thick bearing wall of hollow brick masonry together with a 20 mm cement and sand plaster layer, was 275 mm and with a U-value of 0.48 W/m²/°K, i.e. less than the maximum U-value of 0.73 W/m²/°K, which is specified by the CTE.

Table 3. Thermal conductivity and U-Values for the façade case study.

Element	Composition of the construction element (from outer side to the innermost side)	Thermal Conductivity [W/m/°K]	Thickness [m]	U-Value [W/m²/°K]
Façade before the energy retrofit work	20 mm Cement and sand plaster layer 150 mm Hollow concrete block 15 mm Gypsum layer	0.720 0.789 0.400	0.185	1.89
Façade after the energy retrofit work	15 mm Stucco layer 15 mm Cement and sand plaster layer 60 mm EPS foam thermal insulation 20 mm Cement and sand plaster layer 150 mm Hollow concrete block 15 mm Gypsum layer	0.720 0.720 0.038 0.720 0.789 0.400	0.275	0.489
Existing floors	10 mm Pavement 40 mm Mortar layer 200 mm Existing structural floor 15 mm Gypsum layer	1.300 1.400 1.667 0.400	0.265	2.996

6.2 Roof

The existing roof consisted of several superimposed layers. From the innermost to the outermost of the existing roof, the following layers were found: a) 15 mm gypsum plaster layer with a final light color paint, b) 200 mm thick existing structural floor consisting of reinforced concrete joists with aluminous cement and precast concrete filler blocks, c) 50 mm sloped lightweight concrete layer, d) 40 mm fiber glass insulation layer (outdated), and e) 40 mm cork layer. Over these layers, there was a 5 mm thick pavement made of ceramic tiles placed on a 5 mm thick mortar layer. The total thickness of the existing roof was 355 mm with a U-value of 0.62 W/m²/°K. However, for the building location defined as C2, the CTE specifies a maximum overall U-value of 0.41 W/m²/°K. Therefore, it was further proposed to build an inverted roof to reduce the existing U-value to a smaller value than the maximum allowed by the CTE.

The energy retrofit roof project had to respect several requirements from the Building Department. The existing roof layers had to be removed where over the years, the building was modified by adding different waterproof or insulation layers. The roof was totally cleaned of existing and outdated additions before

installation of the new roof energy retrofit. The Building Department required the addition of an external insulation layer of Extruded Polystyrene (XPS) foam with a minimum thickness of 80 mm. This is a rigid insulation resistant to moisture and manufactured by a polystyrene polymer. The XPS is a very common material to be used over the roof membrane as an inverted roof solution. It was also proposed to build an inaccessible inverted roof finished with a ballast layer, as shown in **Figure 7**.

a. Existing roof sampling and drain

b. Waterproof layer over the thermal insulation c. Finish with a ballast layer

Figure 7. Overall view of the energy roof retrofit construction process.

Table 4. Thermal conductivity and U-Values for the façade case study.

Element	Composition of the construction element (from outer side to the innermost side)	Thermal Conductivity [W/m/°K]	Thickness [m]	U-Value [W/m²/°K]
Roof before the energy retrofit work	5 mm Ceramic tiles pavement	0.850	0.355	0.625
	5 mm Mortar layer	1.400		
	40 mm Cork layer	0.040		
	40 mm Fiber glass insulation	Out of date		
	50 mm Sloped light weight concrete layer	0.170		
	200 mm Existing structural floor	1.667		
	15 mm Gypsum layer	0.400		
Roof after the energy retrofit work	100 mm ballast	0.360	0.465	0.308
	80 mm XPS foam insulation	0.034		
	Geotextile	---		
	10 mm Cement mortar layer	0.720		
	Vapor Barrier	---		
	10 mm Cement mortar layer	0.720		
	50 mm Sloped light weight concrete layer	0.170		
	200 mm Structural floor	1.667		
	15 mm Gypsum layer	0.400		

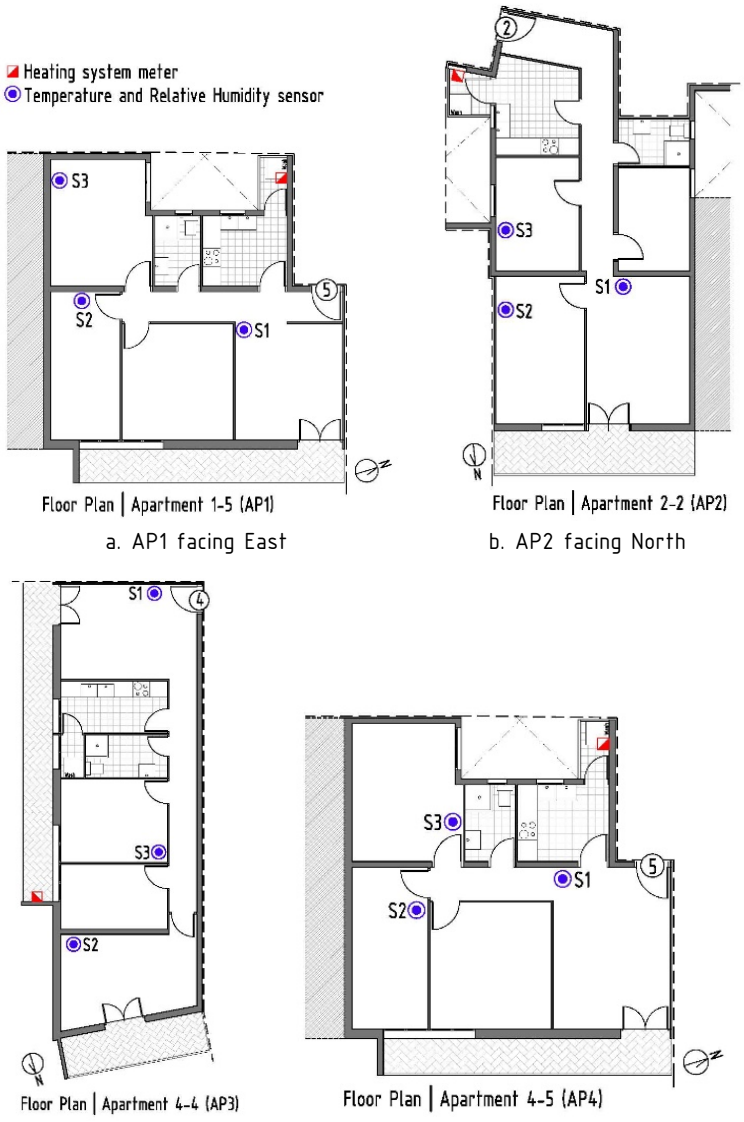
The final energy retrofit roof construction solution consisted of a 15 mm gypsum plaster layer on the innermost side with a final light color paint placed under a 200 mm thick existing structural floor of reinforced concrete joists with aluminous cement and precast concrete filler blocks. Over the floor, there was an existing 50 mm sloped lightweight concrete layer. A 10 mm thick cement mortar layer was placed under a vapor barrier and another 10 mm thick cement mortar layer was placed and protected with a bituminous membrane and a geotextile fabric. Finally, the XPS foam insulation of 80 mm thickness was placed and the roof was finished with a 100 mm thick ballast layer. The total thickness of the energy retrofitted roof was 465 mm with a U-value of 0.30 $W/m^2/^oK$, smaller than the maximum U-value of 0.41 $W/m^2/^oK$ required by the CTE.

7. APARTMENTS INSTRUMENTACION AND MEASUREMENTS

The Montcada i Reixac Building Department together with the Construction Technologic Center iMat assessed the energy efficiency improvement by the retrofit of the building case study. The study comprised four dwellings with the following goals: a) To assess the energy efficiency savings of the apartments by comparing the before and after conditions with respect to the retrofit of the building envelope, i.e. façades and roofs, and b) To assess the occupants comfort improvement. As shown **Figure 8**, the four dwellings were monitored during two different winter periods, namely during winter of 2009 (before the energy retrofit work) and during winter of 2010 (after the energy retrofit work). The monitored four dwellings are summarized in **Table 1**. The selection of these four test units was based on the acceptance by the tenants to participate in the research and because the units had a heating system of natural gas with water radiators. These apartments are owned by tenants of low incomes where energy savings would be an important goal. Moreover, the aim of the energy assessment was to obtain data from a number of different apartments distributed along the different levels and façade orientations of the case study building. It was especially important to have at least one apartment located just under the roof and one facing each façade of the building.

7.1 Preliminary Survey

iMat conducted a personal survey among the tenants of the four monitored apartments in March 3rd 2009. The objective was to identify their daily living behavior to understand and assess the data collected later from the different sensors. None of the four apartments had an air condition and all four dwellings were outfitted with a gas stove in the kitchen. The monitored dwellings had exterior doors and windows made of aluminum frames with a single glass pane without insulation. The obtained results of the survey were similar amongst the four apartments and they can be summarized as follows: a) The dwellings were constantly in use because there was someone home at all times; b) Tenants from the four monitored dwellings had breakfast, lunch and dinner at home; c) All tenants daily ventilated the apartments between 15 to 90 minutes and a small window in the bathroom or kitchen remained open for the whole day; d) Some tenants did not use the heating system very often due to economic reasons and as a result they had low energy consumption accompanied with low level of comfort; and e) None of the occupants had a cold feeling in their dwellings and did not use additional heating when they used the heating system, which was typically turned off when they went to sleep.



a. AP1 facing East b. AP2 facing North

c. AP3 facing East d. AP4 facing East

Figure 8. Locations of temperature/relative humidity (circles) and thermal energy (squares) instruments in the apartments.

7.2 Instrumentation

Between January and February 2009, instruments were installed in the four apartments before starting the energy retrofit project. The sensors were calibrated with different tests to assure their accuracy.

7.2.1 Temperature and Relative Humidity

To measure the interior temperature (°C) and relative humidity (%), data loggers model HOBO U10, **Figure 9a**, were used. As the aim of the study was to obtain consistent results, the devices were placed on interior partitions away from the façades, radiators, lamps, electrical appliances, etc. The loggers were installed at a height of 1.70 m from the floor. As shown **Figure 8**, each monitored apartment had three loggers: one placed in the living room (S1) and the other two (S2 & S3) placed in two different bedrooms. One was an interior bedroom facing the interior light well and the other facing the exterior façade. This allowed the observation of the difference in the thermal behavior between interior and exterior rooms.

7.2.2 Thermal Energy

The consumed thermal energy of the heating system of each apartment was measured by a thermal meter model KAMSTRUP MULTICAL 601, **Figure 9b**. This is a static meter based on the ultrasonic measuring principle to measure the energy consumption of heating systems that use water. Moreover, energy calculations were based on flow readings (measured with Portable Ultrasonic Flowmeter model PT500) and the difference of temperature between the beginning and ending of the heating system. As shown **Figure 8**, each monitored apartment had a thermal meter placed on the natural gas boiler.

7.2.3 Exterior Weather Conditions

A weather station, **Figure 9c**, was placed on the roof of the building case study to measure the exterior weather conditions, namely temperature (°C), relative humidity (%), wind speed (m/s) and direction, and solar radiation (W/m^2). The weather station was installed on February 13th 2009 and from that day onward started to collect data. During the second monitoring winter period of 2010, the weather station experienced some technical problems and weather data had to be obtained from the official weather station placed in Cerdanyola del Valles, a small town close to Montcada i Reixac. As variation between the two locations was small (only 1 °C during the day and 2 °C during the night), the data obtained from the official weather station was used in the present energy assessment.

a. Data logger for interior temperature (°C) and relative humidity (%)

b. Thermal meter near the natural gas boiler

c. Weather station placed on the building roof

Figure 9. Installed instruments in the four monitored dwellings and roof of the building.

7.3 Results Before the Energy Retrofit Work (Winter 2009)

The building case study is based on the actual building operation conditions. The measurements for the first period took place between January 15th and March 22nd 2009, i.e. 66 monitored days, except for AP4 which was monitored for only 37 days due to some logistical issues. Within this period, the coldest week took place between February 2nd and 8th. The obtained results are related to the following data: a) Exterior temperature (°C), relative humidity (%), solar radiation (W/m^2), and wind direction and speed (m/s) through the weather station, recorded every 5 minutes; b) Three interior temperatures (°C) and relative humidity (%) in the living room and two bedrooms recorded every 5 minutes; and c) Thermal energy consumption from the heating system recorded every hour.

In **Figure 10**, the box plot shows the median interior temperatures (°C) for the three monitored rooms of each of the four assessed apartments. These results[1] are summarized in **Table 5**. Not only the medians are unequal but also the interquartile ranges differ. The position of the rooms within the apartment have a strong effect on the results where the monitored living room, which is commonly occupied during the day by the tenants, together with the interior Room 2 had the highest values. This is due to the following reasons: 1) In each apartment, the variation of temperature of the median is mainly based on the occupancy of the rooms through the day according to the number of people occupying the room, duration of occupancy, and activity conducted in the room. In the studied apartments, the living room was the most occupied by the tenants according to the conducted survey. 2) The living room and Room 1 are facing directly the exterior façades and Room 2 is an interior room without direct contact with the exterior building envelope. Therefore, Room 2 is protected against the direct weather changes and it kept the interior temperature constant.

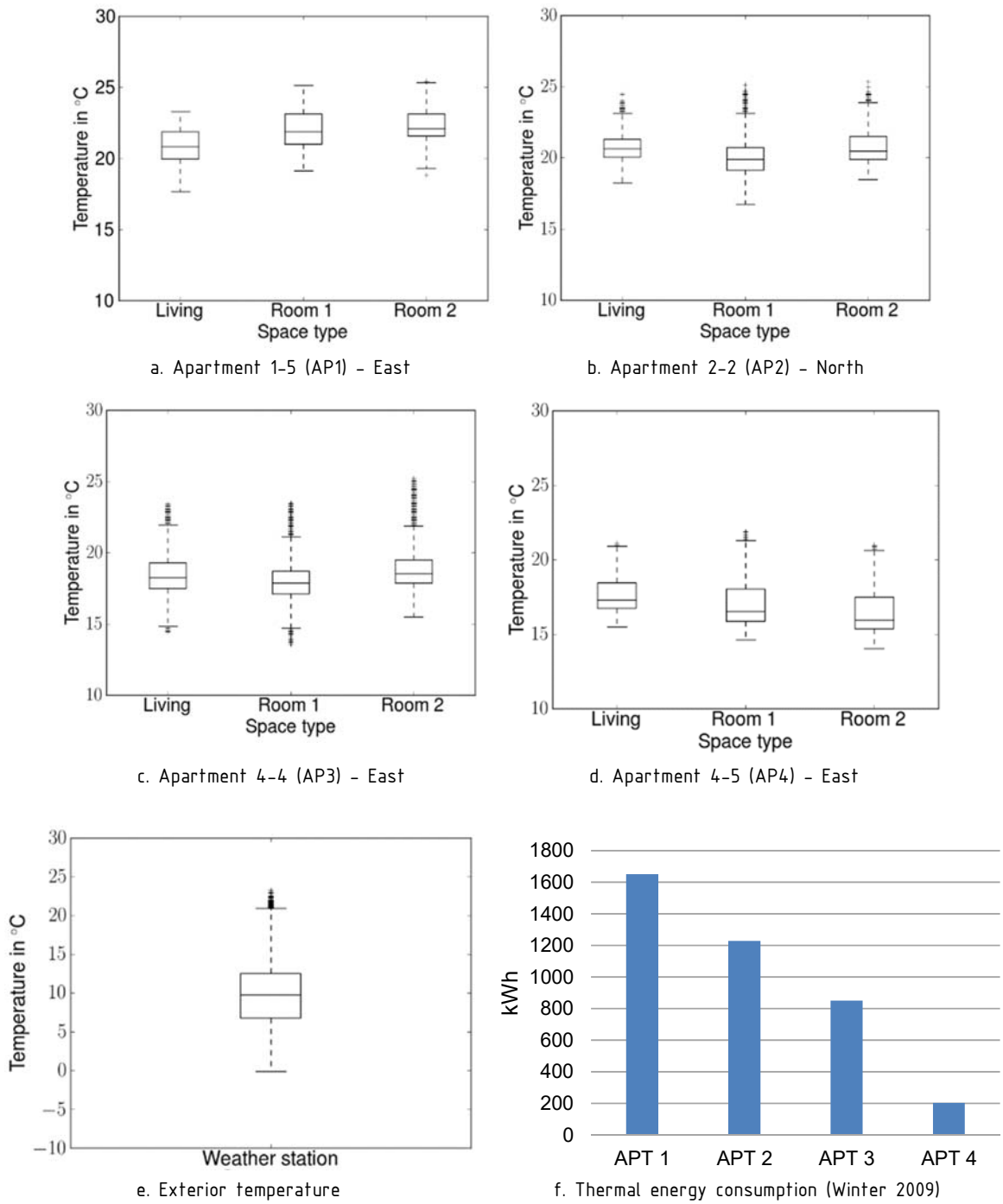
Table 5. Temperature (°C) results before the energy retrofit work (Winter 2009).

Unit	Room	Median	First Quartile	Third Quartile
AP1	Living room	20.81	19.95	21.86
	Bedroom 1	21.85	20.99	23.10
	Bedroom 2	22.05	21.57	23.10
AP2	Living room	20.62	20.04	21.28
	Bedroom 1	19.85	19.09	20.71
	Bedroom 2	20.42	19.85	21.47
AP3	Living room	18.24	17.48	19.28
	Bedroom 1	17.86	17.09	18.71
	Bedroom 2	18.52	17.86	19.47
AP4	Living room	17.28	16.71	18.43
	Bedroom 1	16.52	15.86	18.05
	Bedroom 2	15.95	15.38	17.48

It is observed in **Figure 10a,** that AP1 had a constant temperature between 21°C and 22°C because tenants kept this constant behavior during the day by using the heating system. However, from **Figure 10f**, AP1 had the highest energy consumption compared to the other dwellings. Moreover, AP2, facing North, had an interior temperature between 19°C and 20°C as shown in **Figure 10b** with 25.6% less energy consumption compared to AP1, where also the tenants kept a constant behavior during the day by using the heating system. AP3 and AP4 are located just below the roof facing the East. In these two apartments, very low energy consumption took place and consequently the interior temperatures were lower (between 18°C and 19°C for AP3 and between 16°C and 17°C for AP4) producing a low interior comfort. The energy consumption for AP3 and AP4 were almost 48.5% and 87.7% less than AP1. From **Figure 10c** and **Figure 10d**, it is

[1] The data obtained directly from the sensors, can be seen in different graphs in Annex – Chapter 2.

observed that the tenants of AP3 and AP4 avoided the use of the heating system due to economic reasons as mentioned above. They used the heating system occasionally for a short time during the night before going to bed. From the survey, tenants of AP3 and AP4 stayed at home for the whole day and preferred not to use the heating system.



a. Apartment 1-5 (AP1) - East

b. Apartment 2-2 (AP2) - North

c. Apartment 4-4 (AP3) - East

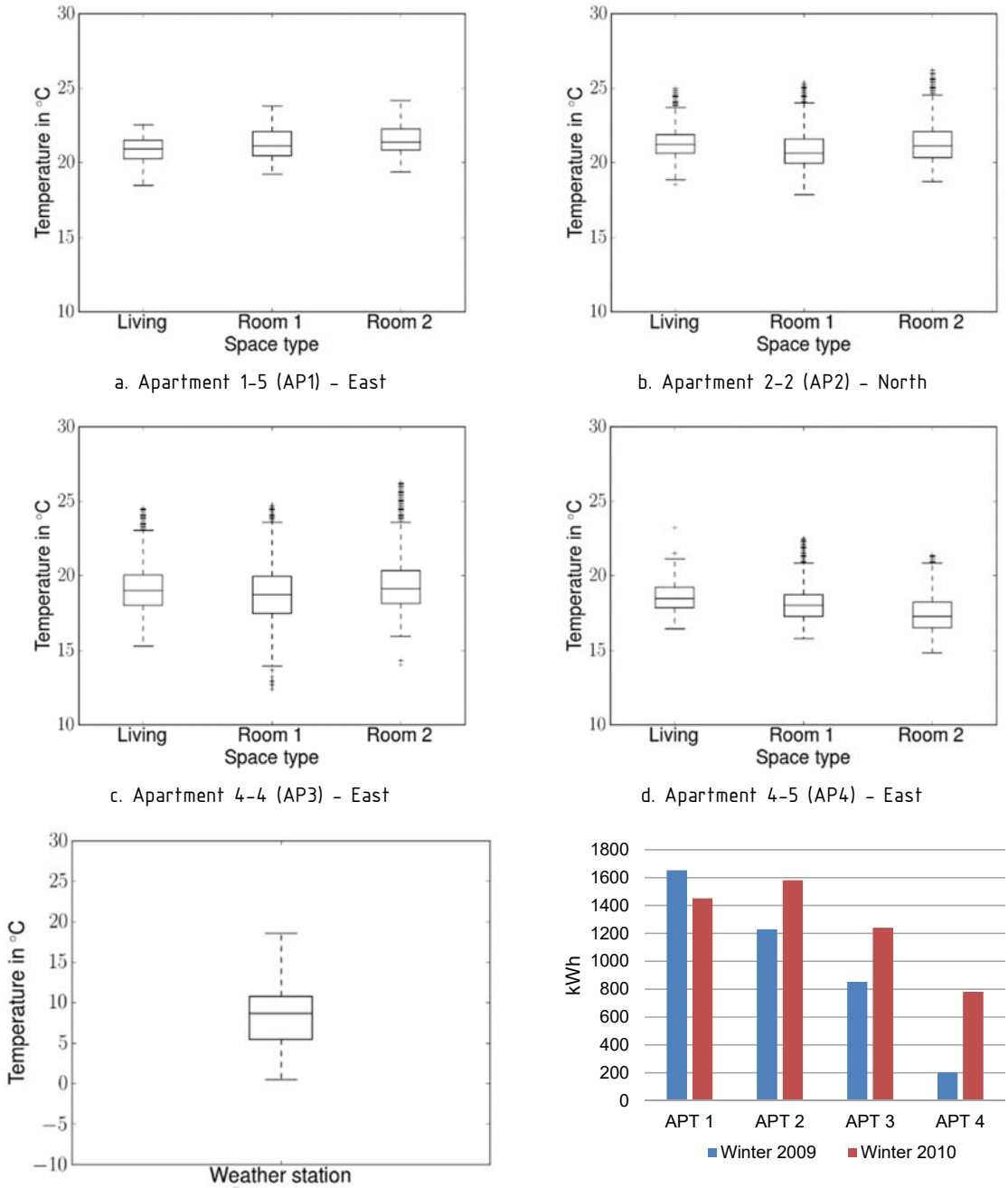
d. Apartment 4-5 (AP4) - East

e. Exterior temperature

f. Thermal energy consumption (Winter 2009)

Figure 10. Box plots for the interior temperature before the energy retrofit work. a) Apartment (AP1); b) Apartment (AP2); c) Apartment (AP3); d) Apartment (AP4); e) Exterior temperature (weather station); f) Energy consumption in Winter 2009.

7.4 Results After the Energy Retrofit Work (Winter 2010)



a. Apartment 1-5 (AP1) - East

b. Apartment 2-2 (AP2) - North

c. Apartment 4-4 (AP3) - East

d. Apartment 4-5 (AP4) - East

e. Exterior temperature.

f. Thermal energy consumption (Winter 2010)

Figure 11. Box plots for the interior temperature after the energy retrofit work. a) Apartment (AP1); b) Apartment (AP2); c) Apartment (AP3); d) Apartment (AP4); e) Exterior temperature (weather station); f) Energy consumption in Winter 2010, in comparison with Winter 2009.

This second winter data collection took place between January 15th and March 22nd 2010, i.e. 66 monitored days. Within this period, the coldest weeks took place between January 11th and 17th and March 8th and 15th. The obtained results[2] summarized in **Figure 11** and **Table 6** are related to the same data sets as those for

[2] The data obtained directly from the sensors, can be seen in different graphs in Annex – Chapter 2.

Winter 2009 before the energy retrofit work of the building envelope. Similar to Winter 2009 data, the results from Winter 2010 data show that the medians and interquartile ranges differ for different apartments and rooms.

Table 6. Temperature (°C) results after the energy retrofit work (Winter 2010).

Unit	Room	Median	First quartile	Third quartile
AP1	Living room	20.90	20.23	21.47
	Bedroom 1	21.09	20.42	22.05
	Bedroom 2	21.38	20.81	22.24
AP2	Living room	21.18	20.62	21.86
	Bedroom 1	20.62	19.95	21.57
	Bedroom 2	21.09	20.33	22.05
AP3	Living room	19.00	18.05	20.04
	Bedroom 1	18.71	17.48	19.95
	Bedroom 2	19.09	18.14	20.33
AP4	Living room	18.43	17.86	19.19
	Bedroom 1	18.05	17.28	18.71
	Bedroom 2	17.28	16.52	18.24

It is observed in **Figure 11a** that AP1 had a constant temperature of about 21°C, which is slightly lower compared to that during Winter 2009. However, from **Figure 11f**, the energy consumption of AP1 was 12.1% lower than that of Winter 2009 and 8.9% lower compared to AP2 during the same period. Therefore, it is confirmed that AP1 had energy savings after the energy retrofit of the façade. On the other hand, during Winter 2010, AP2 had 28.7% more energy consumption than that of Winter 2009, and consequently the interior temperature was about 21°C. AP3 and AP4 had low energy consumption but higher than those of Winter 2009 (45.7% and 285.4% more, respectively). This is explained from the survey results where during Winter 2010, the tenants used the heating system more often because Winter 2010 was colder than Winter 2009. However, the interior temperatures were still low, about 19°C for AP3 and between 17°C and 18°C for AP4. Other observations during Winter 2009, mentioned above, were also observed in Winter 2010.

8. CONCLUSIONS

The primary conclusions of the assessment of the retrofit work of the building envelope case study are summarized as follows:

- After the diagnosis of the building envelope case study, it can be stated that the importance of doing maintenance on the building over the years is a way to expand its lifespan. In addition, it is demonstrated that poorly or badly constructed solutions of façades and roofs result in a loss of energy and consequently in tenant's waste of money.

- The collected data illustrated useful information about the thermal energy behavior of apartments occupied by tenants with low income. When the exterior weather conditions are occasionally extreme, the tenants choose to make use of the heating system. Therefore, it is concluded that health and comfort are important parameters in lieu of saving money.

- All tenants had low thermal energy consumption due to economic reasons as clearly observed in apartments AP3 and AP4 where before and after retrofit, tenants elected to have low comfort in the dwellings instead of using the heating system more often. However, after the retrofit, they significantly

increased their thermal energy consumption by about 46% (AP3) and 285% (AP4) because winter 2010 after the energy retrofit was exceptionally colder in Catalonia than winter before the retrofit.

- The rooms that did not directly face the exterior façades and roof, experienced constant interior temperatures. Moreover, living rooms had higher temperatures because they are commonly the most occupied rooms during the day by the tenants. On the other hand, apartments AP3 and AP4 located just under the roof remained at low temperatures after the energy retrofit by avoiding the use of the heating system for economic reasons.

- Apartment AP1 had a constant thermal behavior caused by the use of the heating system before and after the retrofit. Therefore, AP1 is the apartment that can provide an accurate result about the energy retrofit work. In this study, AP1 led to reduction in the thermal energy consumption by about 12% with constant interior temperature. Thus, the retrofit work indeed improved the interior thermal comfort while also improved the energy savings.

- The retrofit work did not significantly reduce the energy consumption or increase the interior comfort. However, it is important to note that the project did not replace the exterior windows and doors. Only the opaque parts of the building envelope were outfitted with new insulation. Thus, with the retrofit work, exterior existing openings created negative thermal breaks which affected the final thermal results.

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CHAPTER 3

Experimental Investigation of Sunlight Permeability by Translucent Concrete Panels as an Energy Efficient Building Envelope

1. ABSTRACT

An energy efficient building envelope is introduced for daylight permeability in an anidolic manner through the opaque parts of exterior façades and roofs. A prefabricated Translucent Concrete Panel (TCP) with embedded Optical Fibers (OF) is coupled with a layer outfitted with Compound Parabolic Concentrators (CPC). Such TCPs have been predominantly used for aesthetic purposes. Moreover, OFs and CPCs are used in many industries, particularly telecommunications and concentration of solar energy, respectively. The goal of this study is to introduce a novel building envelope construction solution that can transmit sunlight to the building's interior. Due to the nature of traditional building materials blocking the passage of natural light, there is a constant requirement of artificial lighting, even during daytime, which consumes much energy in the form of artificial electrical light. This proposed building envelope is a viable solution to alleviate this inefficiency. Experimental results demonstrate the effectiveness and limitations of the proposed solution, which are discussed herein.

KEYWORDS
Anidolic Concentrator, Building Envelope, Energy Saving, Light Transmission, Optical Fiber, Translucent Concrete.

2. INTRODUCTION

Over the last 10 to 15 years, several companies have developed techniques for manufacturing light transmitting concrete, e.g. Litracon™. These products typically use Optical Fibers (OF) to transmit natural and artificial light through precast concrete blocks suitable for non-structural applications. While most of the current work has focused on decorative applications, there is a tremendous potential for light transmitting concrete to provide daylighting in the interior of buildings. There has been little or no research to quantify this potential or to compare the performance of OF with other light transmitting materials. An exception is the computational study by Ahuja et al. **[1]**. There is usually an excess of sunlight outdoor compared to the indoor lighting required in most buildings, e.g. commercial buildings, apartments, public buildings, etc. This sunlight can be concentrated and transmitted to the inside of the building using OFs or acrylic rods (AR), as conducted in this study. The substitution of electrical lighting by natural lighting effectively reduces the energy consumption of the building and accordingly the portions of the electricity bills associated with artificial lighting **[2]**.

The objective of this research is to introduce a novel energy efficient building envelope sub-system which allows lighting energy savings for different building types, e.g. residential, office, commercial, or public. It is to be noted that in architecture, sub-system refers to the collection of construction elements that work together for the same objective in a building system. Past studies confirm that daylighting can reduce artificial lighting consumption by 50-80% **[3]**. Moreover, artificial lighting consumption can contribute 20-60% of the total electric consumption in an office building. A building can achieve energy savings, i.e. reducing dependence on artificial or electrical lighting, by using passive solar lighting **[4]**.

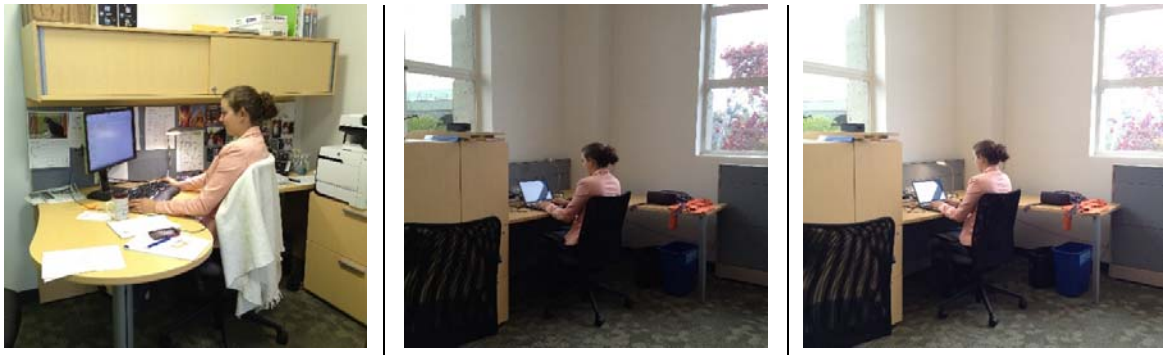
3. BACKGROUND

3.1 Visual Effects Of Lighting

The studies of visual effects of lighting started over 500 years ago by Leonardo da Vinci and Isaac Newton. The lighting quality should always be high enough to guarantee sufficient visual performance for the tasks a person is conducting at a specific time and place. Many codes specify the lighting quality aspects for different interior types and associated activities. However, the actual visual comfort of a person depends also upon one's own visual acuity, where here age is an important factor since lighting requirements usually increases with age **[5]**. Lighting has a powerful influence on the workplace offering a stimulating environment for the workers. Moreover, daylight is an important factor determining the quality of living and human comfort and healthfulness.

Solar radiation or sunlight is a universal free source of renewable energy. The quality of life and maintaining of health as conditions of environmental comfort and prosperity are dependent on the effective use of these resources **[6]**. Daylight penetrates into the building only for several hours each day considering its dependence on the orientation and cloud cover in the sky. The dynamic and varying character of sunlight

in both intensity and color, contributes greatly to a good working environment and has a positive influence on people's mood and stimulation. However, dynamic artificial lighting is advantageous as well **[5]**. In 1997, a study conducted by Begemann et al **[7]** demonstrated how people prefer artificial lighting in addition to the daylight present in an office environment, **Figure 1**. It is known that daylight has beneficial health effects where the eye controls the biological clock and takes part in regulating some important hormones through regular light-dark rhythms. In the morning, light synchronizes the internal body's clock to the earth's 24 hour light-dark rotational cycle. The absence of normal light-dark rhythm can produce a de-synchronization causing alertness and sleepiness during incorrect hours. Daylight has an important effect on alertness and mood of individuals **[5]**. People spending their days in non-daylight permeating buildings may therefore be in biological darkness contributing to reduced performance **[8]**. Summarizing, daylight offers health and psychological advantages, e.g. less absence at work **[2]** and higher productivity.



a. Office with artificial lighting.

b. Office with natural lighting.

c. Office with natural and artificial lighting.

Figure 1. Office building lighting types.

There are many advantages of using sunlight, in addition to partial replacement of electrical lighting and reduction in heating. It is important to illuminate inner spaces with natural daylight such that there is a connection between the indoor to the outdoor. However, daylight may produce external or internal glare effects. Some ergonomic studies discuss the proper positioning of workspaces to avoid glare. Too much glare has a negative impact on a person productivity and may cause fatigue. However, the glare effect is out of the scope of the presented study in this paper.

3.2 Compound Parabolic Concentrators For Interior Daylighting

The Compound Parabolic Concentrator (CPC) is a geometric sunlight collector which can concentrate solar beams. It is to be noted that there are three different types of light concentrators: 1) Geometrical (passive) concentrator; 2) Fluorescent luminescent, and 3) Hybrid system **[9]**. The longitudinal cross-section of the CPC, **Figure 2**, is used for light ray tracking in non-imaging (anidolic) systems **[10]**, and its shape is similar to a truncated cone **[9]**. Usually, during the solstices, it is common to face problems of collecting solar radiation due to the sunlight inclination. Sunlight collection is possible only for few hours of the day (approximately between 6 to 8 hours) **[10]**, which can be exploited in generating power, heating of water or air conditioning **[11]** with heat exchanger equipment. The first step of the research presented in this paper is to test a geometrical light concentrator together with a light channeling element, i.e. OF, to transmit natural light from the exterior to the interior of a building in an anidolic manner, leading to energy savings, e.g. by reduction in electricity use for lighting.

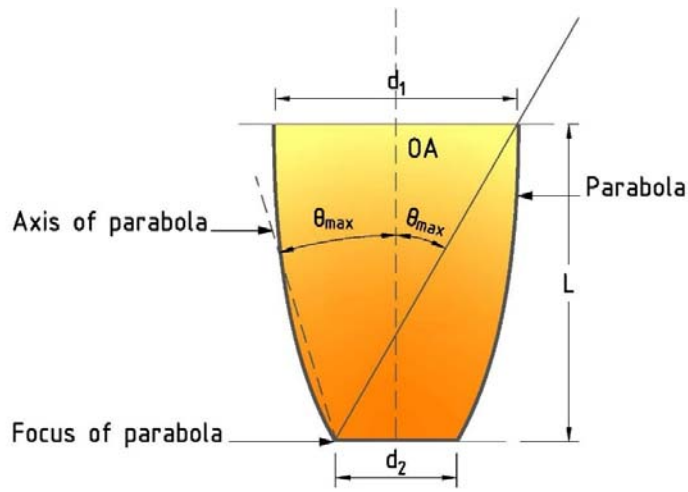


Figure 2. CPC profile of an ideal concentrator (axis of the parabola is inclined at angle θ_{max} to the optical axis, *OA*).

The presented application of the CPCs needs to consider the climate change **[12]**, and the sunlight incidence angle of the considered geographical location. This innovation does not avoid filtering of light and controlling the energy entering into and exiting from the building. Some other specific technologies are compatible and synergistic with CPCs, e.g. convertible structures **[13]**, shading devices **[14]**, double façades **[15]**, new glazing technologies **[16]**, kinetic devices **[17]**, water cooling **[18]**, and electrochromic panels **[19]**. The interaction between the presented approach with natural ventilation **[20] [21]**, acoustic effects **[22]**, and glare effect, are not considered in this paper.

The CPC equation is expressed in polar coordinates with origin centered at the focus of the parabola. Defining ρ as the radial distance to a point on the parabola and ϕ as the angle between the tangent to the parabola at its focus and the radial distance, the 3D geometry of a CPC can be given by **Equation 1** and **Equation 2**:

$$\rho(\phi) = 2f/(1-\cos\phi), \quad 2\theta_{\max} \le \phi \le \theta_{\max} + \pi/2 \qquad \textbf{Equation 1}$$

$$f = d_2(1+\sin\theta_{\max})/2 \qquad \textbf{Equation 2}$$

where d_2 is defined in **Figure 2**. For the present study, the CPC **[10] [23]** is proposed as a non-imaging optical design to achieve the goals of the study. To the best of the authors' knowledge, most of the uses of CPCs have been limited to solar energy, light concentration, and optical signal measurements. Therefore, the present application tackles new frontiers in the use of CPCs in an anidolic manner for energy efficiency and sustainability of our built environment for almost all building typologies. Moreover, the present research allows building designers to use anidolic daylight concentrators in structural elements.

3.3 Optical Fibers For Interior Daylighting

The OF system follows Snell's law, **Equation 3**, which explains how to send light signals over any distance, **Figure 3**. Due to the weakness of microwave transmission, OF technology came up as one of the preferred methods of digital transmission. Conceptually, OF system is similar to a microwave system but the former offers many benefits. OFs have been widely used for data transmission in telecommunications but can also be used for daylighting, harnessing solar power **[24]**, and scattering light within a building (demonstrated

here using a translucent concrete panel, TCP), **Figure 4**. Basically, the OF is a thin and flexible transparent cylindrical material which can transmit visible or infrared (natural or artificial) light through it. The core of an OF is either made up of plastic or glass.

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \qquad \textbf{Equation 3}$$

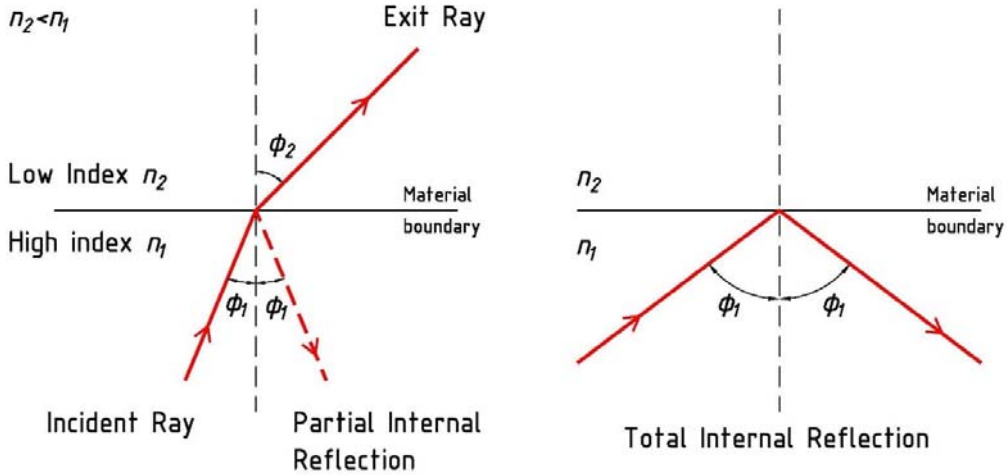
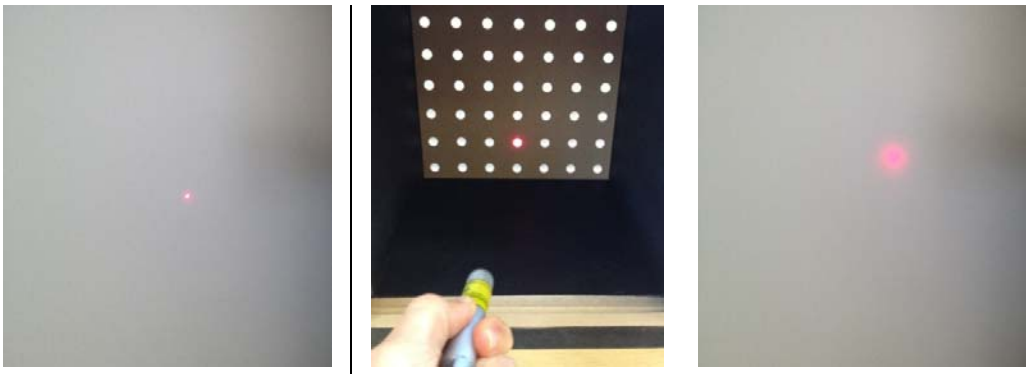


Figure 3. Snell's law and light ray diagrams.



a. Collimated laser. b. Laser through an OF in a TCP.

Figure 4. Light transmission in an OF.

4. PROPOSED MULTI-FUNCTIONAL BUILDING ENVELOPE SOLUTION

Transporting concentrated solar energy by OFs was studied in 1980 by a group of French investigators **[25]**. They proposed placing OFs at the focus of a CPC such that focused energy is introduced into the fibers. The OFs in that research were of low quality and the design cost was high, limiting the study to a theoretical investigation. Nowadays, solar energy can be transmitted by high quality and inexpensive OFs with large diameter and large numerical aperture (NA). It is noted that the NA is a parameter that dictates the light concentration ability of the OF. It is important to choose fibers with large NA, i.e. with large differences in the refractive indices **[24]** of the core and the cladding (the outer shell of the fiber). The primary advantage of lighting systems with solar concentrators is the potential to reduce energy consumption compared to conventional systems **[8]**. Moreover, there are studies about transmission of concentrated solar energy through single strands of OF or bundles of fibers. It is worth mentioning that

an OF is a chemically resistant material which can be used in different environments. One of the architectural OF properties is transmitting light in an anidolic way where one source of light is possible to produce many light spots. Nowadays, in the market there are lighting systems that allow to bring the sunlight into an interior room. In that regard, a receiver is located on the outside and the OF cables transport the light through the interior. Therefore, integrating OF lighting from solar energy is an energy efficient option for illuminating interior spaces without enough natural daylight **[8]**. Moreover, OFs have the potential to eliminate light wells in the floor plan giving much more flexibility to the architectural design and maximizing the use of the floor plan.

OF solar energy transmission and concentration provide a flexible way of handling concentrated solar energy **[24]**. The high flux of solar energy transmission by a flexible OF bundle integrated with a specially-designed CPC can offer many new applications for solar energy concentrators. The OFs transporting daylight from outside to inside a building can vary in length, size and configuration. It is important to pay attention to the placement of the light source which determines the length and configuration of the fiber between the light source and a light fixture end. These parameters affect the output of an OF lighting system. Bundled small-core glass and plastic fibers and large-core plastic ones are commercially available **[26]**. Knowing the OF performance, it is possible to optimize the design of an OF lighting system. Lighting designers using OFs consider two important parameters: 1) the quantity and 2) the quality of the light **[26]**. OFs can be considered as an optimal solution system for daylight transmission. Therefore, the research presented in this paper focuses on the use of OFs for daylight transmission. Most past studies on OFs are about data transmission and very limited research is available about OFs as daylight systems.

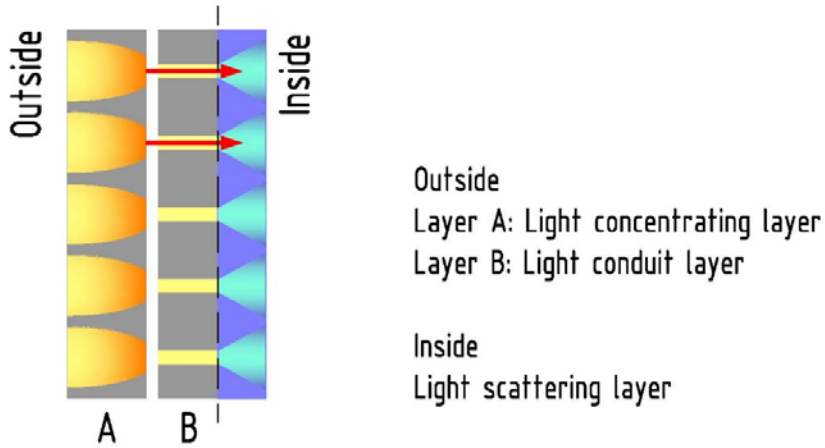


Figure 5. Concept of multi-layer light concentrating structural sub-system.

A new energy efficient building envelope construction solution, **Figure 5**, is proposed herein. It has been designed and tested for daylighting. It consists of a structural translucent concrete panel, TCP, consisting mainly of two layers:

1. Layer (A) is reinforced concrete (RC) with embedded symmetric CPCs, i.e. non-imaging concentrators **[10]**, to concentrate maximum natural sunlight from the outside in a geometrical way without mechanizing the panel.

2. Layer (B) is RC with embedded OFs as a structural sub-system to act as a conduit for the natural sunlight from the outside to the interior space which turns the TCP into a translucent construction solution for the opaque part of the building envelope.

In addition, the TCP integrates two concepts:

1. The TCP has thermal properties to control the heat transmitted from the outside to the interior of the building.

2. The TCP through the OFs scatters the light into the interior of the building.

The TCP is viewed as an advanced energy efficient wall technology with the property to transform an energy liability to an energy source providing daylight. As the TCP needs sunlight to be used, the present construction solution is dynamic. In order to optimize the design, it is required to assess the proposed energy efficient multi-layer sub-system under exterior weather changes for several hours and different days throughout the year. However, it has to deal with the fact that it cannot be computationally modeled on a practical commercial scale because there is not open software in the market able to simulate the daylight performance of the CPCs and OFs **[1]**. For this reason, the present experiment study explained in this document, is only based on basic outdoor tests.

5. EXPERIMENTAL STUDY APPROACH

For Layer (B) in **Figure 5**, fifteen opaque panels (made of wood and to be replaced with RC in the future) with embedded OFs and ARs were fabricated and tested under direct sunlight conditions where the panels were placed in a horizontal position. For the present research, four tests were conducted which are divided into the following categories:

1. Test 1 for same density of OFs distribution, **Figure 6a**.
2. Test 2 for same grid of OFs, **Figure 6b**.
3. Test 3 for same spacing of OFs, **Figure 6c**.
4. Test 4 for variable panel thickness and light transmission conduit materials, **Figure 6d**.

For the construction of Layer (A) in **Figure 5**, six panels outfitted with CPCs and straight cones (SCs) are fabricated by a 3D printer and tested together with Layer (B) under direct sunlight conditions. In this case, two tests were conducted:

1. Test 5 Layer (A) outfitted with CPCs together with Layer (B), **Figure 8**.
2. Test 6 Layer (A) outfitted with SCs together with Layer (B), **Figure 8**.

5.1 Outdoor Portable Test Bed

As shown in **Figure 7**, a light-tight test box made of wood is designed to hold the test panels for different daylight tests. It is constructed from 19.1 mm thick panels of medium density fiberboard (MDF) with interior clear dimensions of 203.2×203.2×203.2 mm^3. It is designed with construction details to prevent infiltration

of exterior light. Side panels are rabbeted (i.e. using a wooden rabbet joint) to the top and bottom ones and a back panel with an opening for the light meter is designed to be removable so that several different sensors can be used during testing. The interior of the box is painted in black color in order to absorb light reflections from the walls.

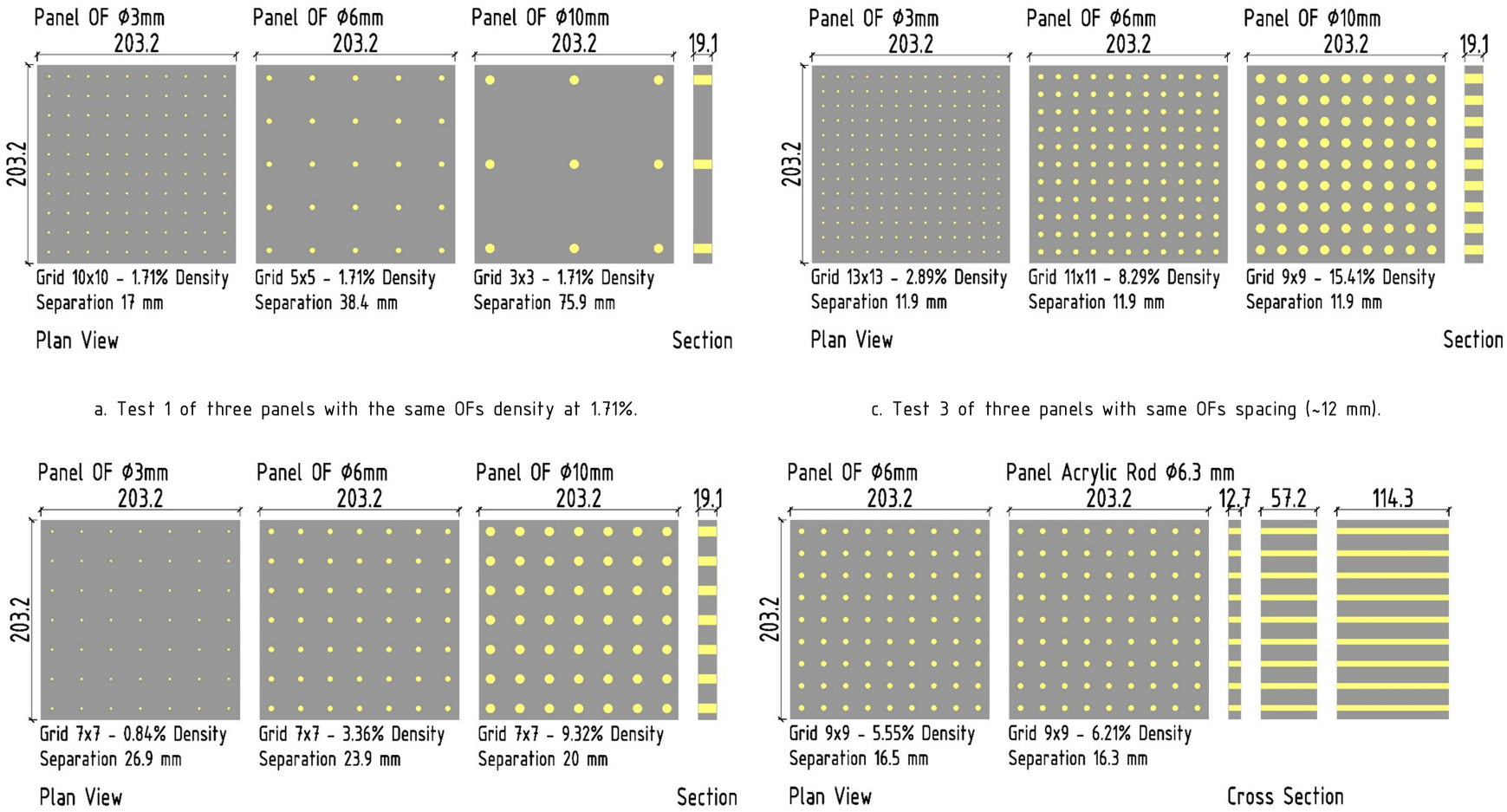
5.2 Prefabricated Test Panels

Fifteen panels from Layer (B) of the proposed construction solution, **Figure 5**, are designed and fabricated from MDF wood material instead of concrete because the main objective of this study is to assess the light transmission. MDF is an opaque material and can be easily manufactured using basic woodworking tools. The panels are 222.5×222.5 mm^2 of varying thicknesses (2 at 12.7 mm, 9 at 19.1 mm, 2 at 57.2 mm, and 2 at 114.3 mm) constructed from 12.7 mm and 19.1 mm thick MDF panels. Holes are drilled in the panels using a computer numerical controlled (CNC) flatbed router. OF and AR are cut to length on a miniature table saw. Once cut to length, these short segments are inserted into the pre-drilled holes of the test panels. In order to produce consistent results, a finishing operation was performed on the ends of the OF and AR segments. Therefore, several techniques for cutting and finishing the OF and AR were considered. After finishing, each of the samples is tested with a light power meter to determine its light transmittance. Test results, shown in **Table 1**, were obtained from 6.3 mm diameter clear cast AR samples. The best results were achieved when the rods were cut with laser, sanded, and finally polished with a buffing pad. Unfortunately, the laser cutter is not strong enough to cut through the thicker 10 mm OF. Therefore, the second best technique (cutting with a table saw before sanding and buffing) is chosen. The wooden panel fabrication consisted of the following steps: 1) The panel is sanded with 120-grit sandpaper to ensure that the length of the OF or AR is consistent with the thickness of the panel; 2) The panel is sanded with a sequence of 220-grit, 400-grit, and 600-grit sandpapers for further smoothing; 3) The panel is buffed with a lamb's wool polishing pad to give the panels and embedded OF or AR material a smooth and uniform finish.

Table 1. Test results for different panel finishing techniques.

Finishing Technique Tested	[W/m²]
1. Laser cut + sanding + buffing	200
2. Table saw cut + sanding + buffing	**185**
3. Laser cut without sanding or buffing	182
4. Table saw cut without sanding or buffing	170

The OF and AR are purchased from different sources. For the OF, the core material consists of Polymethyl-Methacrylate Resin and its refractive index profile is based on Step-Index Multi Mode. Since the intention is to ultimately cast the TCP from RC, the holes pattern in the wooden test panels accounted for RC design considerations, e.g. the minimum distance between the OFs or ARs was ~12 mm. This allows a maximum aggregate size of ~10 mm to provide sufficient strength for most relevant applications. The following subsections present different studies for the constructed Layer (B) of the test panels.



a. Test 1 of three panels with the same OFs density at 1.71%.

c. Test 3 of three panels with same OFs spacing (~12 mm).

b. Test 2 of three panels with the same OFs 7×7 grid.

d. Test 4 of six (3 with OFs + 3 with ARs) panels with different thickness.

Figure 6. Overall Layer (B) test panels design. [Dimensions are in millimeters.]

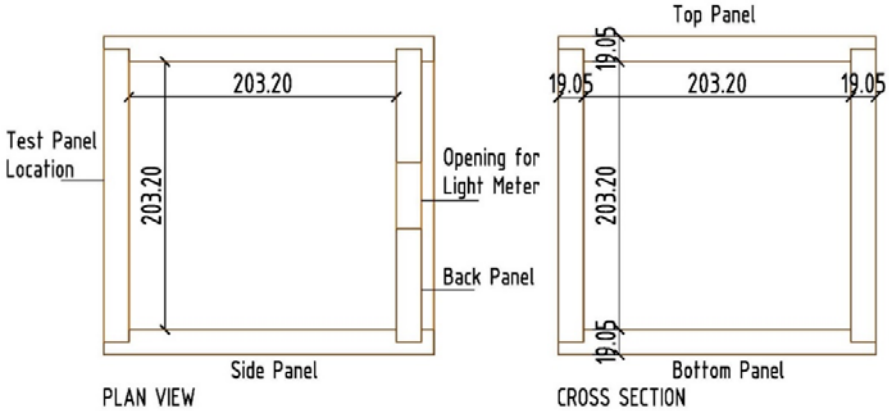


Figure 7. Light-tight box design. [Dimensions are in millimeters.]

5.2.1 Test 1 - Same Density

This test consists of 3 panels with embedded OFs and characterized by differences in grid pattern, i.e. diameter and spacing. The density of OFs, defined as the ratio between the total cross-sectional area of the OFs and the planar area of the panel, is kept constant at 1.71%. The objective of the test is to determine the influence of the grid configuration of the OFs on the light transmission, **Figure 6a**.

5.2.2 Test 2 - Same Grid

This test consists of 3 panels with embedded OFs of different diameter and spacing. The OFs in the panels are arranged in a 7×7 grid. The objective of the test is to determine the influence of the OFs density, by varying the OFs diameter and spacing for the same grid, on the light transmission, **Figure 6b**.

5.2.3 Test 3 - Same Spacing

This test consists of 3 panels with embedded OFs of different diameter. The edge-to-edge spacing between the OFs is kept constant at ~12 mm, simulating TCP constructed with maximum aggregate size of ~10 mm. Because the minimum spacing between OFs is critical in TCPs, the objective of this test is to determine the influence of the OF density on the light transmission by varying the OFs diameter and grid for the same spacing, **Figure 6c**.

5.2.4 Test 4 - Varying Thickness And Material

This test consists of 6 panels with thicknesses 12.7, 57.2, and 114.3 mm with the same grid. Two panels are constructed for a specific thickness with embedded 6 mm OFs or 6.3 mm ARs. The objectives of the test is to determine the influences of panel thickness and material type (OF vs. AR) on the light transmission, **Figure 6d**.

5.3 3D Printed Panels

As seen in **Figure 8**, in tests 5 and 6, six panels of 222.5×222.5 mm^2 are designed and fabricated using a 3D printer with a Polylactic Acid (PLA) polymer filament for Layer (A) of the proposed construction solution. Each panel is printed with 49 CPCs or SCs arranged in a 7×7 grid. They are painted with a layer of mirror-like paint coating. The external surfaces of the panels are painted in black to absorb natural sunlight.

The two independent variables of the CPC and a SC are considered as the maximum *(d_1)* and minimum *(d_2)* diameters, **Figure 2**, which define the geometry of the concentrator. For the present design, d_1=25.4 mm and d_2=10.2 mm. The three considered lengths of CPCs and SCs are L = 40.7, 33.0, and 19.6 mm corresponding to the half acceptance angles of θ_{max} = 23.6°, 30°, and 48.6°, respectively. The separation between the CPCs or SCs at the side with d_1 diameter is taken as 4.6 mm.

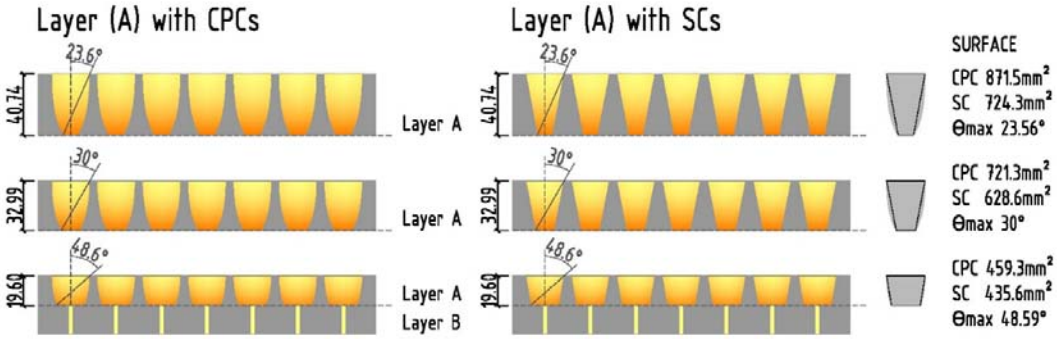


Figure 8. Overall Layer A+B test panels design. [Dimensions are in millimeters.]

5.3.1 Test 5 – Layer (B) + Layer CPCs

This test consists of 3 panels (Layer B) with embedded OFs of different diameter and spacing but with the same 7×7 grid. The panels are outfitted with CPCs of 3 different half acceptance angles (Layer A) and tested together. The objective of the test is to determine the influence of CPCs with OFs on the light transmission, **Figure 8**.

5.3.2 Test 6 – Layer (B) + SCs Layer

Test 6 is the same as test 5, but in this case the 3 panels (Layer B) are outfitted with SCs of 3 different half acceptance angles (Layer A) and tested together. The objective of the test is to determine the influence of SCs with OFs on the light transmission, **Figure 8**.

6. LIGHT TRANSMISSION TESTS RESULTS

The ultimate goal of the conducted tests is to demonstrate the light transmission effectiveness of the aforementioned proposed building envelope using TCPs. The results can be used as a first step towards the optimization of the light conduit diameter and spacing, i.e. density, and panel thickness for maximum daylight transmission through the panels. The tests took place outdoors on the UC-Berkeley campus.

The present research did not attempt to test for the Daylight Factor (DF). Even though the (DF) is the most used daylight metric by the professionals, it is known that it was never defined to be used as a good daylighting design method **[26]**. In addition, some research studies, like the one conducted by Oteiza and Soler **[27]**, do not recommend its use because the estimated external illuminance values are far from reality. For this reason, the introduced tests were designed according to the needs of the project considering the OF light transmission properties together with its density ratio distributed in the test panel.

6.1 Outdoor Tests Results For Layer (B)

In this case, the fifteen panels were tested under direct sunlight over the course of two days. The panels were held in a horizontal position on the test box and measurements were taken with an illuminance meter (Lux) that was placed at the back (bottom) of the box. The purpose of this test is twofold:

1. To observe the behavior of the test panels with embedded OFs under direct beam radiation from the daylight source.
2. To observe the effect of solar incidence angle on the amount of light transmitted through the panels.

a. Tests 1, 2 and 3 Set up. b. Illuminance meter.

Figure 9. Overall images of the set up for Test 1, 2 and 3.

a. Test 4 Set up. b. Illuminance meter.

Figure 10. Overall images of the set up for Test 4.

The tests were conducted on two different days. Tests 1 to 3 were conducted on July 1st, 2013 from 10:30 to 15:15, **Table 2**, and test 4 was conducted on June 7th, 2013 from 11:00 to 15:30, **Table 3**. The test box was placed on a bench to raise it above nearby obstructions. The illuminance meter (Lux) was inserted into a hole at the bottom of the test box to measure the light transmission from the outside to the inside of the box. The illuminance readings were recorded every 15 minutes for each test panel. The test setups are shown in **Figure 9** and **Figure 10**. In both cases, the weather conditions were relatively constant throughout the tests. According to the Florida Solar Energy Center **[28]**, the maximum solar incidence angle at solar noon in San Francisco on the days of tests 1 to 3 and test 4 were 75.46° (13:15 civil time) and 75.24° (13:10 civil time), respectively.

Table 2. Light transmission results in (Lux) for tests 1, 2 and 3.

Civil Time	TEST 1 Same Density			TEST 2 Same Grid			TEST 3 Same Spacing		
	3mm [Lux]	6mm [Lux]	10mm [Lux]	3mm [Lux]	6mm [Lux]	10mm [Lux]	3mm [Lux]	6mm [Lux]	10mm [Lux]
10:30	175.3	296.6	228.4	87.7	750	1,003	345	1,354	1,509
10:45	276.6	363.4	366.6	107.7	678	1,341	520	1,769	2,201
11:00	436	449	544	159	861	1,898	778	2,373	3,402
11:15	589	557	524	303	1,054	2,770	1,085	3,333	5,450
11:30	798	655	**666**	367	1,254	3,589	1,387	4,280	6,500
11:45	997	748	625	425	1,450	4,220	1,530	5,190	7,700
12:00	1,118	838	453	463	1,618	4,300	1,750	5,700	8,700
12:15	1,168	933	360	528	1,785	5,300	1,960	6,190	**9,280**
12:30	1,198	997	340	535	1,865	4,860	**2,040**	6,540	8,660
12:45	1,218	1,055	368	487	1,889	**5,410**	2,020	6,700	**8,000**
13:00	1,228	**1,062**	334	483	**1,914**	4,680	2,030	6,740	8,080
13:15	1,233	1,025	**306**	473	1,905	4,980	2,000	**6,920**	8,470
13:30	**1,245**	997	313	480	1,869	4,600	1,940	6,770	8,200
13.45	1,208	962	360	536	1,797	4,580	1,860	6,380	8,230
14:00	1,148	888	435	**558**	1,655	4,860	1,710	5,850	**8,870**
14:15	1,020	797	573	495	1,477	4,170	1,490	5,180	8,020
14:30	830	698	**632**	398	1,266	3,514	1,309	4,470	7,310
14:45	678	601	600	304	1,070	2,745	1,081	3,722	4,880
15:00	519	501	476	223	875	2,024	773	2,714	3,133
15:15	343.2	404	280	154	714	1,420	518	1,966	2,082

6.1.1 Test 1 Results – Same Density

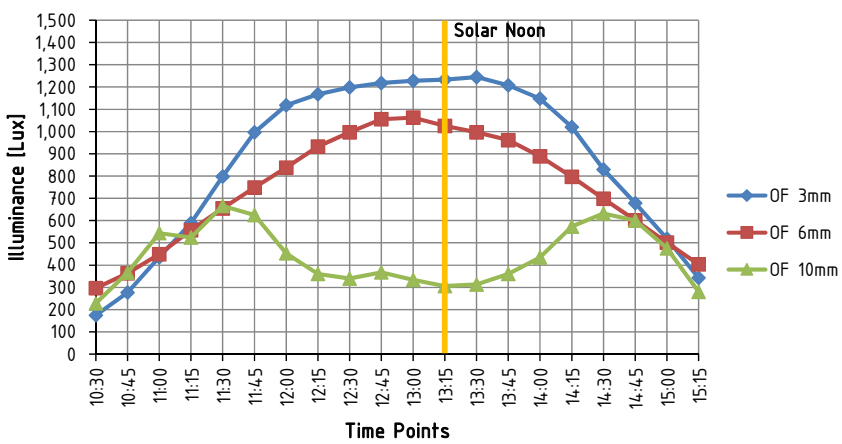


Figure 11. Illuminance results from Test 1 (Same density).

From **Figure 11**, at the beginning and at the end of the test duration, the three panels roughly transmitted the same amount of light. The highest illuminance readings were recorded with the 3 mm OF panel and were observed at around solar noon (i.e. 13:15 civil time). On the contrary, the readings in the panel with 10 mm OF decreased during the middle of the day and were highest at 11:30 and 14:30 civil time. It is noticed that the panels with 3 mm and 6 mm OFs show a similar trend in the variation of their light transmission over the course of the day. Unlike panels with 3 mm and 6 mm OFs, the panel with 10 mm OF shows a decrease

in light transmission in the middle of the day. The maximum light transmission through the 10 mm panel was observed at 11:30 and 14:30 civil time.

6.1.2 Test 2 Results – Same Grid

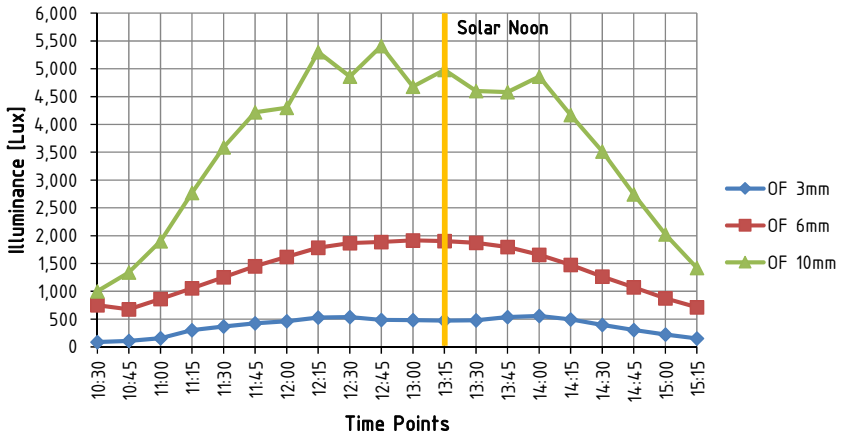


Figure 12. Illuminance results from Test 2 (Same grid).

Throughout the test, the illuminance readings were greater in panels with larger OF diameters (and larger cross-sectional areas of OF). The results from the three panels deviated significantly and the maximum values were observed in the middle of the day, **Figure 12**. At every point throughout the day, the quantity of light transmission per unit of cross-sectional area of the OF was greatest in the panel with 3 mm OFs.

6.1.3 Test 3 Results – Same Spacing

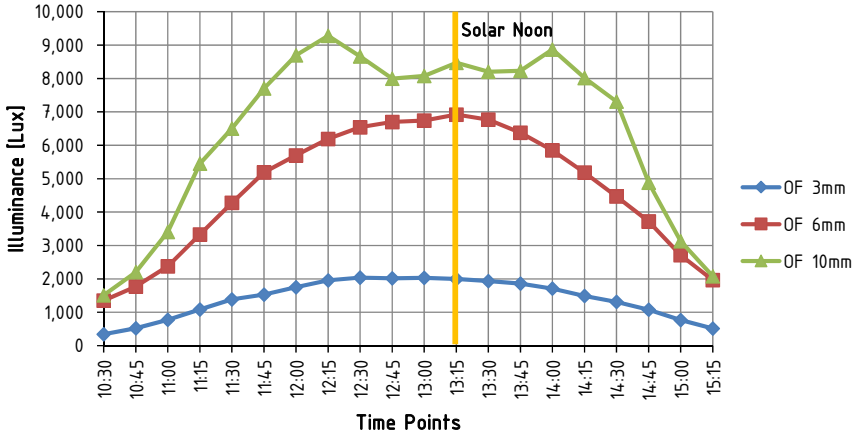


Figure 13. Illuminance results from Test 3 (Same spacing).

From **Figure 13**, the illuminance readings were greater in the panels with larger OF diameters (and larger cross-sectional areas of OFs). The results from the three panels deviated significantly and the greatest deviation was observed in the middle of the day which did not remain proportional throughout the test duration. The panel with 10 mm OF exhibited a behavior similar to that of test 1, with readings decreasing in the middle of the day. The light transmission through the 10 mm OF panel was greatest at 12:15 and

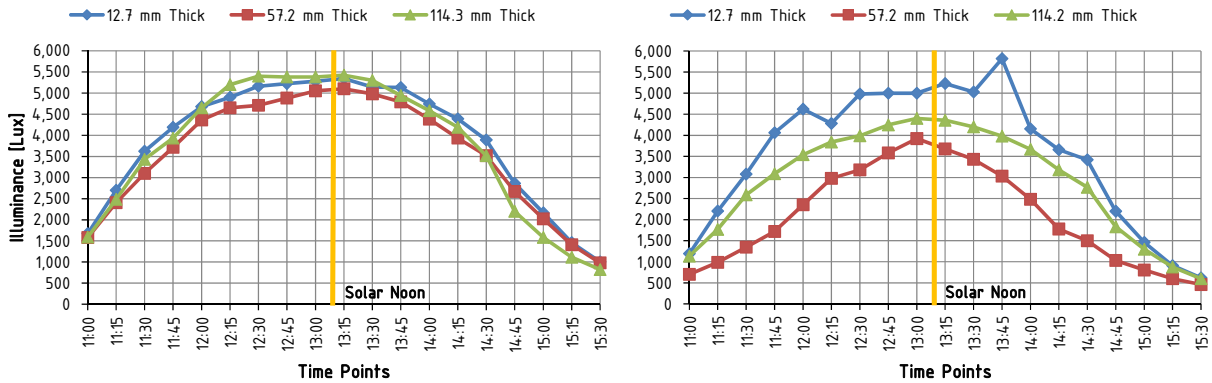
14:00 civil time. At every point throughout the day, the quantity of light transmission per unit of cross-sectional area of the OF was largest in the panel containing the 6 mm OFs.

6.1.4 Test 4 Results - Varying Thickness And Material

All the panels with OFs transmitted the greatest amount of light at solar noon (readings taken at 13:15 civil time). The highest readings in the AR panels are less consistent and observed within 35 minutes from solar noon. The maximum value in light transmission occurred when the solar incidence angle was at its highest position. As shown **Figure 14**, at most points in time, the highest readings were observed with the panels that were 12.7 mm thick where the panel with ARs gave higher readings for every test whereas that with the OFs gave higher readings only at the beginning and end of the day. On the contrary, the lowest readings were observed in the 57.2 mm thick panels. The relationship between the readings from the three panels remained constant in the AR tests but varied significantly in the OF tests. The 114.3 mm thick panel with OF gave the highest readings in the middle of the day but performed worse than the thinner panels when the sun incidence angle was lower (at the beginning and end of the day).

Table 3. Light transmission results in Lux for Test 4.

Civil Time	OF 12.70 mm Thick [Lux]	OF 57.20 mm Thick [Lux]	OF 114.30 mm Thick [Lux]	AR 12.70 mm Thick [Lux]	AR 57.20 mm Thick [Lux]	AR 114.30 mm Thick [Lux]
11:00	1,674	1,578	1,586	1,194	700	1,137
11:15	2,700	2,403	2,485	2,205	990	1,768
11:30	3,620	3,100	3,433	3,082	1,345	2,585
11:45	4,190	3,710	3,930	4,060	1,720	3,090
12:00	4,680	4,360	4,650	4,620	2,350	3,540
12:15	4,900	4,650	5,200	4,280	2,980	3,840
12:30	5,160	4,710	5,400	4,980	3,180	3,990
12:45	5,220	4,880	5,380	5,000	3,580	4,250
13:00	5,280	5,050	5,380	5,000	**3,920**	**4,400**
13:15	**5,340**	**5,100**	**5,420**	5,230	3,680	4,360
13:30	5,140	4,980	5,300	5,030	3,430	4,200
13:45	5,130	4,790	4,940	**5,820**	3,030	3,980
14:00	4,740	4,380	4,580	4,150	2,480	3,670
14:15	4,390	3,930	4,190	3,660	1,780	3,180
14:30	3,890	3,518	3,515	3,422	1,501	2,768
14:45	2,860	2,670	2,200	2,200	1,030	1,830
15:00	2,165	2,020	1,582	1,460	804	1,297
15:15	1,461	1,405	1,113	913	598	877
15:30	1,000	977	821	618	463	598



a. TCPs with embedded optical fibers. b. TCPs with embedded acrylic rods.

Figure 14. Optical fibers and acrylic rods Illuminance results from Test 4 (Varying thickness).

6.1.5 Visual Result Of The Tests

The following images, **Figure 15**, aim to visually show all the results obtained during the outdoor tests. The photos were taken from the inside of the wooden testing box in a room with artificial light. The photos demonstrate the visual difference of light transmission among the different panels according to: density, **Figure 15a**; grid, **Figure 15b**; separation, **Figure 15c**; and thickness, **Figure 15d**. This visual difference matches with the obtained results outdoors.

Test 1 - Density

3mm OF - Grid 10x10 6mm OF - Grid 5x5 10mm OF - Grid 3x3

a. Visual result of Test 1

Test 2 - Same Grid

3mm OF - Grid 7x7 6mm OF - Grid 7x7 10mm OF - Grid 7x7

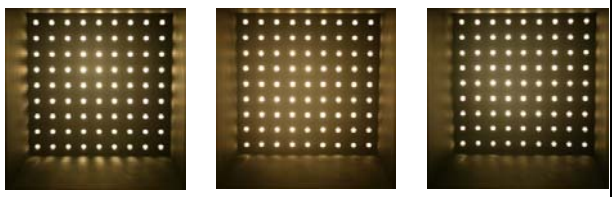
b. Visual result of Test 2

Test 3 - Same Spacing

3mm OF - Grid 13x13 6mm OF - Grid 11x11 10mm OF - Grid 9x9

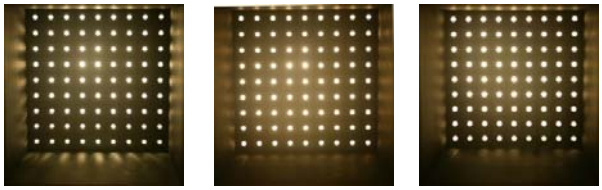
c. Visual result for Test 3

Test 4 - Thickness OFs



Thickness 12.7 mm Thickness 57.2 mm Thickness 114.3 mm

Thickness ARs



Thickness 12.7 mm Thickness 57.2 mm Thickness 114.3 mm

d. Visual result of Test 4

Figure 15. Overall visual results of the Tests 1, 2, 3 and 4.

6.2 Outdoor Tests Results For Layer (A) + Layer (B)

In this test series, 6 panels outfitted with CPCs or SCs were tested under direct sunlight throughout the day and integrated with 3 panels outfitted with OFs (the same test panels from test 2). As previously mentioned, the test panels were placed horizontally on the test box and measurements were taken with an illuminance meter (Lux) that was placed on the south side of the testing box, directly facing opposite to the sun. The purpose of these tests is twofold: 1) To observe the behavior of both layers (A) and (B), working together under direct beam radiation with a sunlight source; and 2) To observe the effects of the incidence angle on the amount of light that is transmitted through the test panels.

Table 4. Light transmission results in Lux for Test 5 and 6.

Civil Time	TCP with OF 3 mm						TCP with OF 6 mm						TCP with OF 10 mm					
	CPC 23.6° [Lux]	SC 23.6° [Lux]	CPC 30° [Lux]	SC 30° [Lux]	CPC 48.6° [Lux]	SC 48.6° [Lux]	CPC 23.6° [Lux]	SC 23.6° [Lux]	CPC 30° [Lux]	SC 30° [Lux]	CPC 48.6° [Lux]	SC 48.6° [Lux]	CPC 23.6° [Lux]	SC 23.6° [Lux]	CPC 30° [Lux]	SC 30° [Lux]	CPC 48.6° [Lux]	SC 48.6° [Lux]
09:30	5.9	5.0	8.8	6.2	16.2	11.1	41.7	37.0	64.1	44.6	84.3	69.6	90.0	71.8	139.7	96.3	220.5	169.0
09:45	6.4	5.9	9.8	6.7	20.4	13.5	93.8	72.7	58.4	45.1	93.8	72.7	96.1	76.4	158.8	103.3	233.7	176.9
10:00	0.0	0.0	0.0	0.0	10.0	3.0	33.0	20.0	62.0	35.0	96.0	74.0	91.0	66.0	166.0	104.0	258.0	202.0
10:15	0.0	0.0	0.0	0.0	12.0	7.0	39.0	34.0	73.0	43.0	121.0	119.0	108.0	86.0	204.0	130.0	301.0	253.0
10:30	0.0	0.0	2.0	0.0	27.0	13.0	54.0	52.0	93.0	58.0	149.0	145.0	130.0	107.0	241.0	156.0	365.0	325.0
10:45	0.0	0.0	4.0	0.0	30.0	18.0	60.0	52.0	109.0	80.0	176.0	157.0	152.0	133.0	275.0	191.0	433.0	390.0
11:00	0.0	0.0	4.0	2.0	37.0	25.0	69.0	69.0	102.0	92.0	185.0	182.0	176.0	160.0	325.0	229.0	552.0	429.0
11:15	1.0	0.0	16.0	7.0	39.0	26.0	78.0	86.0	123.0	94.0	253.0	219.0	196.0	188.0	365.0	290.0	654.0	548.0
11:30	23.4	20.7	41.3	33.7	52.0	26.0	101.0	109.0	163.0	135.0	219.0	163.0	225.0	247.0	393.0	350.0	854.0	1,150.0
11:45	12.0	4.0	36.0	35.0	65.0	24.0	124.0	135.0	210.0	200.0	265.0	244.0	264.0	277.0	425.0	400.0	1,241.0	1,194.0
12:00	19.0	8.0	43.0	43.0	114.0	38.0	145.0	156.0	202.0	221.0	443.0	457.0	304.0	327.0	473.0	508.0	1,184.0	1,304.0
12:15	29.0	18.0	60.0	73.0	95.0	92.0	166.0	191.0	247.0	280.0	422.0	458.0	319.0	366.0	545.0	630.0	1,712.0	1,530.0
12:30	42.0	31.0	68.0	73.0	106.0	70.0	192.0	208.0	256.0	305.0	708.0	782.0	394.0	430.0	583.0	680.0	2,000.0	1,869.0
12:45	**48.0**	43.0	**70.0**	77.0	133.0	90.0	**215.0**	235.0	**282.0**	334.0	733.0	718.0	437.0	452.0	645.0	769.0	**2,022.0**	**2,040.0**
13:00	45.0	38.0	64.0	72.0	120.0	**94.0**	213.0	237.0	268.0	342.0	582.0	**785.0**	**462.0**	477.0	**658.0**	786.0	1,793.0	1,910.0
13:15	43.0	**47.0**	59.0	**82.0**	**142.0**	83.0	207.0	239.0	268.0	**350.0**	658.0	625.0	445.0	**487.0**	610.0	813.0	1,753.0	1,885.0
13:30	37.0	38.0	63.0	75.0	139.0	78.0	194.0	225.0	240.0	340.0	703.0	737.0	435.0	480.0	599.0	**850.0**	1,813.0	1,959.0
13:45	29.0	30.0	48.0	72.0	121.0	63.0	178.0	208.0	224.0	314.0	**752.0**	674.0	418.0	450.0	545.0	784.0	1,780.0	1,570.0
14:00	21.0	24.0	29.0	50.0	43.0	59.0	157.0	173.0	196.0	287.0	610.0	579.0	363.0	374.0	498.0	681.0	1,661.0	1,674.0
14:15	18.0	17.0	28.0	46.0	46.0	52.0	136.0	140.0	170.0	245.0	482.0	425.0	342.0	353.0	440.0	570.0	1,422.0	990.0
14:30	10.0	8.0	25.0	30.0	30.0	25.0	107.0	126.0	146.0	206.0	242.0	337.0	282.0	285.0	381.0	467.0	790.0	881.0
14:45	4.0	6.0	19.0	13.0	18.0	15.0	89.0	104.0	123.0	165.0	117.0	161.0	240.0	228.0	332.0	336.0	543.0	496.0
15:00	1.0	0.0	11.0	5.0	14.0	15.0	78.0	77.0	102.0	98.0	134.0	137.0	212.0	189.0	289.0	292.0	255.0	375.0
15:15	0.0	0.0	6.0	2.0	9.0	20.0	63.0	60.0	82.0	71.0	116.0	142.0	167.0	158.0	247.0	225.0	350.0	437.0
15:30	0.0	0.0	1.0	0.0	6.0	19.0	43.0	44.0	70.0	63.0	94.0	135.0	144.0	122.0	214.0	182.0	243.0	343.0
15:45	0.0	0.0	0.0	0.0	5.0	16.0	35.0	34.0	58.0	41.0	93.0	132.0	114.0	87.0	180.0	138.0	257.0	336.0

a. Tests 5 and 6 set up.

b. Layer A + Layer B panels.

c. Illuminance meter.

Figure 16. Overall images of the set up for Test 5 and 6.

The test was conducted on September 4th, 2013 from 9:30 to 15:45, **Table 4**. The test box was placed on a cart to raise it above nearby obstructions. The illuminance meter (Lux) was inserted into a hole in the

south facing panel of the test box and was used to measure the light transmission to the inside of the box. The illuminance readings were recorded every 15 minutes for each test panel. The test set ups are shown in **Figure 16**. In both cases the weather conditions were relatively constant throughout the tests. According to the Florida Solar Energy Center **[28],** the maximum solar incidence angle in San Francisco on the day of tests 5 and 6 was 59.30° at solar noon (13:08 civil time).

6.2.1 Test 5 and Test 6 Results

All the panels transmitted the maximum amount of light at solar noon (readings taken at 13:15 civil time). However, it is observed in **Figure 17**, that the tests using only layer (B) panels transmitted higher amount of light into the box as compared to the case when layers (B) and (A) were tested together. In another scenario, it is observed that panels with SCs that form layer (A) transmitted more light through the OFs into the testing box in comparison to the panels with CPCs. It is observed from the graphs that a system of CPCs or SCs and OFs with a half acceptance angle of 48.6° for the cones, allowed higher transmission of light. This is due to the fact that bigger acceptance angles can capture sunlight over larger solar altitudes as compared to CPCs or SCs with smaller half acceptance angles. All the cones accepted the same amount of light because all of them had the same maximum d_r. Therefore, for the panels, the same amount of light falls on top of their surfaces where part of that light is either transmitted or reflected.

7. CONCLUDING REMARKS

From outdoor tests 1 to 4, one concludes that OFs provide more light transmission in comparison to AR. In spite of this, the light transmission behavior is similar for both cases. For layer (B) tests, it is confirmed that the distribution and separation between edge-to-edge of the fibers are important in order to obtain a larger light transmission through the panels, e.g. in test 1 where a panel with 3 mm OF is embedded, one was able to have more light transmission compared to the other panels with larger diameters and larger OF densities. In general, apart from the OF density in the panel, OFs with a small diameter work better during the noon in comparison with OFs with larger diameters. Therefore, it is necessary to: 1) explore other inclinations of the panels, and 2) improve the OFs geometry for transmitting more natural sunlight in vertical or horizontal orientations without the necessity to incline the panel.

It is observed that cones with bigger acceptance angles can transmit more sunlight through the OFs in comparison to cones with smaller angles. Initially, the results seem inconsistent but it is necessary for maximum efficiency that the rays of sunlight fall within the numerical aperture (NA) of the OF. In this case, the cones had similar acceptance angles as the NA of the OFs. Thus, major part of the sunlight is lost and not able to exit from the other end of the cone. It is necessary to: 1) explore other CPCs and SCs with an appropriate half acceptance angle that is compatible with the one from the OF, and 2) improve the cones distribution for transmitting more natural sunlight in vertical or horizontal orientations without the need to incline the panel.

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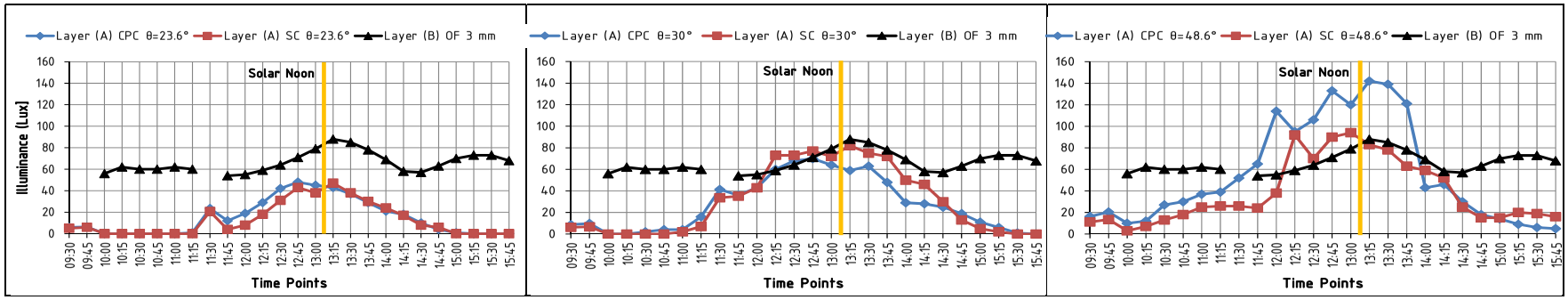
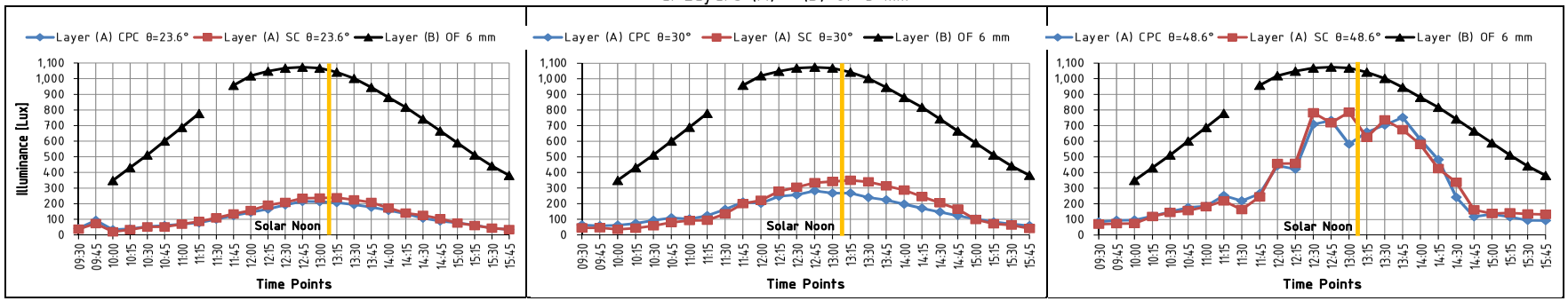
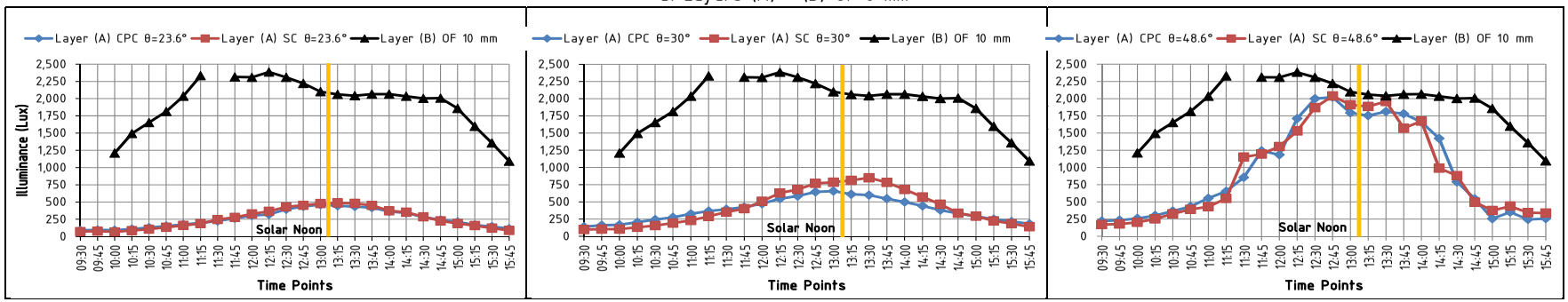


a. Layers (A) + (B) OF 3 mm



b. Layers (A) + (B) OF 6 mm



c. Layers (A) + (B) OF 10 mm

Figure 17. Layer (A) and Layer (B) outdoor results.

CHAPTER 4

Optical Fiber Light Scattering Outdoor Tests for Interior Daylighting

1. ABSTRACT

In building construction, most traditional building materials block the passage of natural light through the building envelope into the building's interior. Therefore, there is an energy demand for artificial lighting of interior spaces during daytime hours in any type of building. Currently, some interior spaces in a building are too much sunlight exposed and as a result some external shading elements for daylight control may be required. Optical Fibers (OFs) are mainly used for data transmission, but previous studies have demonstrated their capability for capturing and channeling sunlight into interior spaces in an anidolic way. The present research introduces different OF tip shapes aligned together with solar concentrators of different geometries. The objective is to assess and improve the basic properties of sunlight capturing, channeling and scattering by an OF. In addition, the research demonstrates the viability of using the OF as a passive daylight system and as an advancement in the energy efficient building envelopes market.

KEYWORDS

Anidolic Light, Daylighting, Energy Savings, Light Scattering, Optical Fiber Tips, Solar Concentrators.

2. INTRODUCTION

A large part of the total primary energy is consumed by buildings located in developed countries. According to **[1]**, about 39% of the total US primary energy today is consumed by buildings. This data clearly indicates the necessity of creating energy efficient buildings to save energy. This is possible by considering some passive and/or active energy efficient strategies **[2]**. However, before reaching this goal, the greatest energy saving is through an energy efficient building design approach, which will allow a reduction in mechanical components, and thus compensate for the additional cost of energy efficiency features **[2]**.

In the past, light was used to send messages. The Greeks used fire signals for sending alarms or calls for help **[3]**. Needless to say that the use of daylighting in architecture is not new. For centuries the humankind has been investigating how to let the light into the buildings. Daylight is an efficient natural source which supplies less heat in providing the same amount of light compared to electric light **[4]**. However, the use of artificial lighting consumes energy and also dissipates waste heat into the building space producing the need for heating or cooling **[5]**. In addition, the current problem of depletion of energy resources and the environmental effects of their applications require architects to design buildings with new daylighting strategies forced with the goal of minimizing energy use for electric lighting and air conditioning (HVAC). Simply, it is possible to save energy in buildings by use of daylighting as a passive solar design technique **[5]**. Daylighting is a passive design strategy in buildings that improves the occupants' visual comfort and the building's energy performance with an affordable cost installation **[6]**. Generally, there is an excess of sunlight striking the exterior of the buildings compared to the required amount of indoor daylight. However, this sunlight can be concentrated and then transmitted from outside to the inside through the building envelope with the help of Optical Fibers (OFs), as was introduced in a basic research by **[7]**. By using OFs, a portion of the electrical lighting load could be replaced by daylighting and as a consequence it is possible to obtain a reduction in the electrical lighting load **[8]**, with proper considerations in the construction process of the building. Summarizing, non-renewable energy consumption can be reduced by simply integrating daylighting systems as a component of the building envelope, which can substitute for electric lighting during daylight hours **[9].**

3. BACKGROUND

3.1 Daylight And Daylighting

Daylight is the combination of direct sunlight and diffuse sky radiation, as shown in **Figure 1a**. This is the full-spectrum of light that matches closest to human visual response and with better quality than electric lighting. For this reason lesser amount of daylight is needed to perform a task than performing it under electric light **[6]**. Moreover, daylight gives better color rendering and visual environment which allows the occupant to see objects properly in a room **[4]**. Nowadays, visual comfort has become an important issue due to the massive use of computers and video display terminals **[6]**. Humans need daylight for daily activities, e.g. work, leisure, display, etc. The properties of daylight affects human alertness, comfort and emotional state **[10]**. On the other hand, daylighting is the controlled admission of daylight into a building, **Figure 1b**. Due to the relationship in a building between the outside and the inside, architects need to optimize the floor plan for daylighting. This exercise is easy to do in a new construction project but difficult to address in the retrofit of an existing building. Generally, people have the perception that daylight offers beneficial light effects on humans than electric light **[11]**. In addition, there is greater

tolerance to daylight uniformity in comparison with electric light **[12].** Thus, the science of daylighting design can provide enough daylight into an interior occupied space but trying to avoid the side effects, e.g. discomforting glare, is out of the scope of the present research.

a. Daylight | b. Daylighting | c. Artificial light

Figure 1. Overall view of daylight, daylighting and artificial light.

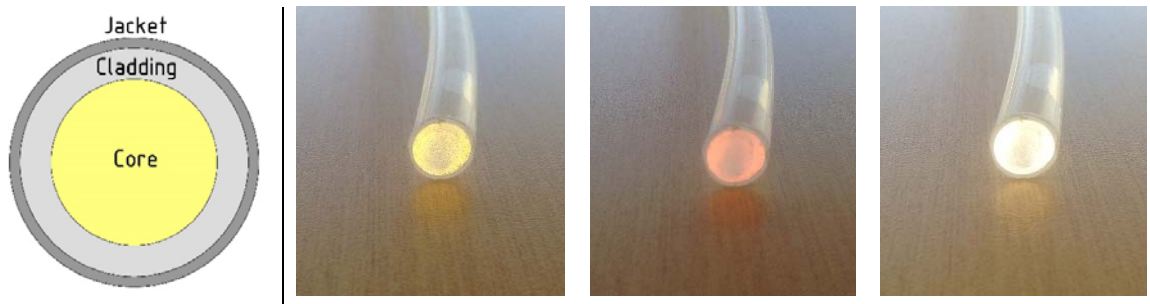
In the last few years, novel daylighting systems have been created which are capable of capturing sunlight and channeling it into the interior of a building under different sky conditions and with different principal phenomena of light propagation, e.g. scattering and diffusion, capillary structure, specular reflection, total internal reflection, light guiding waves, optical refraction, prismatic films, and optical diffraction **[9].** However, a good daylighting design must deal with both sunny and cloudy days including the location and orientation of the building. According to a research conducted by Smith **[10]**, nowadays it is possible to find construction materials that can improve the daylight and daylighting luminous efficacy, visual comfort and color management, which includes but not limited to, 1) Transparent polymer or glass sheets, and 2) Translucent polymer like Poly Methyl Methacrylate.

3.2 Artificial Lighting

Visible light is based on electromagnetic (EM) radiation in the range from 400 to 780 nm which can be perceived by the human eye. Basically, artificial light, **Figure 1c**, is composed of visible light, i.e. visible spectrum, and some ultraviolet (UV) and infrared (IR) spectrum. In general, artificial light seldom causes health problem, however, some light sources emit blue light and ultraviolet radiations. For this reason, some lamps and light fixture can be detrimental to humans, especially for their skin and eyes **[13]**. According to SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), the light which is incident on a user or observer depends on the light absorption properties of the media present between the light emission and the observer. Generally, this is provided by the medium in which light is generated as well as its envelope or surrounding air. Another important parameter to consider is the geometric arrangement of the light source and the geometry and reflective properties of the room and/or the lights. Before the electric lighting was invented, the predominant source of light was by using flames, i.e. candles and oil lamps. Nowadays, electric lighting follows Plank's law of radiation, which is generated by a process based on many thermal excitations. Plank's law says that with increasing temperature of the irradiating material, the peak intensity of the irradiated electromagnetic spectrum is observed at higher characteristic frequencies. This implies that at about 5,000 °K the emitted spectrum is similar to that of the sun's radiation through clear skies at midday. Therefore, each spectrum is related to a color temperature, which defines the sensation on the human eye, a photographic film and also affects the color perception **[13]**.

3.3 Optical Fiber

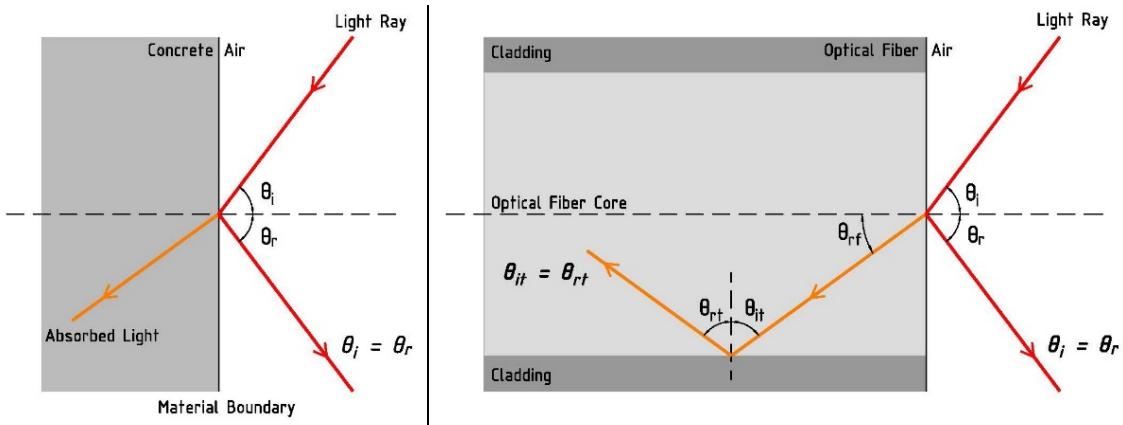
In electrical system, data is usually transported by superimposing the information signal onto a sinusoidally varying electromagnetic wave, i.e. the carrier. Any increase in the carrier frequency provides a larger information capacity. The optical portion of an OF is the element used as a transmission medium for the electromagnetic spectrum. The OF is a material which has greater flexibility and resistance to impacts and vibrations, and also couples light from the light source. Due to these properties, OFs have been used as a light transmission guide in displays utilized in sensors and telecommunications cables, for instance **[14]**.



a. OF cross sectional area

b. OF emitting light from different colored light sources

Figure 2. Overall view of a single Optical Fiber.



a. Concrete medium.

b. Optical fiber medium.

Figure 3. Optical fiber light propagation through two different media.

OFs for communications are highly flexible waveguides compounded by transparent dielectric materials. As seen in **Figure 2a**, its cross-section is usually circular and generally composed of three layers, i.e. core, cladding, and jacket which is a protective exterior cover **[14]**. The core is directly surrounded by a cladding which protects the core and also allows light to propagate by total internal reflection (TIR) at the core-cladding interface. Cladding is surrounded by an overcoat, i.e. jacket, for protection. Often the jacket is surrounded by another layer called buffer, which aims to protect the OF from damage. According to the type of OF supplier, the thickness of these three parts can vary. However, the capability of the OF to collect light depends on the core diameter and the numerical aperture (NA). The light propagates through the length of the OF core which can be made of glass (silicon dioxide) or plastic (Poly Methyl MethAcrylate). The core must have a larger refraction index compared to the cladding to allow the propagation of light using TIR **[15]**, **Figure 3**.

As is observed in **Figure 3**, a ray of light incident on an OF embedded in concrete, undergoes three light phenomena: Reflection and refraction on its cross-sectional surface and TIR along the inside walls of the OF. However, the light that is refracted into the OF may or may not undergo TIR. For the TIR to occur within an OF, where n_{core} and $n_{cladding}$ are the refractive indices for the OF core and cladding materials, respectively light rays need to follow **Equation 1**. In case they do not follow **Equation 1**, then they get converted to heat within the OF. Light is also dissipated inside the core of the OF due to scattering and absorption **[16]**.

$$n_{core} \sin \Theta_i > n_{cladding} \qquad \textbf{Equation 1}$$

The light scattering process in a single OF can be explained physically as a ray traveling through the OF finds microscopic variation in the refractive index of an OF and rises to the refraction and reflection phenomena **[14]**. When coupling the light emitted by the source into the OF, light rays coming from the source are refracted, passing from the OF core and the ray paths and angles vary throughout this process. The incident angle of rays travelling inside the core, have to subtend an angle lesser than the angle of aperture of the *admission cone,* which is the cone containing all the possible ray directions in the air for rays to be bound when they enter the fiber. The sine of the angle of aperture of this cone is called the numerical aperture (NA), and is given by **Equation 2**:

$$\mathrm{NA} = \sin \theta_{i\max} = \sqrt{n_{core}^2 - n_{cladding}^2} \qquad \textbf{Equation 2}$$

In OF basic physics, the NA is an important parameter which indicates the OF capacity for accepting and guiding light. The OFs that have a high NA can allow more light through them **[14]**.

4. EXPERIMENTAL STUDY APPROACH

Four small wooden specimens are embedded with single OFs with modified tips, **Figure 4** and **Figure** , have been manufactured and individually tested outdoors under direct sunlight in horizontal position for several days from January through July 2015 on the roof of Cory Hall building at UC Berkeley campus. The obtained results will be further used in research on computational modeling optimization of the OF daylight scattering behavior. Therefore, the purpose of these tests is twofold:

1. To calculate the % of the amount of sunlight captured and later scattered through the aforementioned different OFs specimens with or without solar concentrators.

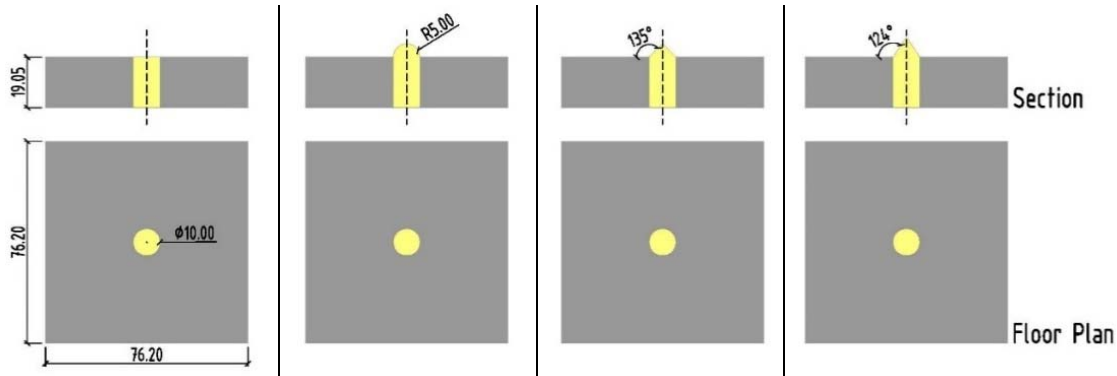
2. To observe and demonstrate the light transmission behavior and effectiveness for sunlight capturing and daylight scattering from the exterior to an interior space under different real sky conditions.

As shown in **Figure 6**, the present study included five tests as follows:

1. Test 1 for OF tip shapes facing the outside, **Figure 6a**.
2. Test 2 for OF tip shapes facing the inside of the test box, **Figure 6b**.
3. Test 3 for CPCs aligned with OF tip shapes facing the outside, **Figure 6c**.

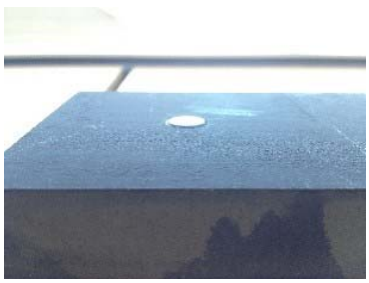
4. Test 4 for CPCs facing the outside and aligned with OF tip shapes facing the inside of the test box, **Figure 6d**.
5. Test 5 for OF tip shapes embedded in CPCs facing the inside of the test box, **Figure 6e**.

The goal of these five tests is to arrive at an OF tip shape geometry with a solar concentrator that works better for sunlight capturing and daylight channeling into an interior space.

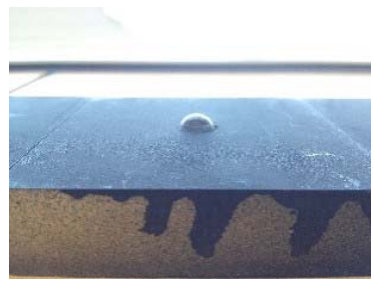


a. Flat OF tip shape. (10 mm diameter) | b. Hemispherical OF tip shape. (r=5 mm) | c. Coned OF tip shape (Inclination α=45°) | d. Coned OF tip shape. (Inclination α=56°)

Figure 4. Tested OF tip shapes specimens. [Units are in millimeters]

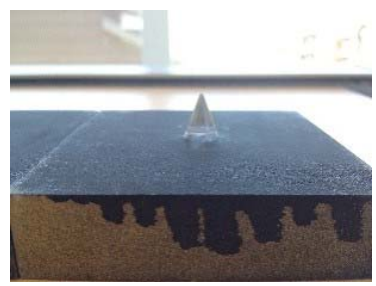


a. Flat OF tip shape.



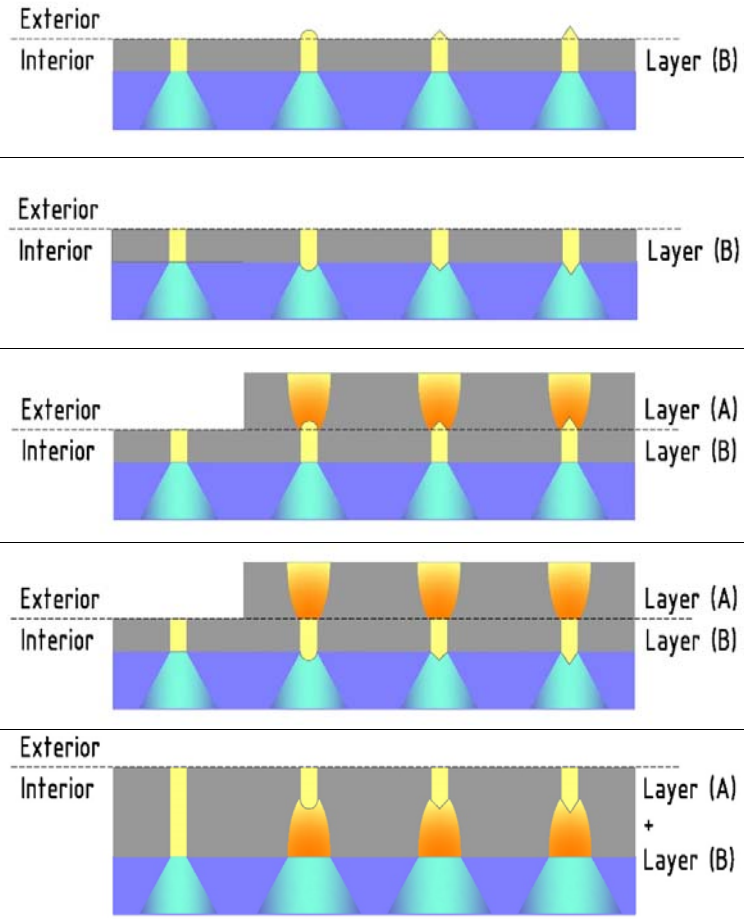
b. Hemispherical OF tip shape.

c. Coned OF tip shape. (α=45°)



d. Coned OF tip shape. (α=56°)

Figure 5. Images of the tested OF tip shapes.



a) Test 1 – OF tip shapes facing the outside.

b) Test 2 – OF tip shapes facing the inside of the test box.

c) Test 3 – CPCs aligned with OF tip shapes facing the outside.

d) Test 4 – CPCs facing the outside and aligned with OF tip shapes facing the inside of the test box.

e) Test 5 – OF tip shapes embedded in CPCs facing the inside of the test box.

Figure 6. Conducted tests for different ends of an OF.

4.1 Outdoor Portable Test Boxes

Four light tight test boxes were manufactured to accommodate wooden specimens with an embedded single OF whose tip has been modified to conduct the daylight tests shown in **Figure 6**. In the present research, each test box was fabricated using a 3D printer, with black color PLA (polylactic acid polymer) filamentand has interior clear dimensions of 71.0×71.0×71.0 mm^3. It was designed with rabbeted sides in order to prevent infiltration of exterior light from the edges of the box and also from the location of the light meter sensor. The boxes had one opening on the top where the different wooden specimens with OFs can be placed. As seen in **Figure 7**, the light meter sensor (Lux) was placed in the center of the opposite side to the test specimen such that the axis of the sensor was perpendicular to the face of the axis of the wooden specimen. With this design the different specimens could be easily changed and also the light meter sensors could be removed in the case of technical issues. The whole box is in black color in order to absorb the light reflections coming from the walls. The test box together with the light meter sensor are protected against exterior climate changes with an additional exterior cladding manufactured with the 3D printer, **Figure 8**.

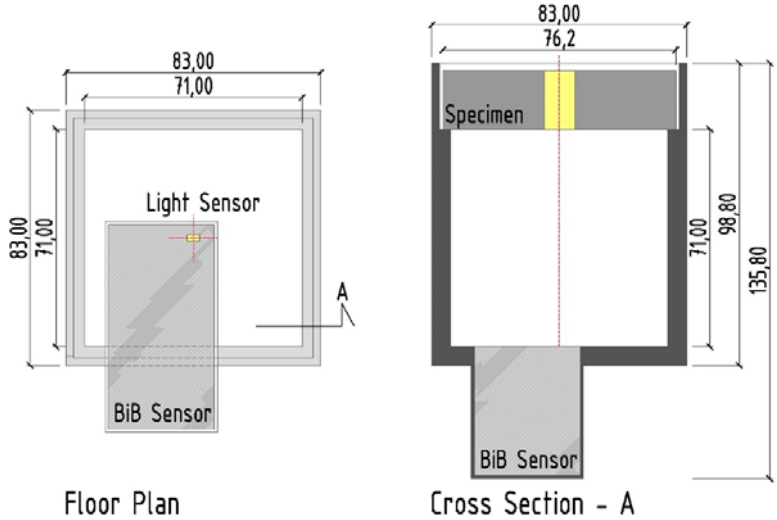


Figure 7. Text box dimensions. [Units are in millimeters]

a. Test set up with test boxes and support raised from floor. b. Illuminance sensors in the test box.

Figure 8. Images of the setup for Tests 1, 2, 3, 4 and 5.

4.2 Test Specimens

Four wooden specimens with an embedded OF of 10 mm diameter were designed and fabricated from MDF wood and painted in black color, **Figure 5**. MDF is an opaque material that can be easily manufactured using basic woodworking tools. Each specimen was 76.20×76.20 mm^2 and 19.05 mm thick. In the center of the wooden specimen a hole had been drilled. The OFs were cut to length on a small table saw and later the different OFs tips were shaped manually with a sander in order to obtain the final geometry. The OFs were inserted into the pre-drilled hole of the test specimen.

Due to the complexity of machining the tip shapes manually, it was not possible to prepare other OFs specimens with smaller diameters than the used size of 10mm. The specifications of the assessed OF of 10 mm diameter, are the following: 1) Acceptance Angle of 80°; 2) NA of 0.65; 3) Spectral Transmission Range of 380-750 nm; 4) Attenuation of 0.8 dB/m; 5) Minimum Bend Radius of 48 mm; 6) Operating Temperature of -40°C to 105°C. The conducted different tests of the OF tips, **Figure 4**, are the following: 1) OF Flat tip aligned with both sides of the base of the wooden specimen, **Figure 4a**; 2) Hemispherical OF tip with a radius of 5 mm, **Figure 4b**; 3) Coned OF tip whose angle with the horizontal is 45°, **Figure 4c**; and 4) Coned OF tip whose angle with the horizontal is 56°, **Figure 4d**. As the OF light transmission losses are not significant for the first 300 mm **[16]**, then the variation along the specimen thickness was not importance

in this research. The following subsections present more details of the study on the constructed specimens with different OF tips.

4.2.1 Test 1 – OF Tip Shapes Facing The Outside

This test consists of four wooden specimens embedded with OFs and characterized by differences in the shape of the tips, namely: flat, hemispherical, coned at 45°, and coned at 56°, **Figure 6a.** In this case, the OF tips are facing outwards from the box. The objective is to compare the ratio of the amount of daylight transmitted (Lux) into the test box from the different OF tips to that from a conventional OF with flat tip.

4.2.2 Test 2 – OF Tip Shapes Facing The Inside Of The Test Box

This test is the same as Test 1 but in this case the four OF tips are facing the inside of the test box, **Figure 6b.**

4.2.3 Test 3 – CPCs Aligned With OF Tip Shapes Facing The Outside

This test consists of four wooden specimens embedded with OFs bearing different tips (as stated in Test 1) and aligned with solar concentrators, as shown in **Figure 6c**. For this case, the solar concentrators are divided into the following 2 categories:

4.2.3.1 Test 3.1 – CPCs With Different Half Acceptance Angles But With The Same Larger Diameter

In this test, three different compound parabolic concentrators (CPCs) were designed and fabricated with a 3D printer in black color to absorb the natural sunlight. The inside of the CPCs were painted with a layer of mirror-like coating. The three independent variables of the CPC are the maximum (d_1) and minimum (d_2) diameters and length (L), which define its geometry. For the present test series, all the CPCs share the same d_1=25.4 mm but different d_2 and L length. CPC1 was defined by d_2=10.2 mm, L=40.7 mm and a half acceptance angle θ_{max}=23.6°. CPC2 was defined by d_2=12.7 mm, L=33 mm and θ_{max}=30°. CPC3 was defined by d_2=19.1 mm, L=19.6 mm and θ_{max}=48.6°. The objective of the test is to compare the ratio of amount of daylight transmitted (Lux) into the test box from different integrated systems of OFs and CPCs to an OF flat tip.

4.2.3.2 Test 3.2 - CPCs With The Same Half Acceptance Angle But With Different Smaller Diameter

This test is the same as Test 3.1, but in this case all the solar concentrators share the same half acceptance angle at θ_{max}=30°. But with different d_1 and d_2. Similar tests, as stated in Test 3.1, are conducted to determine the best combination of CPC and OF tips which will transmit the maximum daylight compared to a conventional OF with a flat tip. For the present design, CPC4 is defined by d_1=25.4 mm, d_2=12.7 mm, and L=33 mm. Straight Cone (SC) is defined by d_1=25.4 mm, d_2=12.7 mm, and L=33 mm. CPC5 is defined by d_1=20.3 mm, d_2=10.2 mm, and L=26.4 mm.

4.2.4 Test 4 – CPCs Facing The Outside And Aligned With OF Tip Shapes Facing the Inside Of The Test Box

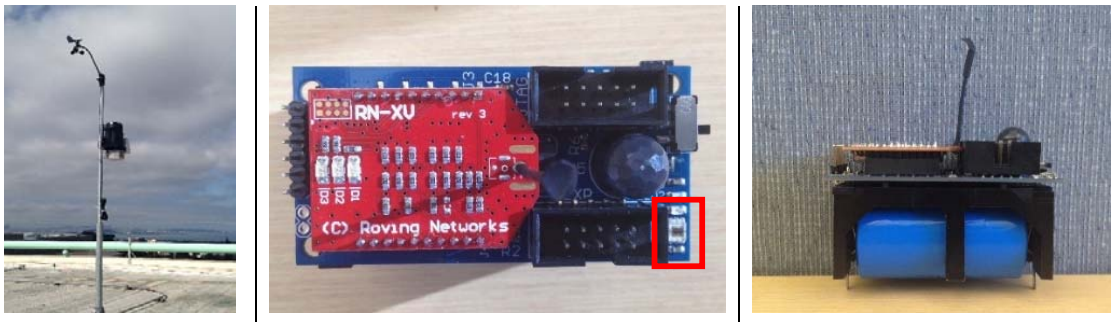
This test is the same as Test 3.1 but in this case the OF tips are facing the inside of the test box, as seen in **Figure 6d**.

4.2.5 Test 5 – OF Tip Shapes Embedded In CPCs Facing The Inside Of The Test Box

This test is the same as Test 3.1 but in this case the OF tips are embedded in the CPCs which are facing the interior of the test box, as seen in **Figure 6e**. The objective of the test is to compare the ratio of the amount of daylight transmitted (Lux) into the test box from different OF tips compared to that from the OF flat tip. In addition, the efficiency of the CPC geometry in helping the OF tips to scatter the channeled daylight into the box is observed.

4.3 The Instrumentation

The present research has been conducted by using instrumentation including a weather station (W/m^2) and light meter sensors (Lux), **Figure 9**. These are discussed in the following sections.



a. Weather station on the roof of Cory Hall.

b. Overall BiB sensor layout and light meter sensor (Lux) location.

c. Overall BiB sensor elevation.

Figure 9. The used weather station and the Building-in-Briefcase (BiB) sensor.

4.3.1 Exterior Weather Conditions

The exterior solar radiation (W/m^2) was measured by a weather station model WIRELESS VANTAGE PRO2, **Figure 9a**. It is placed on the roof of Cory Hall at UC Berkeley to measure the exterior weather conditions, namely temperature (°C), relative humidity (%), wind speed (m/s) and direction, solar radiation (W/m^2), rain collection (mm), and so on. The weather station was installed on September 2013 and from that day onward started to collect data every 30 seconds and forwarded it to a central database over the Internet. With this method, it is possible to visualize the trends in real time on the web portal where all the data are stored in a database. The test boxes, were placed close to the weather station. Therefore, the exterior solar radiation from the weather station accurately represents that of the test boxes.

4.3.2 Building-in-Briefcase (BiB)

For the conducted tests Building-in-Briefcase (BiB) portable sensors network platform were used, **Figure 9b** and **Figure 9c**. BiBs are low cost and wireless sensors which are easy to carry and deploy. Once the sensors were put into the test boxes and protected from water, then together with the aforementioned OF with or without a solar concentrator specimen, were ready for outdoor testing. BiBs collect and communicate the data every 1 minute to the BiB router which then securely forwards the data to the central database over the Internet to a website. The BiB sensor can read Ambient Visible Light (Lux), which employs AMS TSL2560 instrument **[17].** The BiB sensors used for the tests where calibrated using a

LICOR 210 light sensor. In this way all the BiB sensors used in the tests were working under the same range of values.

5. LIGHT TRANSMISSION TESTS RESULTS

The ultimate goal of the present study is to validate the use of the OF as a passive daylight system through the building envelope. Therefore, the conducted tests shown in **Figure 6**, aim to demonstrate which of the proposed OF tips together with a solar concentrator is more efficient for sunlight capturing and daylight scattering into the building's interior in an anidolic way through the building envelope. The tests took place on the roof of Cory Hall at UC-Berkeley campus under the outdoor sky conditions over the course of different days from January through July 2015 (throughout winter-spring-summer time) during solar hours. The experimental setup was placed in a horizontal position, facing the zenith, as shown in **Figure 8**. Each test was conducted at least two times for different months as a way to validate the results and to also see the effects of the sunlight incidence angles on the different OF shaped tips. As the sky conditions are changing daily, the obtained results slightly differed from one day to another. In the present research, all the data acquired under overcast skies were filtered out. It was observed that under a cloudy day any OF specimens were able to match the results from OF flat tip, which was being used as a reference for the comparisons. Therefore, for the present research, only fully sunny or partial sunny skies were considered. However, UC-Berkeley campus is located in the Bay Area in California, USA, and is known for frequent fog banks that quickly cover the sky, where the weather can vary quiet drastically at any time of the day. As a result, several of the test days were rejected in the present study. For this reason, a criterion was used to decide whether the sunlight incident on the sensors originated from an overcast sky or a clear sky. If the average of sunlight incidence between 10:00 and 15:00 was less than 450 W/m^2 for the case of January through March, or less than 750 W/m^2 for the case of April through June, the sky experienced overcast conditions and the readings were not accounted for that day. All tests were conducted for different hours in a day, and in some cases for more than two days in a row. However, complete data was available for times between 9:00 to 16:00. Occasionally some data were not recorded because of technical issues with the sensors. But if the test day was not overcast, i.e. it was sunny or partially sunny, then the obtained results were considered as valid. In all the tests, the sunlight incidence angle and the solar noon were obtained from the Florida Solar Energy Center **[18].** As seen in **Figure 8**, the four test boxes were placed horizontally on a flat surface raised from the floor avoiding nearby obstructions produced by shadows. The light meter sensor (Lux) was placed at the center of the test box and perpendicular to the specimen for measuring the light transmission from the outside to the inside of the box, **Figure 7**. The illuminance (Lux) readings were recorded every 1 minute for each specimen at the same time together with the solar radiation (W/m^2).

5.1 Test 1 – OF Tip Shapes Facing The Outside

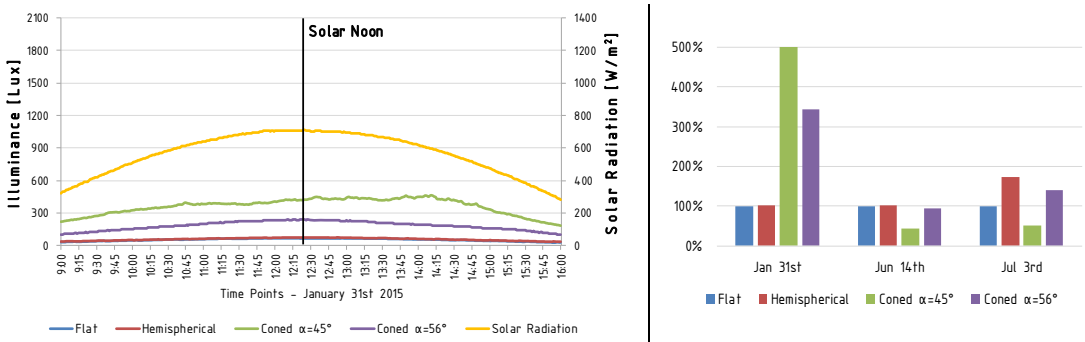
The parameters of Test 1 are shown in **Table 1**. In this test, the OF flat specimen was used as an element of comparison with the rest of specimens. From **Figure 10b**[1], the percentage of illuminance (Lux) obtained during the winter, e.g. January 31st, with a low sunlight incidence angle compared to the OF flat specimen was over 500% for the OF tip coned with an angle of 45° followed by the OF tip coned with an angle of

[1] The data obtained from the different test days, can be seen in Annex – Chapter 4.

56°, which increased the illuminance by over 300%. However, during the summer with a high sunlight incidence angle, the hemispherical specimen had the best values followed by the OF tip coned with an angle of 56°. It is noted that during the summer, e.g. June 14th and July 3rd, the OF tip coned with an angle of 45° never matched the OF flat specimen.

Table 1. Parameters of Test 1.

Day	Hour	Max. Solar Incidence Angle	Solar Noon	Solar Radiation [W/m²] Average (10:00 to 15:00)
Jan 31st	9:00	35.13°	12:25	635.02
Jun. 14th	to	75.69°	13:11	864.09
Jul. 3rd	16:00	75.34°	13:15	977.65



a. Sample readings throughout January 31st

b. Illuminance results in (%)

Figure 10. Readings and illuminance (%) results from Test 1.

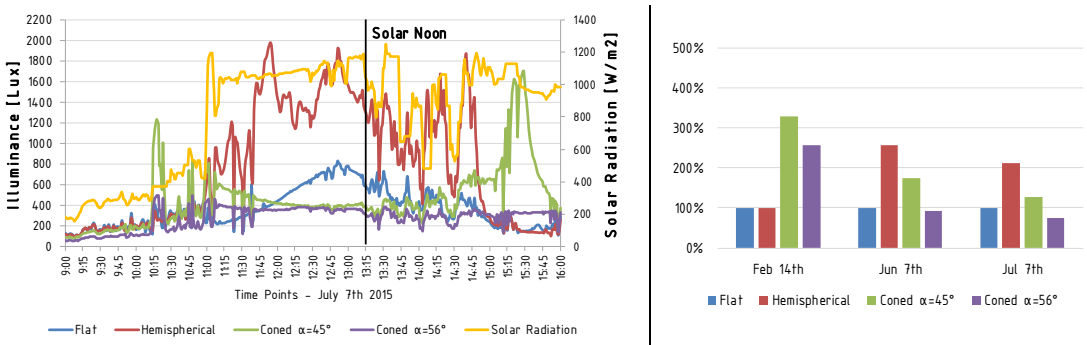
5.2 Test 2 – OF Tip Shapes Facing The Inside Of The Test Box

The parameters of Test 2 are shown in **Table 2**. In this test the OF flat tip was used as an element of comparison with the rest of specimens. From **Figure 11b**[2], the percentage of illuminance (Lux) obtained during the winter, e.g. February 14th, with a low sunlight incidence angle compared to the OF flat specimen was over 300% for the OF tip coned with an angle 45°. It was followed by the OF tip coned with an angle 56°, which resulted in an increase of illuminance (Lux) over 250%. However, during the summer, e.g. June 7th and July 7th, with a high sunlight incidence angle, the hemispherical specimen gave the best values with illuminances values (Lux) over 200% compared to the flat specimen. This was followed by the OF tip coned with an angle of 45° with results that were over 100% as compared to the OF flat tip. Nevertheless, during the summer, the OF tip coned with an angle of 56° never matched the OF flat specimen.

Table 2. Parameters of Test 2.

Day	Hour	Max. Solar Incidence Angle	Solar Noon	Solar Radiation [W/m²] Average (10:00 to 15:00)
Feb. 14th	9:00	39.51°	12:26	703.74
Jun. 7th	to	75.19°	13:10	928.01
Jul. 7th	16:00	74.96°	13:16	885.54

[2] The data obtained from the different test days, can be seen in Annex – Chapter 4.



a. Sample readings throughout July 7th

b. Illuminance results in (%)

Figure 11. Readings and illuminance (%) results from Test 2.

5.3 Test 3.1 – CPCs Aligned With OF Tip Shapes Facing The Outside

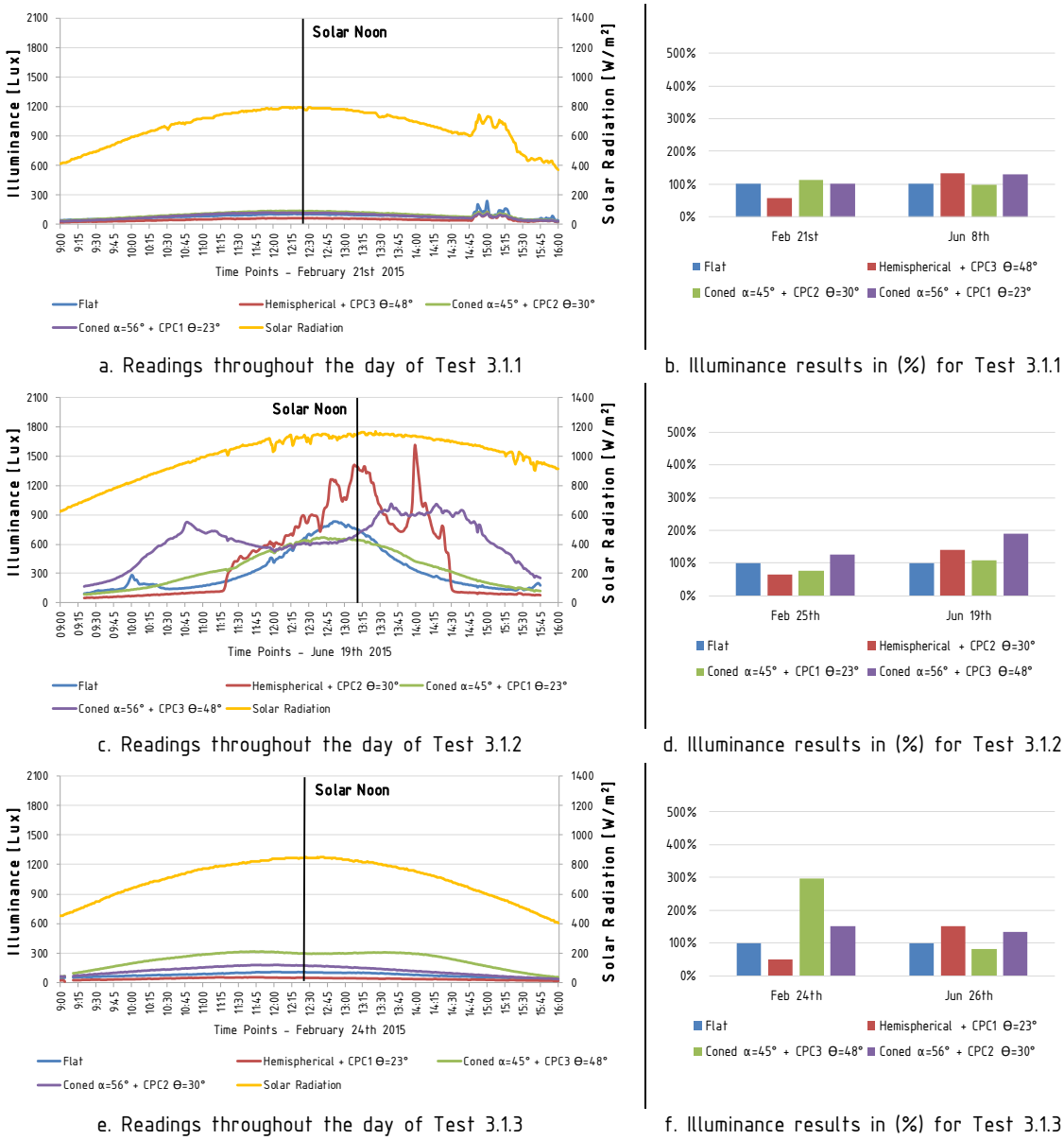
Table 3. Parameters of Test 3.1

References of the Specimens			Parameters of the Test days				
Test	**Specimens**	**Reference Specimens**	**Day**	**Hour**	**Max. Solar Incidence Angle**	**Solar Noon**	**Solar Radiation [W/m²] Average (10:00 to 15:00)**
Test 3.1.1	Hemispherical + CPC3 Tip 45° + CPC2 Tip 56° + CPC1	H-CPC3 45-CPC2 56-CPC1	Feb. 21st Jun. 8th	9:00 to 16:00	41.98° 75.28°	12:25 13:10	720.20 1031.40
Test 3.1.2	Hemispherical + CPC2 Tip 45° + CPC1 Tip 56° + CPC3	H-CPC2 45-CPC1 56-CPC3	Feb. 25st Jun. 19th		43.45° 75.84°	12:25 13:12	710.80 1064.70
Test 3.1.3	Hemispherical + CPC1 Tip 45° + CPC3 Tip 56° + CPC2	H-CPC1 45-CPC3 56-CPC2	Feb. 24st Jun. 26th		43.08° 76.79°	12:25 13:14	766.60 1026.30

This test consisted of a series of three tests[3] with varying parameters according to the CPCs aligned in front the OF specimens, as defined in Section 3.2.3.1. The test parameters and name references are shown in **Table 3**. For Test 3.1.1, the hemispherical tip was aligned with CPC3 (H-CPC3), OF tip coned with an angle of 45° with CPC2 (45-CPC2) and OF tip coned with an angle of 56° with CPC1 (56-CPC1). As shown in **Figure 12b**, the percentage of illuminance (Lux) during the winter, e.g. February 21st, with a low sunlight incidence angle was slightly over 100% for (45-CPC2) followed by (56-CPC1). Nevertheless, the (H-CPC3) never matched the OF flat tip used as a reference. However, during the summer, e.g. June 8th with a high sunlight incidence angle, (H-CPC3) had the best values followed by (56-CPC1). However, all the obtained data during the winter and summer, never exceeded more than 150% from the OF flat specimen used as a reference. For Test 3.1.2, the hemispherical tip was aligned with CPC2 (H-CPC2), OF tip coned with an angle of 45° with CPC1 (45-CPC1) and OF tip coned with an angle of 56° with CPC3 (56-CPC3). From **Figure 12d,** the percentage of illuminance (Lux) during the winter, e.g. February 25th, with a low sunlight incidence angle was slightly over 100% for (56-CPC3). The rest of the specimens obtained values lower than the OF flat tip used as a reference. However, during the summer, e.g. June 19th, with a high sunlight incidence angle, (56-CPC3) had results over 150% followed by (H-CPC2) slightly lower than 150% compared to the OF flat tip. For Test 3.1.3, the hemispherical tip was aligned with CPC1 (H-CPC1), OF tip coned with an angle of 45° with CPC3 (45-CPC3), and OF tip coned with an angle of 56° with CPC2 (56-CPC2). As seen in **Figure 12f**, the percentage of illuminance (Lux) during the winter, e.g. February 24th, with a low sunlight incidence angle

[3] The data obtained from the different test days, can be seen in Annex – Chapter 4.

was slightly over 300% for (45-CPC3) followed by (56-CPC2) which obtained results slightly over 150% compared to the OF flat tip used as a comparison. Nevertheless, (H-CPC1) never matched the OF flat specimen. However, during the summer, e.g. June 26th, with a high sunlight incidence angle, (H-CPC1) obtained a percentage slightly over 150% compared to the OF flat tip followed by (56-CPC2). On the other hand, (45-CPC3) never matched the OF flat tip specimen used for comparison. In conclusion, it is noted that OF coned with an angle of 45° works much better with low sunlight incidence angles and the hemispherical specimen works much better with high sunlight incidence angles. However, in both cases the CPC with a large half incidence angle, i.e. θ_{max}>30°, is more effective in order the capture and transmit sunlight.



a. Readings throughout the day of Test 3.1.1

b. Illuminance results in (%) for Test 3.1.1

c. Readings throughout the day of Test 3.1.2

d. Illuminance results in (%) for Test 3.1.2

e. Readings throughout the day of Test 3.1.3

f. Illuminance results in (%) for Test 3.1.3

Figure 12. Readings and illuminance (%) results from Test 3.1

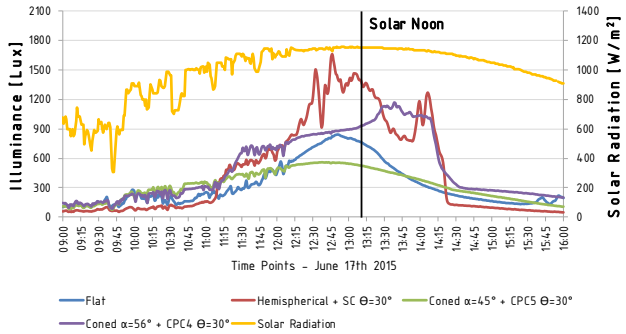
5.4 Test 3.2 – CPCs With The Same Half Acceptance Angle And Different Smaller Diameter

This test consisted of a series of three tests[4] with varying parameters according to the CPCs aligned in front of the OFs specimens as defined in Section 3.2.3.2. The test parameters and name references are shown in **Table 4**. In Test 3.2.1, the hemispherical tip was aligned with a SC (H-SC), the OF tip coned with an angle of 45° with CPC5 (45-CPC5), and the OF tip coned with an angle of 56° with CPC4 (56-CPC4). From **Figure 13b**, the percentage of illuminances (Lux) during the winter, e.g. March 9th, with a low sunlight incidence angle was slightly over 100% for (56-CPC4). The rest of specimens obtained lower values than the OF flat tip specimen used as a reference. However, during the summer, e.g. June 17th, with a high sunlight incidence angle, the (H-SC) together with (56-CPC4) had values slightly over 150% compared to the OF flat tip. In Test 3.2.2, the hemispherical tip was aligned with CPC4 (H-CPC4), the OF tip coned with an angle of 45° with SC (45-SC) and the OF tip coned with an angle of 56° with CPC5 (56-CPC5). As seen in **Figure 13d**, the percentage values of illuminance (Lux) obtained in all the specimens during the winter, e.g. March 13th, with a low sunlight incidence angle, were not able to match the OF flat tip specimen used as a reference. However, during the summer, e.g. June 12th, with a high sunlight incidence angle, (56-CPC5) values over 150% followed by (H-CPC4) with values lower than 150% compared to the OF flat tip. In Test 3.2.3, the hemispherical tip was aligned with CPC5 (H-CPC5), the OF tip coned with an angle of 45° with CPC4 (45-CPC4), and the OF tip coned with an angle of 56° with a SC (56-SC). From **Figure 13f**, the percentage values of illuminance (Lux) obtained in all the specimens during the winter, e.g. March 12th, with a low sunlight incidence angle, were not able to match the OF flat tip specimen used as a reference. However, during the summer, e.g. June 18th, with a high sunlight incidence angle, (56-SC) and (H-CPC5) had values slightly over 150% compared to the OF flat tip. In conclusion, it is observed that the CPC and the SC had similar results, but the CPC is able to concentrate sun during the winter while the SC cannot. Moreover, it is confirmed that the CPC with smaller diameter (d_2) similar to the OF diameter, is able to capture and transmit more sunlight compared to a CPC with the same half acceptance angle but with larger d_2 than the OF.

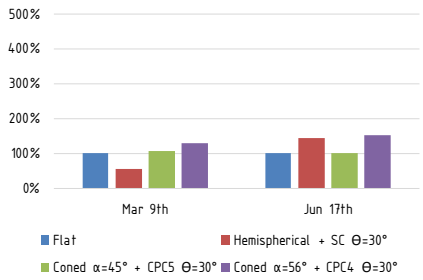
Table 4. Parameters of Test 3.2

References of the Specimens			Parameters of the Test days				
Test	**Specimens**	**Reference Specimens**	**Day**	**Hour**	**Max. Solar Incidence Angle**	**Solar Noon**	**Solar Radiation [W/m²] Average (10:00 to 15:00)**
Test 3.2.1	Hemispherical + SC Tip 45° + CPC5 Tip 56° + CPC4	H-SC 45-CPC5 56-CPC4	Mar. 9th Jun. 17th	9:00 to 16:00	48.04° 75.80°	13:21 13:12	749.40 1063.40
Test 3.2.2	Hemispherical + CPC4 Tip 45° + SC Tip 56° + CPC5	H-CPC4 45-SC 56-CPC5	Mar. 13th Jun. 12th		49.61° 75.58°	13:21 13:12	728.70 1046.90
Test 3.2.3	Hemispherical + CPC5 Tip 45° + CPC4 Tip 56° + SC	H-CPC5 45-CPC4 56-SC	Mar. 12th Jun. 18th		49.22° 75.82°	13:21 13:12	783.90 1067.20

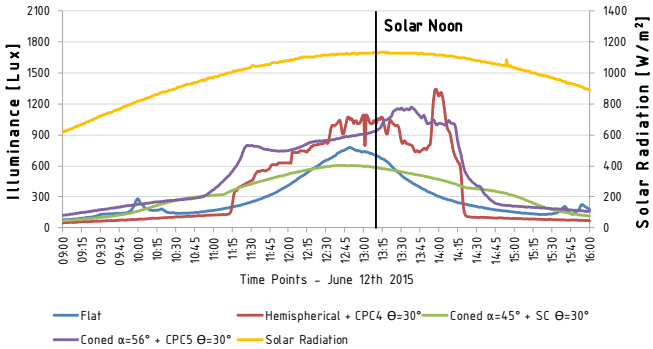
[4] The data obtained from the different test days, can be seen in Annex – Chapter 4.



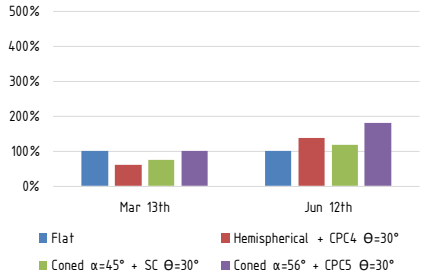
a. Readings throughout the day of Test 3.2.1



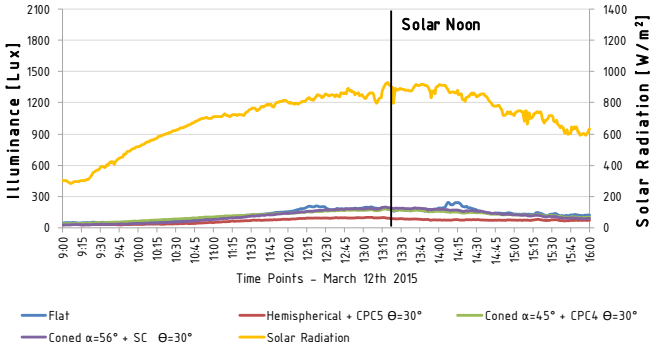
b. Illuminance results in (%) for Test 3.2.1



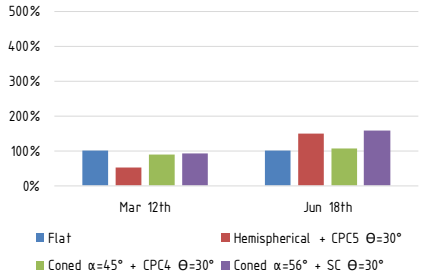
c. Readings throughout the day of Test 3.2.2



d. Illuminance results in (%) for Test 3.2.2



e. Readings throughout the day of Test 3.2.3



f. Illuminance results in (%) for Test 3.2.3

Figure 13. Readings and illuminance (%) results from Test 3.2

5.5 Test 4 – CPCs Facing The Outside And Aligned With OF Tip Shapes Facing The Inside Of The Test Box

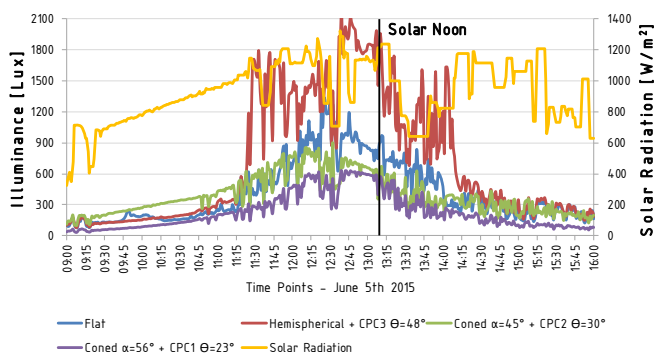
This test consisted of a series of three tests[5] with varying parameters according to the CPCs aligned in front the OF specimens. The test parameters and name references are shown in **Table 5**. In Test 4.1, the hemispherical tip was aligned with CPC3 (H-CPC3), the OF tip coned with an angle of 45° with CPC2 (45-CPC2), and the OF tip coned with an angle of 56° with CPC1 (56-CPC1). From **Figure 14b**, the percentage of illuminance (Lux) during the winter, February 23rd, with a low sunlight incidence angle was slightly over 100% for (45-CPC2). The rest of specimens obtained lower values compared to the OF flat tip used as a reference. However, during the summer, e.g. June 5th, with a high sunlight incidence angle, (H-CPC3) had values over 150% compared to the OF flat tip specimen but the rest of specimens obtained lower values

[5] The data obtained from the different test days, can be seen in Annex – Chapter 4.

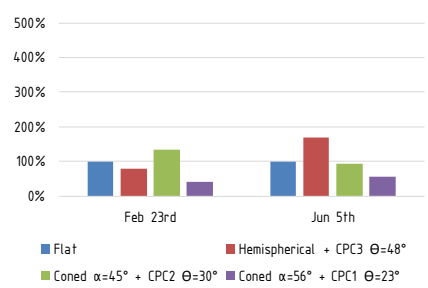
than 100%. In Test 4.2, the hemispherical tip was aligned with CPC2 (H-CPC2), the OF tip coned with an angle of 45° with CPC1 (45-CPC1), and the OF tip coned with an angle of 56° with CPC3 (56-CPC3). As seen in **Figure 14d**, the percentage of illuminance (Lux) obtained in all test specimens during the winter and summer times respectively with low and high sunlight incidence angles, were not able to match the OF flat tip specimen used as a reference. In Test 4.3, the hemispherical tip was aligned with CPC1 (H-CPC1), the OF tip coned with an angle of 45° with CPC3 (45-CPC3), and the OF tip coned with an angle of 56° with CPC2 (56-CPC2). From **Figure 14f**, the percentage of illuminance (Lux) during the winter and summer times respectively with low and high sunlight incidence angles were slightly over 100% for (45-CPC3). However, the rest of specimens obtained lower values than the OF flat tip used as a reference. In conclusion, the results obtained are the same for Test 3.1. Again, the OF tip coned with an angle of 45° works much better with low sunlight incidence angles and the hemispherical specimen works much better with high sunlight incidence angles. However, in both cases the CPC with a large half acceptance angle, i.e. θ_{max}>30°, is more effective in order the capture and transmit sunlight. However, the amount of illuminance (Lux) was lower, in Test 4 compared to Test 3.1. This clearly indicates the importance of having a shaped tip embedded into the CPC.

Table 5. Parameters of Test 4.

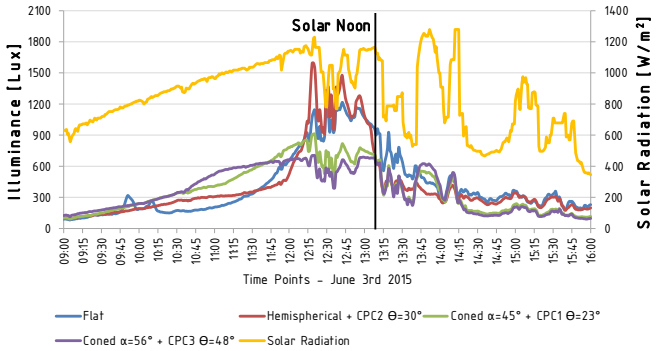
References of the Specimens			Parameters of the Test days				
Test	**Specimens**	**Reference Specimens**	**Day**	**Hour**	**Max. Solar Incidence Angle**	**Solar Noon**	**Solar Radiation [W/m²] Average (10:00 to 15:00)**
Test 4.1	Hemispherical + CPC3 Tip 45° + CPC2 Tip 56° + CPC1	H-CPC3 45-CPC2 56-CPC1	Feb. 23rd Jun. 5th	9:00 to 16:00	42.71° 74.99°	12:24 13:09	747.00 1060
Test 4.2	Hemispherical + CPC2 Tip 45° + CPC1 Tip 56° + CPC3	H-CPC2 45-CPC1 56-CPC3	Mar. 4th Jun. 3rd		46.10° 74.76°	12:23 13:09	786.10 924.10
Test 4.3	Hemispherical + CPC1 Tip 45° + CPC3 Tip 56° + CPC2	H-CPC1 45-CPC3 56-CPC2	Mar. 5th Jun. 2nd		46.49° 74.64°	12:23 13:09	802.40 890.00



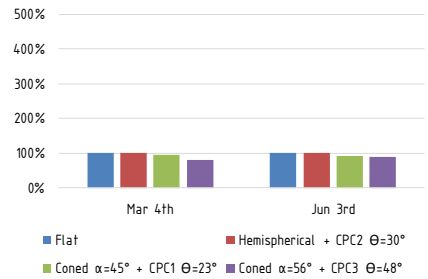
a. Readings throughout the day of Test 4.1



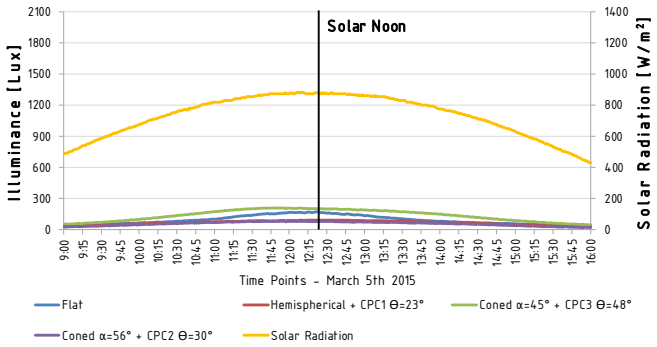
b. Illuminance results in (%) for Test 4.1



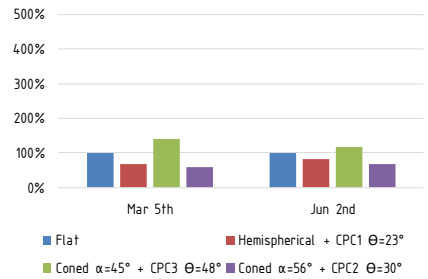
c. Readings throughout the day of Test 4.2



d. Illuminance results in (%) for Test 4.2



e. Readings throughout the day of Test 4.3



f. Illuminance results in (%) for Test 4.3

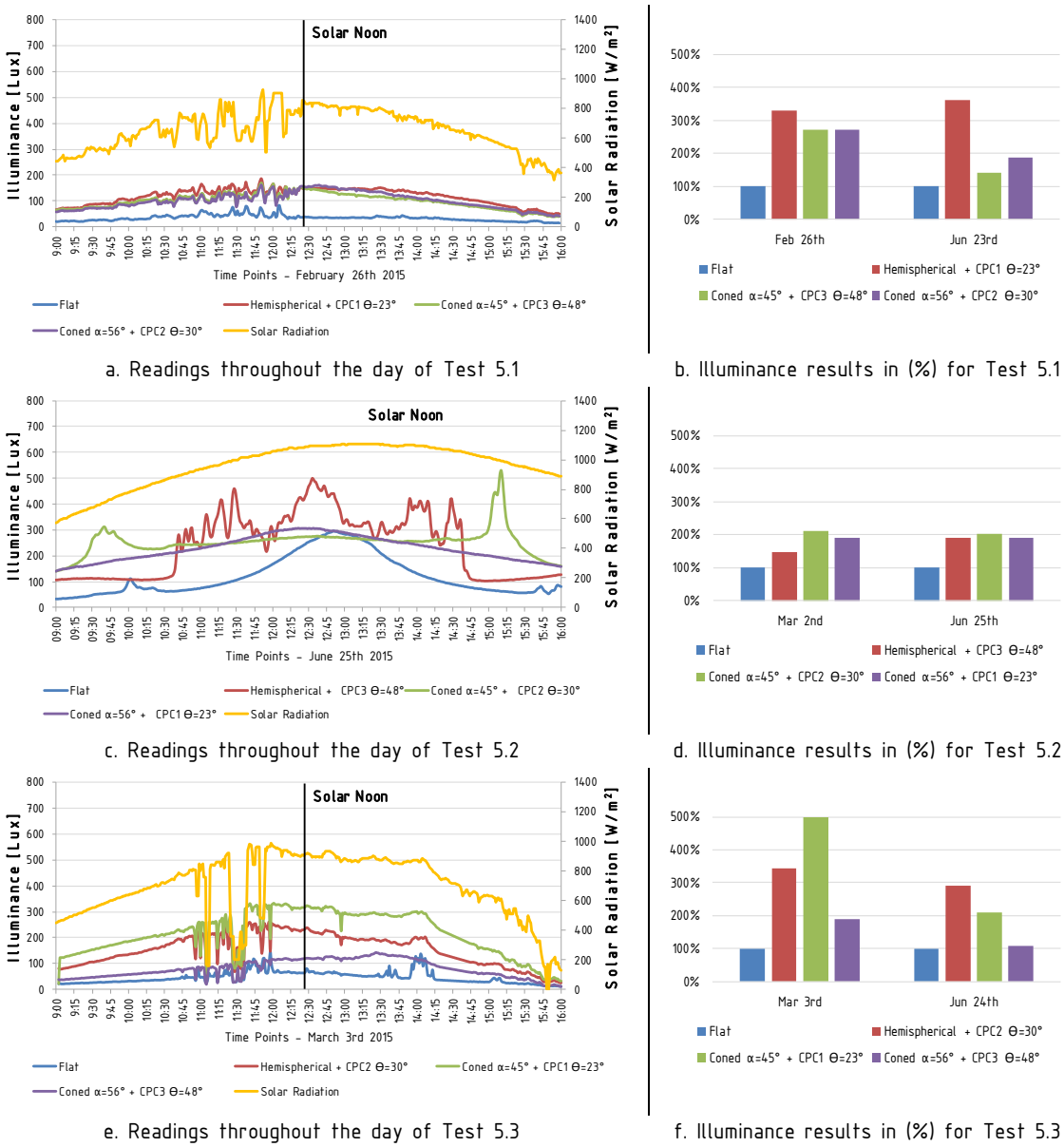
Figure 14. Readings and illuminance (%) results from Test 4.

5.6 Test 5 – OF Tip Shapes Embedded In CPCs Facing The Inside The Test Box

This test consisted of a series of three tests[6] with varying parameters according to the CPCs aligned in front the OF specimens. The test parameters and name references are shown in **Table 6**. In Test 5.1, the hemispherical tip was aligned with CPC1 (H-CPC1), the OF tip coned with an angle of 45° with CPC3 (45-CPC3), and the OF tip coned with an angle of 56° with CPC2 (56-CPC2). From **Figure 15b**, the percentage of illuminance (Lux) obtained during the winter, e.g. February 26th, with a low sunlight incidence angle compared to the OF flat tip specimen was over 300% for (H-CPC1) followed by (45-CPC3) and (56-CPC2), which obtained results over 250%. However, during the summer, June 23rd, with a high sunlight incidence angle, (H-CPC1) had the best values, over 350%, followed by (56-CPC2), slightly under 200%, compared to tip OF flat tip specimen used as a reference. In Test 5.2, the hemispherical tip was aligned with CPC3 (H-CPC3), the OF tip coned with an angle of 45° with CPC2 (45-CPC2), and the OF tip coned with an angle of 56° with CPC1 (56-CPC1). From **Figure 15d**, the percentage of illuminance (Lux) obtained during the winter, e.g. March 2nd, with a low sunlight incidence angle compared to the OF flat tip specimen was about 200% for (45-CPC2) had followed by (56-CPC1). However, during the summer, e.g. June 25th, with a high sunlight incidence angle, (45-CPC2) had values slightly over 200% followed by (H-CPC3) and (56-CPC1) compared to the OF flat tip specimen used as a reference. In Test 5.3, the hemispherical tip was aligned with CPC2 (H-CPC2), the OF tip coned with an angle of 45° with CPC1 (45-CPC1), and the OF tip coned with an angle of 56° with CPC3 (56-CPC3). From **Figure 15f**, the percentage of illuminance (Lux) obtained during the winter, e.g. March 3rd, with a low sunlight incidence angle compared to the OF flat tip specimen was close to 500% for (45-CPC1) followed by (H-CPC2) which obtained results over 300%. However, during the summer, e.g.

[6] The data obtained from the different test days, can be seen in Annex – Chapter 4.

June 24th, with a high sunlight incidence angle, (H-CPC2) had values slightly under 300% followed by (45-CPC1), over 200% compared to the OF flat tip specimen used as a reference. In conclusion, the OF tip coned with an angle of 45° works much better with low sunlight incidence angles and the hemispherical specimen works much better with high sunlight incidence angles. However, in both cases, the CPC facing the building interior with a small half incidence angle, i.e. θ_{max}<30°, is more effective in order the transmit daylight into the building's interior.



a. Readings throughout the day of Test 5.1

b. Illuminance results in (%) for Test 5.1

c. Readings throughout the day of Test 5.2

d. Illuminance results in (%) for Test 5.2

e. Readings throughout the day of Test 5.3

f. Illuminance results in (%) for Test 5.3

Figure 15. Readings and illuminance (%) results from Test 5.

Table 6. Parameters of Test 5.

References of the Specimens			Parameters of the Test days				
Test	**Specimens**	**Reference Specimens**	**Day**	**Hour**	**Max. Solar Incidence Angle**	**Solar Noon**	**Solar Radiation [W/m²] Average (10:00 to 15:00)**
Test 5.1	Hemispherical + CPC1 Tip 45° + CPC3 Tip 56° + CPC2	H-CPC1 45-CPC3 56-CPC2	Feb. 26th Jun. 23rd	9:00 to 16:00	43.82° 75.83°	12:24 13:13	721.50 1043.10
Test 5.2	Hemispherical + CPC3 Tip 45° + CPC2 Tip 56° + CPC1	H-CPC3 45-CPC2 56-CPC1	Mar. 2nd Jun. 25th		45.33° 75.79°	12:24 13:14	482.60 1020.50
Test 5.3	Hemispherical + CPC2 Tip 45° + CPC1 Tip 56° + CPC3	H-CPC2 45-CPC1 56-CPC3	Mar. 3rd Jun. 24th		45.72° 75.81°	12:24 13:13	783.70 1046.40

6. CONCLUDING REMARKS

From the outdoor tests, the primary conclusions are summarized as follows:

- In all the case, the light transmission behavior of the OF specimens changed throughout the months according to the sunlight incidence angle. Moreover, during the winter, there was lower solar radiation compared to the summer which affected the results, i.e. the total amount of illuminance recorded was low during the winter and high during the summer. However, this research only indicates the percentage of sunlight captured and channeled into the building compared to the OF flat tip specimen.

- OFs with a modified tip helped to capture and scatter more light in comparison to the flat tip. The tip shapes (with or without solar concentrators), have the capability of increasing the number of hours of effectiveness. On the contrary, as it is seen in the different graphs, the OF flat tip reaches the maximum peak around the solar noon but the results reduce drastically later in the day.

- The CPCs are more effective with high sunlight incidence angles by improving the light transmission of the OF specimens. However, with low sunlight incidence angles, the CPCs do not perform very well rendering less than optimal results.

- From the conducted tests, independent from the solar concentrator, it was confirmed that the cone shaped tip with an angle of 45° for OFs, works very well with low sunlight incidence angles, i.e. during the winter. On the other hand, the hemispherical OF tips obtained the best results with high sunlight incidence angles, i.e. during the summer. However, the OF tip shaped as cone with an angle of 56° mostly gave results lower the other two specimens, and its light behavior was kept constant throughout the different sunlight incidence angles.

- Both ends of the OFs should be modified as either cones or hemispheres as a way to transmit and scatter more sunlight into a room.

- The CPC that works much better is the one whose smaller diameter (d_2) matches with the OF diameter.

- CPC facing the outside with a large half incidence angle, i.e. Θ_{max}>30°, is more effective in capturing and transmitting sunlight during the winter and summer seasons. On the contrary, CPC facing the inside

with a lower half incidence angle, i.e. Θ_{max}<30°, is more effective in transmitting sunlight into the building during the year.

- Summarizing, according to the results obtained from the conducted five tests, it is recommended that the OF tip shaped as cone with an angle of 56°, should face the exterior and embedded in a CPC with a half incidence angle, i.e. Θ_{max}>30°. The results obtained from this OF tip were slightly lower compared to the other OF specimens, but its output light behavior was uniform throughout the different sunlight incidence angles, allowing it to be used in both summers and winters. The other end of the OF tip facing the interior should be designed as a hemisphere and embedded in a CPC with a half incidence angle Θ_{max}<30°. The light transmission results from this combination were recorded to be uniform during the summer and winter seasons.

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CHAPTER 5

A Portable Test Bed For Daylight Performance Assessment of Translucent Concrete Panel

1. ABSTRACT

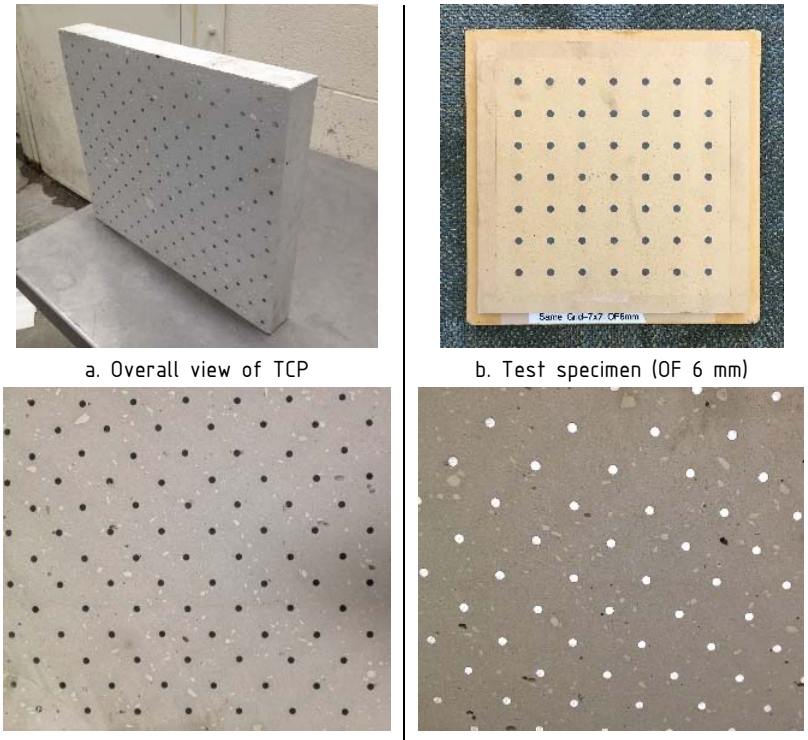
The construction industry is looking at sustainable and low-energy buildings which have motivated the professionals to offer new building envelope solutions with novel components and geometries. Nevertheless, due to the unusual nature of their construction, many times these new products have difficulties being tested according to the current available procedures. This is the case of the Translucent Concrete Panel (TCP) which is a novel energy efficient building envelope consisting of concrete panel embedded with Optical Fibers (OFs). This construction solution can alleviate the daylight inefficiency in buildings by allowing sunlight permeability through the opaque part of the exterior walls. Therefore, the present research is looking at ways to evaluate the light scattered from this novel construction solution which has translucent but not homogeneous sunlight transmission properties, by the dynamic daylight performance (DDP) as a light metric. For the TCP case study, a small portable test bed (SPTB) was designed. The SPTB was also developed to support experiments for testing and analyzing other building envelope components. It has an integrated control system that can actively respond to the fluctuating outdoor or controlled indoor conditions. Specifically, for the TCP case study, the SPTB was placed outdoors for testing different daylight parameters under real sky conditions which collected the data and forwarded them to a central

database over the Internet. The results monitored from the TCP using the SPTB are presented in this paper.

KEYWORDS
Daylighting, Dynamic Daylight Performance, Energy Savings, Multifunctional Building Envelope, Test Bed, Translucent Concrete.

2. INTRODUCTION

At present, there are many innovative building solutions in the market that attempt to solve issues related to either saving energy and improving indoor conditions **[1].** Due to different circumstances, these innovations can succeed or fail in the construction industry. However, the key factor for their success is by showing that these innovations are able to reduce cost and enhance quality or performance **[1].** The emerging concern about energy depletion is forcing the building community to design and build advanced buildings which offer minimal impacts on the nation's energy resources. Currently in building research, there is a high interest in developing innovative building envelope components and materials. In fact, there is a need to develop multifunctional building envelopes, which are able to change their characteristics, properties and functions, in order to suit the occupant's demand and reduce the building's energy consumption **[2]**. Therefore, for the scientific community, it is important to learn about these emergent technologies under different contexts, especially before they are implemented **[3]**. In many cases, these innovative solutions cannot be tested following standard procedures requiring the scientific community to develop new ways for scientifically enhancing new products. Thus, suitable design tools and working methods are required for the design process before the final construction product can be implemented.



a. Overall view of TCP

b. Test specimen (OF 6 mm)

c. TCP without light source

d. TCP with light source

Figure 1. TCP as an innovative solution of energy efficient building envelope.

On the other hand, widely used among architects are the scale models to assess the daylight performance under real sky conditions. For this reason, it is important to develop accurate models to represent the geometry and the materials accurately to mimic the real full-scale building. On the other hand, the imperfections in the model can produce inaccuracy and errors in the light quantity measurements and distribution **[4]**. Translucent Concrete Panel (TCP), **Figure 1**, is a novel energy efficient technology for building envelopes which is capable of capturing and delivering artificial daylight into the building's interior through the opaque part of the wall with the help of embedded Optical Fibers (OFs). Moreover, the TCP is leading to energy savings by reduction in electricity use for alighting in any type of building. In 2001, the Hungarian Architect Áron Losonczi invented the TCP **[5]** but it was primarily used for decoration. Recently, some authors are currently envisioning the use of TCP as a structural building component **[6]** **[7]** for building envelopes. However, the TCP does not have usual daylight transmission properties due to its geometrical design and choice of raw materials. In addition, this construction solution cannot be purely computer simulated because no software is available to model the daylight performance of the OFs, or the entire construction solution. For this reason, one of the objectives of this research is to design and build a Small Portable Test Bed (SPTB) to assess the outdoor dynamic daylight performance (DDP) of a non-scaled prototype of the TCP. In future studies, the obtained data will be used to develop computational programs similar with RADIANCE **[8]**, for instance.

3. BACKGROUND

3.1 Test Bed And Prototype Selection

A test bed is an experimental platform which is outfitted with instruments and is used for testing, getting feedback, making revisions and studying selected properties under working conditions. It is a living laboratory mainly used for experimentation, measurement and assessment. It may harness software, hardware and networking components as a way to collect data. In addition, it combines different training techniques, i.e. prototyping, business analysis, team work, etc. to understand the element characteristics and their conditions **[3]**. The test bed can use virtual, scaled or full-scale real models or prototypes. The choice is usually according to the objectives and needs of the research and also according to the properties of the product and material to be tested. The test bed computer simulation is one of the most common techniques to answer questions about physical building parameters. It can model specific parameters of a building and provide veracious results in a short time. However, sometimes there is not software in the market available to simulate some building features, and as a result there are parameters that must be obtained from conducting preliminary tests. Furthermore, for architects, it is important to observe the real environment of a space and compare the effectiveness of solutions in this space qualitatively, which in general, cannot be obtained by using computer simulations only **[9]**. How can we verify that the model or prototype is a good and reliable one? and is valid for its intended use? **[10]**. For this purpose, the prototype is used to assess the effectiveness of the technology before it is implemented in a full scale **[3]**. For this reason, when this is possible, it is essential to compare the experimental results with the reality. In fact, usually the computer simulations are based on real simulations of the model. In conclusion, a test bed comes out from the relationship between thinking and making by providing physical inputs to validate the tests **[11]**.

3.2 Daylight Metrics

Performance metrics can be used for comparative studies to guide building design or to benchmark a building for other buildings **[12]**. The definition of a well-daylight space has not evolved too much over the years. Daylight illuminance level in a room is a dynamic parameter which is constantly changing both in intensity and in spatial distribution with the position of the sun and the sky. These two sources, i.e. the sun and the sky, interact with the geometry and physical properties of the assessed model or prototype affecting the exterior and interior conditions of the model **[13]**.

3.2.1 Daylight Factor Analysis

The Daylight Factor (DF) is a simplified single point-in-time. This is a well-known method which gives a distribution of light in space **[13].** However, it is also common to use the sun path diagram or dynamic solar shading analysis as a way to assess the projection and track the sunlight in a space. Both procedures are mostly used by professionals as a way to see how daylight is distributed within a space but these methods never consider the daylight illumination levels nor the variation over time **[13]**. Based on research conducted by Reinhart et all **[12]**, the DF is an intuitive measurement technique that was published by Waldram **[14] [15]** early in the 20th century. It is defined in **Equation 1**, where E_i *and* E_o are, respectively, the internal and external diffuse illuminances on a horizontal plane for the CIE overcast skies. This method only uses ratios instead of absolute values as a way to avoid dealing with fluctuations in the daylight available outside.

$$DF = 100\ (E_i\ /\ E_o)$$ **Equation 1**

To predict the illuminance within a room from the frequency distributions of external illuminance, it is necessary to know if the ratio of internal to external light remains constant. If not, it is necessary to know how the ratio alters with the external conditions **[16]**. According to research conducted by Reinhart et al. **[12]**, although the DF is widely used, it is not a good daylighting design method because it only gives a minimum acceptable requirement. This method only calculates values under an overcast sky, which is considered as the worst sky scenario. As a consequence, a building designed by the DF is going to admit too much daylight which will possibly seem like a building with a fully glazed envelope. Furthermore, the DF applies the same parameters for all façade compass orientations, locations, times of the day, etc. enchaining a number of consequences, e.g. it cannot protect occupants from glare for different façade configurations and in certain parts of the building**.** In addition, some research studies like the one conducted by Oteiza et al. **[17]**, do not recommend the use of the DF because the estimated external illuminance values are far from reality. To summarize, the DF is not a good metric option for interior daylight performance assessment.

3.2.2 Dynamic Daylight Performance

Dynamic Daylight Performance (DDP) is a new alternative to DF. It is based on time series of illuminances or luminances obtained in an interior space, which are based on external conditions and the annual solar radiation data for the building site **[12]**. It is also demonstrated that the RADIANCE raytracer **[8],** combined with the daylight coefficient approach and the Perez Sky Model **[18],** calculates the time series of illuminances and luminances within a building. As a consequence, the dynamic daylight metrics provide a huge amount of data that is sometimes hard to manage. Currently, the following DDPs are available:

1. Daylight Autonomy (DA) **[12]**
2. Continous Daylight Autonomy (DA_{con}) **[12]**
3. Useful Daylight Illuminance (UDI) **[12]**
4. Annual Light Exposure (ALE) **[12]**
5. Daylight Saturation Illuminance (DSI)
6. Daylight Saturation Percentage (DSP).

The DDP metrics for an interior space require the following steps: 1) selecting the number of sensors and locations. It is recommended to place the sensor in a grid line of distribution; 2) deciding the time series of the year to test; and 3) choosing a criteria which verifies that the daylight situation at a sensor is correct at a particular point in time.

3.3 TCP As A Dynamic Building Envelope

The building envelope is a term which can be compared to human skin behavior by regarding its reaction to different exterior thermal conditions like low and high temperatures and humidity levels. It consists of all the exterior construction components of a building and its complexity is based on its needs to prevent water and air infiltration in order to avoid moisture accumulation, and control the flow of heat through it. As the sunlight irradiates over the whole building envelope, i.e. façades and roofs of a building, the exterior walls and fenestration undergo the following:

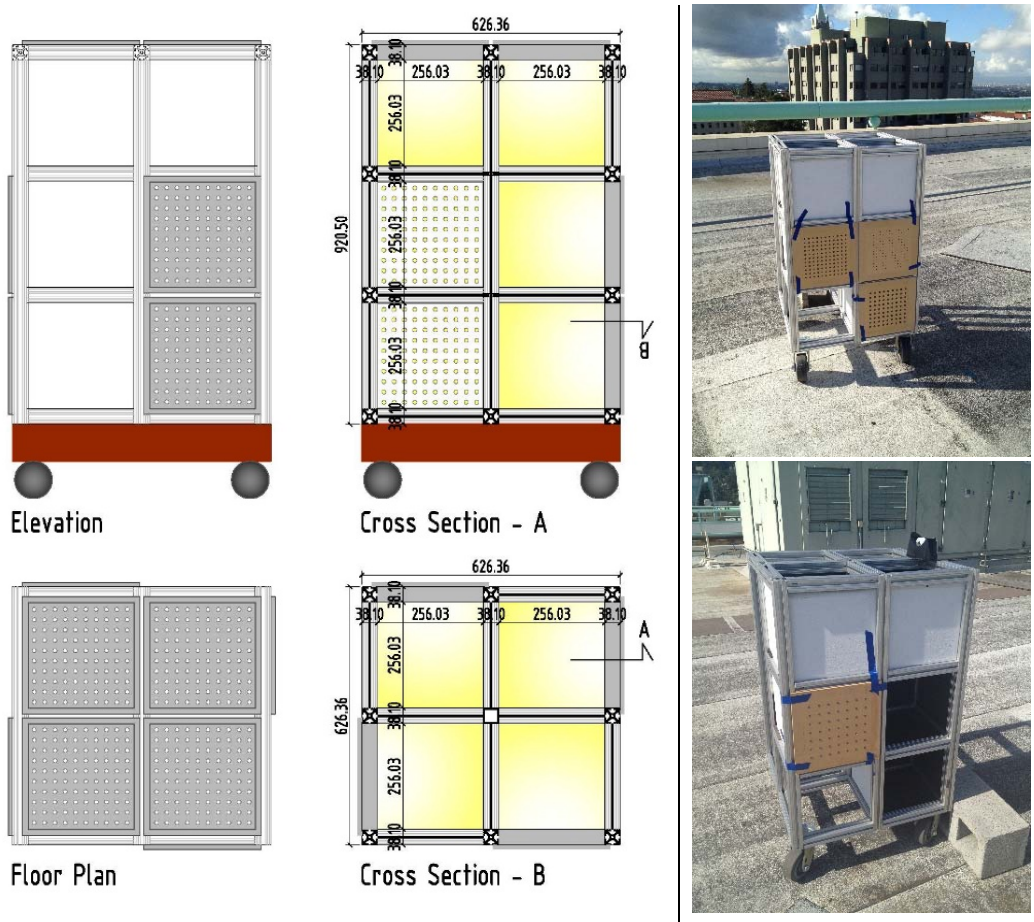
1. Some amount of energy is transmitted into the building's interior through the walls and glass.
2. A portion of energy is reflected away from the walls and glass.
3. The remaining energy is absorbed by the building envelope components.

However, materials and technological variations introduced into the building envelope can affect its dynamic performance by altering the envelope characteristics. This is the case of the Dynamic Building Envelope (DBE) sub-system, which attempts to achieve a near optimum energy efficient environment meeting occupant needs throughout the year by adapting to dynamic meteorological conditions and changing occupant preferences in real time **[19]**. There is another example with the novel Climate Adaptive Building Shell (CABS). This is a dynamic envelope placed on the outermost of a static building envelope which has the ability to repeatedly and reversibly change some of its functions, features or behavior throughout the day in response to changing performance requirements and variable boundary conditions, with the aim of improving the overall building performance **[20]**. Therefore, the OFs embedded into the TCP for daylighting, affect its static performance by providing some daylight transparency through the opaque part of the walls, rendering a type of DBE which evolves with the sunlight and exterior weather conditions thorough the year.

4. SMALL PORTABLE TEST BED

The present research is focused on the design and construction of a SPTB, **Figure 2,** which is proposed to assess the DDP of the TCP case study under real sky conditions and weather changes. The present SPTB has been designed as an integrated control system that actively responds to the changing outdoor or indoor conditions.

4.1 Design And Construction



a. Floor plan, elevation and cross section of the SPTB. b. The SPTB testing outdors.

Figure 2. Overall design of the proposed small portable test bed. [Units are in millimeters]

The design and concept of the SPTB was envisioned as a light, movable and convertible structure to test a scaled or non-scaled prototype of the TCP and/or other construction components or sub-systems. This is a modular structure which is able to support different building envelope prototypes at the same time. The assessments can be conducted independently or at the same time which save costs of large scale tests by providing preliminary scaled or non-scaled results. The SPTB is a light movable cuboid-like, which simulates the building envelope by facing the four basic orientations (i.e. north, south, east and west), and also simulates a flat roof on the top, **Figure 2**. Its structural design consists of a re-adjustable structure of columns and beams made of aluminum. It was built with a light structural modular frame, which is easy to assemble and adjust. If it were necessary, it can be reshaped to other dimensions and configurations. It was manufactured with the 80/20's T-slotted extruded profiles of 38.1 mm × 38.1 mm cross-section. As shown in **Figure 2b**, this cuboid is divided into three stories where each story contains four independent small cubicles for testing. The total floor dimensions are 626.4 mm × 626.4 mm, and the structure is 920.5 mm high, **Figure 2a**. In a test bed, it is required that the specimens can be changed during simulation run-time. Therefore, it was necessary to come up with a manageable dimension of the test specimen by keeping a clear relation with the actual building. For this reason, one of the key factors of the design of the SPTB was to decide on the geometrical dimensions of the test cubicles and specimens. The SPTB has a total of twelve independent test cubicles with dimensions of about 256 mm × 256 mm × 256 mm. The interior

partitions of the SPTB were made of plywood and all of them were painted in black color to absorb all the reflected daylight of the walls. According to Bodart et all, **[4]** it is important to choose materials for testing that have a reflection coefficient and a brightness close to the actual material's values at full scale. For this reason, the SPTB's interior finish was similar to the interior partitions used in buildings. Due to the geometry (section profile) of the aluminum structure, the wooden partitions can be embedded into the structure which blocks the entrance of light from outside. Moreover, this test bed is outfitted with four wheels, which are able to support the structure of the SPTB together with the test specimens. In addition, these wheels allow easy transportation of the SPTB, along with the test specimens from one location to another. It should be highlighted that when it was built, all the test cubicles were tested with a light meter (Lux) to verify that light does not leak into the space through the joints.

4.2 Instrumentation

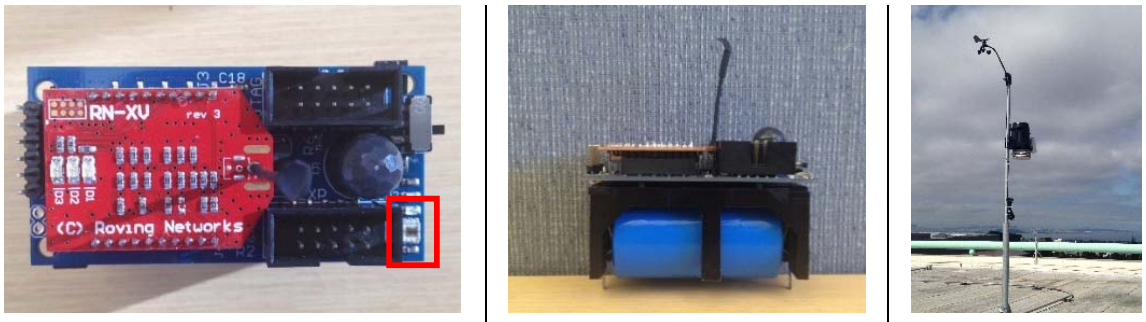
The present SPTB has been designed as an integrated control system that actively responds to the changing outdoor or indoor conditions. In the TCP case study, the instrumentation consists of a weather station (W/m^2) and wireless light meter sensors (Lux) to generate and store data on and an online database. However, due to its versatility, it can be outfitted with other types of sensors according to the test that need to be conducted.

4.2.1 Exterior Weather Conditions

The exterior solar radiation (W/m^2) was measured by a weather station called WIRELESS VANTAGE PRO2, **Figure 3c**. It was placed on the roof of Cory Hall at UC Berkeley to measure the exterior weather conditions, namely temperature (°C), relative humidity (%), wind speed (m/s) and direction, solar radiation (W/m^2), rain collection (mm), etc. It was installed on September 2013 when it started collecting data every 30 seconds and forwarding them to a central database over the Internet. With this method, it was possible to visualize the trends in real time on the database web portal. The SPTB was placed close to the weather station in order to accurately represent the exterior conditions of the test bed.

4.2.2 Building-in-Briefcase (BiB)

The SPTB was initially designed to be used with Building-in-Briefcase (BiB) **[21]** portable sensor network platform, **Figure 3a** and **Figure 3b**. BiBs are low cost and wireless sensors which work on a battery of 3.7V Lithium-Thionyl and are easy to carry and deploy in different locations. Once the sensors are installed into the SPTB, they are ready for taking measurements and all the collected data are communicated to the BiB router via TCP/IP protocol and WiFi technology which forward the data securely to a central database over the Internet. A BiB sensor can read the following parameters: 1) Temperature (°C) (°F) and Humidity (%) using the embedded Measurement Specialties HTU21D instrument, 2) Orientation of the BiB measured by LIS3DH and accelerometer by ST Microelectronics, 3) Motion Detection measured by Panasonic's AMN41121 passive infrared (PIR) motion detector module, and 4) Ambient Visible Light (Lux) measured by AMS TSL2560 instrument. This design incorporates two light-sensing photodiodes: one measuring visible and infrared light (IR) from 300 nm to 1100 nm, and the other measuring IR light from 500 nm to 1100 nm. **[21].** The BiB sensors used for the tests where calibrated by a LICOR 210 sensor (Lux). In this way, all the BiB sensors used in the tests were working under the same range of values.



a. Overall BiB sensor layout and light meter sensor (Lux) location.

b. Overall BiB sensor elevation view.

c. Weather Station.

Figure 3. Instrumentation of the SPTB.

4.2.3 Central Database Over The Internet

As seen in **Figure 4**, the central database is a web based visualization tool which receives and stores data obtained from wireless BiB sensors from all different deployment sites in an easy and secure manner. It provides live and historical information and exchanges batch data with other web parts. With the database website, it is possible to visualize the trends in real time while allowing investigating with real-time information, including time series, relational, and web services information. Data can be combined from different sources: real-time, maintenance systems, production planning systems, and financial systems. The excel web access provides the ability to view excel workbooks in a browser.

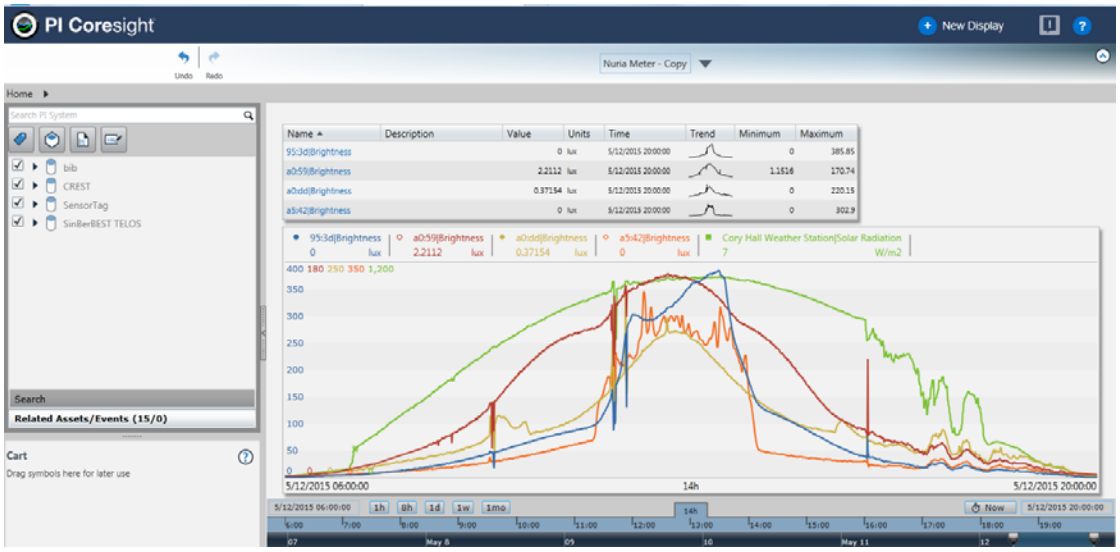


Figure 4. Overall view of the database website.

5. EXPERIMENTAL STUDY APPROACH

A non-scaled TCP test specimen embedded with 6 mm OFs, **Figure 1b**, was manufactured and tested outdoors under direct sunlight. The specimen was installed in a vertical position facing south in one of the cubicles of the SPTB for several days from August to October 2015, installed on the roof of Cory Hall building at UC Berkeley campus. The obtained results will be further used in research for computational modeling optimization of the TCP daylight transmission. Therefore, the purpose of the tests was twofold: 1)

Demonstrate the viability of the SPTB as a portable and easy testing tool for obtaining consistent preliminary results under real outdoor conditions, and 2) Observe and assess the behavior of the walls of the test cubicle daylight scattered and diffused by the TCP with the DDP metric. For the present research, three groups of DDP tests were conducted, **Figure 5**, as follows:

1. Test 1.1 – Visual test without the TCP test specimen.
2. Test 1.2 – Visual test with the TCP.

3. Test 2.1 – DDP of the TCP.
4. Test 2.2 - DDP of the TCP with diffuser #1.
5. Test 2.3 – DDP of the TCP with diffuser #2.

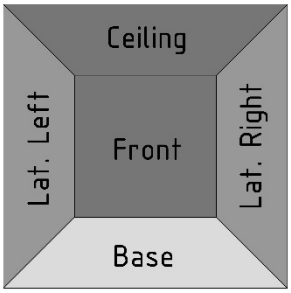
6. Test 3.1 - DDP of the TCP with sensors placed on the base of the cubicle.
7. Test 3.2 - DDP of the TCP with sensors placed on the frontal side of the cubicle.
8. Test 3.3 - DDP of the TCP with sensors placed on the lateral right side of the cubicle.
9. Test 3.4 - DDP of the TCP with sensors placed on the lateral left side of the cubicle.

5.1 Conducted Outdoor Tests

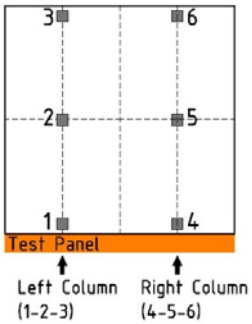
As shown in **Figure 1b**, a TCP test specimen was designed and fabricated from MDF wood material instead of concrete because the main objective of this study was to assess its DDP in the SPTB. The test panel had an area of 254×254 mm^2, and was 19.1 mm thick. It was embedded with OFs 6 mm in diameter arranged in a 7×7 grid with an edge-to-edge spacing between the OFs of ~23.9 mm. The holes were drilled in the TCP using a computer numerical controlled (CNC) flatbed router. OFs were cut to length and inserted into the pre-drilled holes of the test panels. In order to produce consistent results, a finishing operation was performed on the specimens. The OF core material consisted of Polymethyl-Methacrylate Resin and its refractive index profile was based on Step-Index Multi Mode Fibers.

The present research had only seven BiB sensors available for testing. Therefore, it was not possible to cover in a grid line the totality of the surface of the test cubicle. As was mentioned before, in order to use the DDP as a daylight metric, it is very important to select the number of sensors and justify their locations. Thus, in the present study, two different tests were set up, depending on the type of grid arrangement of the light sensors where the light meter sensors were placed in a grid line. In the first, six BiB sensors were arranged in two different columns (1-2-3 and 4-5-6) at a spacing of 63.5 mm from the lateral sides of the test box, as seen in **Figure 5c.** With this distribution, it was possible to uniformly cover the length of the test box with the sensors, including the back of the cubicle. This grid was used to assess the scattering and diffusing of daylight. In the second, seven BiB sensors were arranged in two rows (1-2-3 and 4-5-6), and one column (2-5-7). In this case, the sensor locations cover the axis of the test box, in addition to parallel planes to the TCP, as seen in **Figure 5d**. However, in both cases, the objective was to verify the behavior of the daylight scattered and diffused by a small non-scaled prototype of the TCP using the DDP as a metric. The illuminance (Lux) readings were recorded every minute for each BiB sensor together with the outdoor solar radiation (W/m^2). Nevertheless, the DDP results shown below in the graphs, only represented three specific hours (i.e. 9:00, 13:00 and 17:00). The present study considers that these times covered the sun movement obtained from the morning to the late afternoon while observing that the solar noon took place around 13:00.

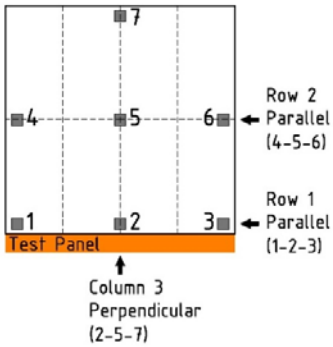
a. Interior view of a test cubicle.



b. Labeled sides of the cubicle.



c. Grid with 6 sensors.



d. Grid with 7 sensors.

Figure 5. Overall view of the test cubicle and location of the sensors during the tests.

5.1.1 Test 1.1 – Visual Test Without The TCP

As seen in **Figure 6a,** the present test aims to visually show the direct interaction of sunlight within the interior of the test cubicle without the use of the TCP. The main objective is to obtain visual data which can justify and later explain the behavior of the daylight, scattered and diffused, in the TCP case study. The test took place throughout the course of a sunny day on October 5th, 2015. In this case, a camera was placed in front of one of the test cubicles of the SPTB without the TCP, and the photos were taken every hour from 9:00 to 17:00, to track the shadows projected into the test box throughout the day.

5.1.2 Test 1.2 – Visual Test With The TCP In The Test Cubicle

In this test, the TCP test specimen was installed in a vertical position facing south in one of the cubicles of the SPTB. The entire arrangement faced the south direction. Similar to Test 1.1, this test took place throughout the course of a sunny day on October 5th, 2015, but in this case the camera was placed into the test box. It took photos hourly from 9:00 to 16:00 of the front, right, left and ceiling of the test cubicle, as shown in **Figure 6b**. In the present test, the interaction of the sunlight transmitted by the TCP and projected on the interior walls of the test box over the course of a day is illustrated. The objective was to explain the interaction of daylight scattered and diffused by the TCP and also compare with results obtained from Test 1.1.

5.1.3 Test 2.1 – DDP Of The TCP

In this test, the TCP test specimen was installed in a vertical position facing south in one of the cubicles of the SPTB. As seen in **Figure 5d**, seven BiB sensors were arranged in two rows (1-2-3 and 4-5-6), and

one column (2-5-7) in a grid line on the base of the test cubicle with the objective of determining the daylight scattered of and diffused by the test specimen. The cubicle containing the TCP was intended for the DDP metric under real sky conditions from 9:00 to 17:00.

5.1.4 Test 2.2 – DDP Of The TCP Attached With Diffuser #1

This test is the same as Test 2.1 but in this case a light diffuser sheet was attached behind the TCP test specimen. Diffuser #1 was a tough white diffusion sheet which creates soft light with minimal color temperature. The objective of the test was to determine the daylight scattered and diffused by the test specimen with the assessment of the DDP under real sky conditions from 9:00 to 17:00, and also compare the results with Test 2.1 in order to determine the effectiveness of diffuser #1 into the test cubicle.

5.1.5 Test 2.3 – DDP Of The TCP Attached With Diffuser #2

This test is similar to Test 2.2 but here a different light diffuser sheet was attached behind the TCP test specimen. The chosen diffuser #2 was a half tough white diffusion sheet and less dense than diffuser #1 which also creates soft light with minimal color temperature. The objective of the test was to determine the daylight scattered by the test specimen with the assessment of the DDP under real sky conditions from 9:00 to 17:00, and also compare the results with Tests 2.1 and 2.2 in order to determine the effectiveness of diffuser #2 in the test cubicle.

5.1.6 Test Group 3 - DDP Of The TCP With Sensors Placed On The Walls Of The Test Cubicle

In this test, the TCP test specimen was installed in a vertical position facing south in one of the cubicles of the SPTB. The objective of the test was to determine the daylight scattered and diffused by the test specimen with the assessment of the DDP under real sky conditions from 9:00 to 17:00. In addition, the daylight variations are observed in the conducted tests because of movement of the sunlight, and the results were compared with the visual tests from Tests 1.1 and 1.2. As seen in **Figure 5c**, six BiB sensors were arranged in two columns (1-2-3 and 4-5-6) and analyzed in a grid installed on the different interior walls of the test cubicle. For this case, the test was divided into the following sub-categories: 1) Test 3.1, the sensors were placed on the base of the test box; 2) Test 3.2, the sensors were placed on the front, opposite to the TCP side of the test box; 3) Test 3.3, the sensors were placed on the lateral right side of the test box; and 4) Test 3.4, the sensors were placed on the lateral left side of the test box.

6. DYNAMIC DAYLIGHT PERFORMANCE ASSESSMENT RESULTS

The ultimate goals of the conducted tests are the following: 1) Demonstrate the effectiveness of the SPTB; 2) Analyze the daylight scattering and diffusing behavior of the TCP inside the room with and without light diffusers; and 3) Investigate the DDP as a consistent daylight metric for daylight assessment. In future, the obtained results from the SPTB will be used towards the optimization of the light conduit diameter and spacing, i.e. density, and panel thickness for maximum daylight transmission through the panels. The data will also be used as a reference for computer program verification that will allow the assessment of the daylight performance of the TCP in a fast and consistent manner. The tests took place on the roof of Cory Hall at UC-Berkeley campus under outdoor sky conditions over the course of different days from August to October 2015 (throughout summer-fall time) during solar hours. As seen in **Figure 2b**, the experimental setup was placed in one of the test cubicles of the SPTB, in vertical position facing the

south. Each test was conducted for two to three days as a way to verify the consistency of the obtained results. The complete data are available for times between 9:00 and 17:00. However, for the DDP assessment, the presented results shown in the graphs are based on illuminance levels (Lux) obtained at 9:00, 13:00 and 17:00, considering that these hours covered the different times and intensities of sunlight during the day. In the present tests, occasionally some data were left out because of technical issues with the sensors. As the sky conditions changes daily, the obtained results slightly differed from one day to another. Under a cloudy day, the illuminance (Lux) obtained from the TCP test specimen was lower but it followed the same behavior as seen on a sunny day. For this reason, in this study all the data acquired under overcast skies were accepted to consider all the sky conditions. In all the tests, the sunlight incidence angle and solar noon were obtained from the values recorded by Florida Solar Energy Center **[22]**.

6.1 Test 1.1 – Visual Test Without The TCP

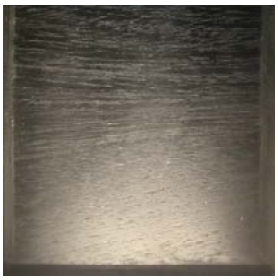
This test was conducted on October 5th, between 9:00 and 17:00. The maximum solar incidence angle in San Francisco during that day was 47.57° at its corresponding solar noon 12:59 civil time. **Figure 6a** shows the projection of sunlight in the test cubicle at different times of the day (at 9:00, 12:00, and 15:00). The cubicle opening was not covered. From the images, one can clearly see the areas that are directly irradiated by the sun or are shaded. No diffused light was observed during the course of the test.

Shadows at 9:00

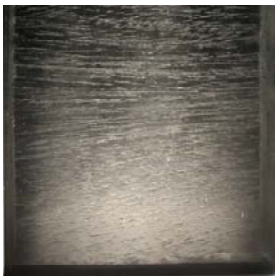
Shadows at 12:00

Shadows at 15:00

a. Trace of the shadows inside the cubicle without the TCP.



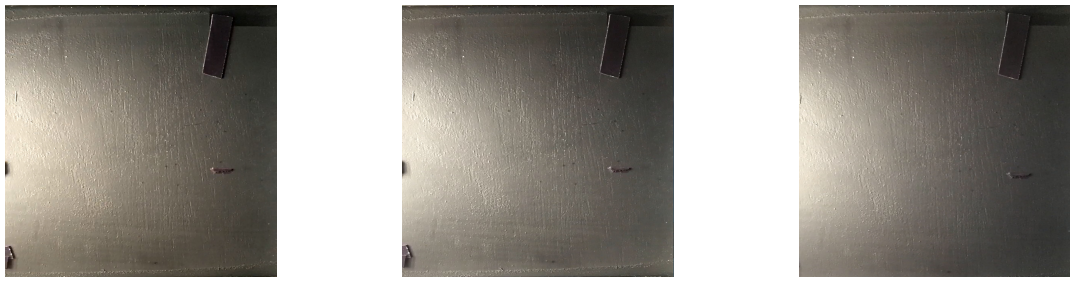
TCP at 9:00



TCP at 12:00

TCP at 15:00

b. Views of the ceiling of the cubicle with the TCP.



TCP at 9:00 TCP at 12:00 TCP at 15:00

c. Views of the left side of the cubicle with the TCP.

TCP at 9:00 TCP at 12:00 TCP at 15:00

d. Views of the right side of the cubicle with the TCP.

Figure 6. Visual assessment of the light transmitted by the TCP within the test cubicle.

6.2 Test 1.2 – Visual Test With The TCP In The Test Cubicle

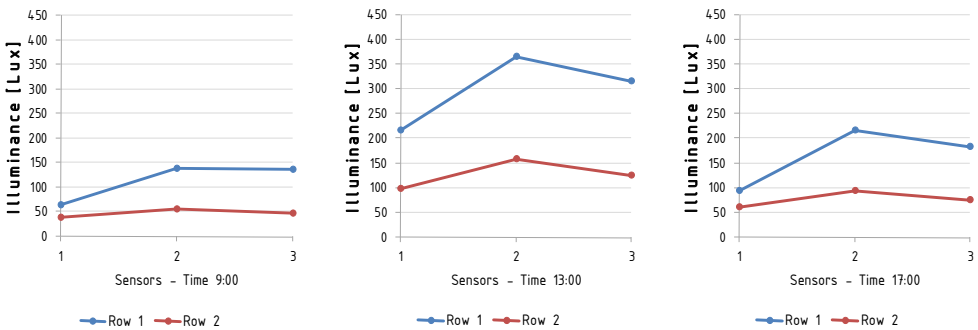
This test took place on the same day and under the same conditions as Test 1.1. From the images obtained in **Figure 6b**, **Figure 6c** and **Figure 6d**, it was clearly observed that the daylight transmitted into the cubicle by the TCP test specimen was scattered and diffused in the test box without any shadows, i.e. there were no dark areas inside de box. However, areas of the test box closer to the test specimen received more concentrated daylight compared to the rest of the side walls of the test cubicle. It is also demonstrated in the following tests that the daylight at areas close to the specimen only varied in intensity throughout the day, with a maximum observed at noon. Moreover, it was difficult to follow the sun path during the test hours. This again shows that the TCP case study really scatters and diffuses the daylight within the cubicle's interior. Besides, it was noticed that the daylight distributed by the OFs, within the box's interior, was not affected by the sun path. However, the only parameter that changed during the test hours was the illuminance level and the variation depended on the hour of the day.

Table 1. Test parameters.

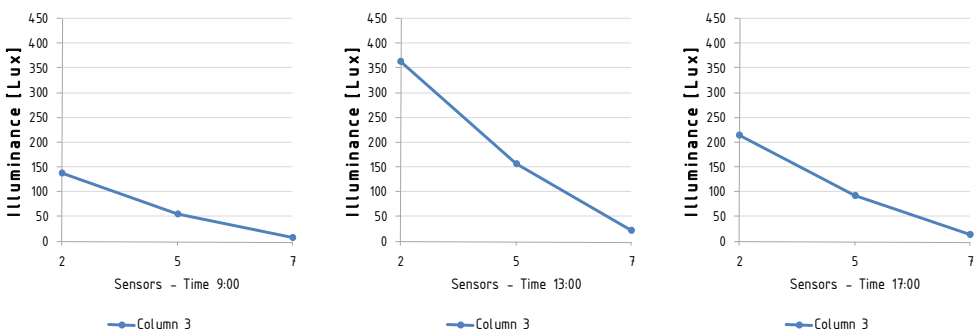
Test	Day	Max. Solar Incidence. Angle	Solar Noon	Solar Radiation [W/m²] Average (9:00 to 17:00)	Test	Day	Max. Solar Incidence Angle	Solar Noon	Solar Radiation [W/m²] Average (9:00 to 17:00)
Test 2.1	Aug. 6th	69.02°	13:18	518.71	**Test 3.1**	Aug. 26th	62.72°	13:12	816.35
	Aug. 7th	68.74°	13:17	787.30		Aug. 29th	61.66°	13:11	526.87
						Aug. 30th	61.20°	13:11	746.30
Test 2.2	Aug. 12th	67.29°	13:16	886.09	**Test 3.2**	Sep. 26th	51.06°	13:03	710.32
	Aug. 14th	66.68°	13:16	850.02		Sep. 27th	50.67°	13:02	590.10
						Sep. 28th	50.28°	13:01	554.57
Test 2.3	Aug. 9th	68.17°	13:17	893.55	**Test 3.3**	Oct. 3rd	48.34°	13:00	685.20
	Aug. 11th	67.59°	13:16	763.67		Oct. 6th	47.19°	12:59	578.33
						Oct. 19th	42.35°	12:55	564.35
					Test 3.4	Sep. 23rd	52.23°	13:03	737.51
						Sep. 30th	49.50°	13:01	165.26
						Sep. 14th	44.17°	12:57	542.16

6.3 Test 2.1 – DDP Of The TCP

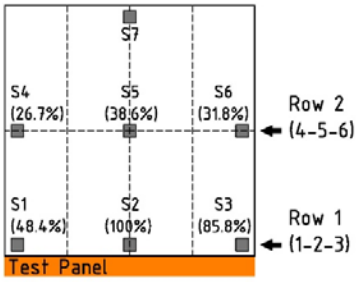
This test[1] was conducted on August 6th and 7th thorough the course of the solar hours. The test parameters are shown in **Table 1**. In this case, sensors (1-2-3) and (4-5-6) were distributed in two rows parallel to the test panel, **Figure 5d**. The obtained results showed during the same trend between rows, confirming that the TCP keeps the same daylight transmission behavior with only one variation which came from the illuminance intensity (Lux) by capturing more intensity around noon. The second row of sensors (4-5-6) obtained an average of about 60% less illuminance compared to the first one. As seen in **Figure 7a**, Sensors 2 and 5 which were located in the middle of the test cubicle, obtained higher results compared to the sensors placed close to the side walls. This was due to the fact that these sensors were not directly surrounded by the test cubicle walls.



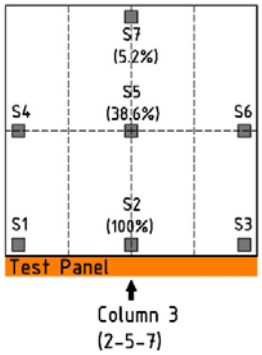
a. Sensors placed parallel to the face of the TCP



b. Sensors placed perpendicular to the face of the TCP



c. Key results obtained from the sensors placed parallel to face of the TCP



d. Key results obtained from the sensors placed perpendicular to the face of the TCP

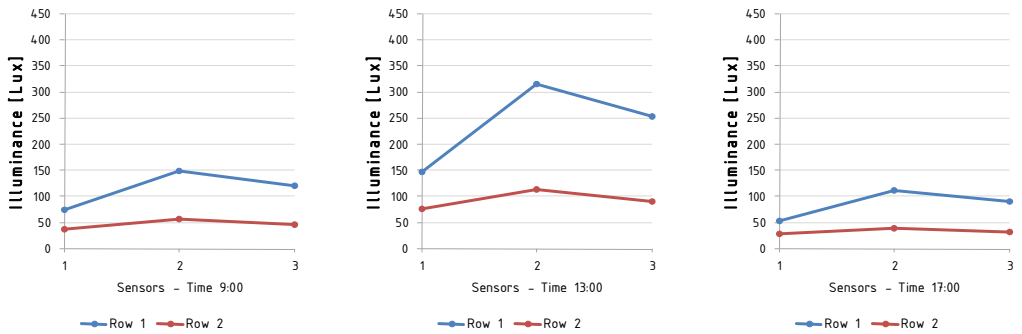
Figure 7. DDP of the TCP. August 7th 2015. (Partial sunny day)

[1] The data obtained from the different test days, can be seen in Annex – Chapter 5.

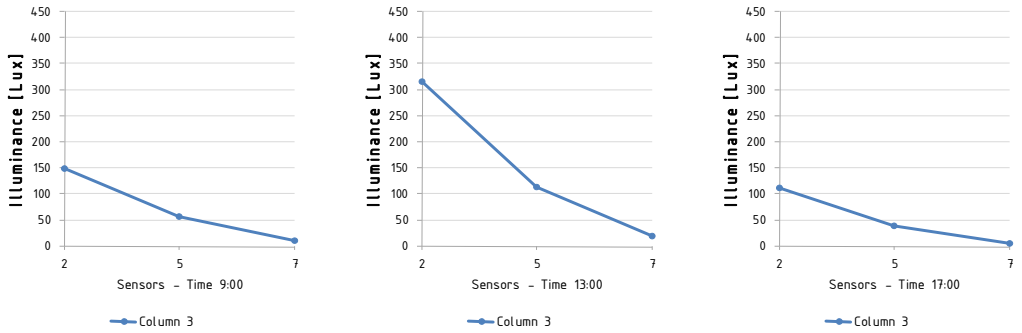
Based on the average of the total amount of illuminance intensity (Lux) data obtained during the solar hours of the test day, sensors (1-2-3) captured, respectively about 48%, 100% and 86% of illuminance compared to sensor 2 used as a reference. On the other hand, sensors (4-5-6) captured respectively, in about 26%, 39% and 32%. Compared to sensor 2 used as a reference. It was noticed that the results of the second row showed less fluctuations compared to the first one which was placed in front of the TCP. On the other side, as seen in **Figure 7b,** sensors (2-5-7) were placed perpendicular to the test panel. From the obtained results, one concludes that there was a linear reduction in the daylight received from the outside to the back of the test box. Based on the average of the total amount of illuminance (Lux) obtained during the solar hours of the test day, sensor 5 received about 39% of illuminance, and sensor 7 recorded only about 5% in comparison to sensor 2 which was used as a reference. It was concluded that the daylight scattered by the TCP did not cover a long distance. As was noticed in sensor 5, the one placed in the middle of the test box, it captured less than the 40% of the illuminance compared to sensor 2 used as a reference.

6.4 Test 2.2 - DDP Of The TCP Attached With Diffuser #1

This test[2] was conducted on August 12th and 14th thorough the course of the solar hours. The test parameters are shown in **Table 1**. From **Figure 8**, it is noted that the behavior in the daylight scattered and diffused, compared to Test 2.1, is the same. However, the light diffuser #1 sheet attached behind the TCP did not help in improving the daylight scattered into the test cubicle. However, the obtained illuminance (Lux) values were somewhat lower by about 6% than Test 2.1 which was used as a reference.

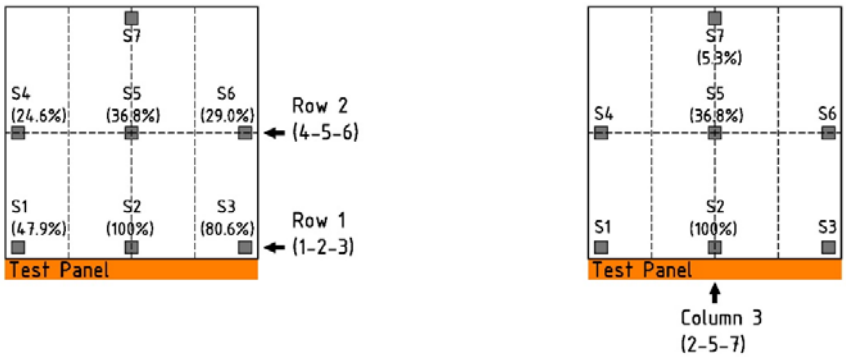


a. Sensors placed parallel to the face of the TCP



b. Sensors placed perpendicular to the face of the TCP

[2] The data obtained from the different test days, can be seen in Annex – Chapter 5.



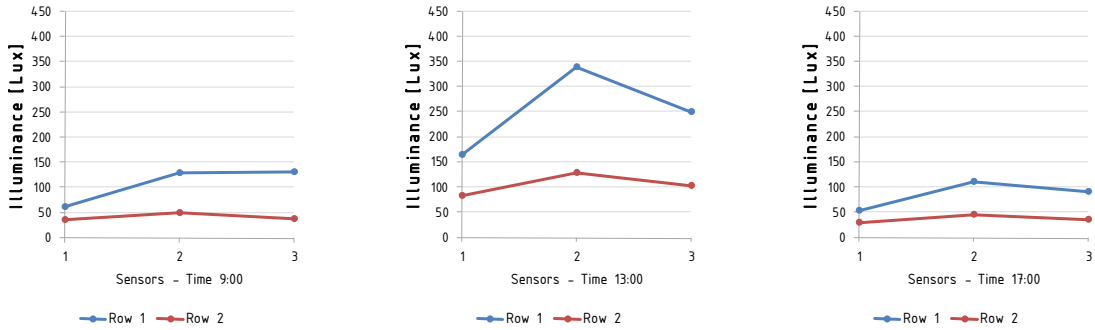
c. Key results obtained from the sensors placed parallel to face of the TCP

d. Key results obtained from the sensors placed perpendicular to the face of the TCP

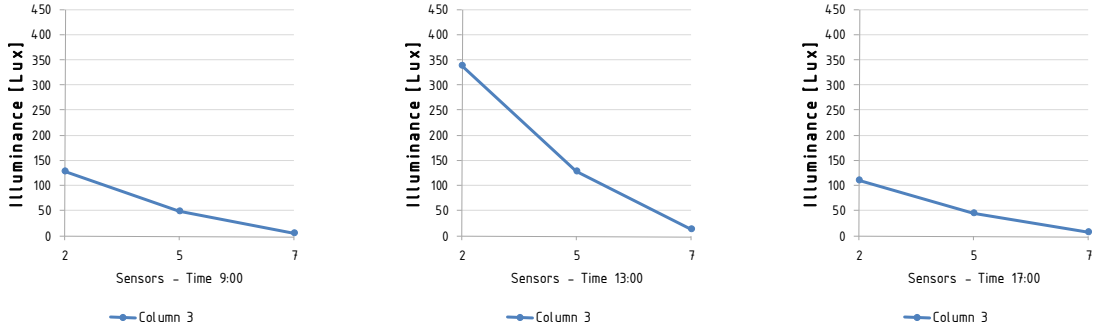
Figure 8. DDP of the TCP with diffuser #1. August 12th 2015. (Sunny day)

6.5 Test 2.3 – DDP Of The TCP Attached With Diffuser #2

This test[3] was conducted on August 9th and 11th thorough the course of the solar hours. The test parameters are shown in **Table 1**. From **Figure 9**, it is noted the behavior in the daylight scattered and diffused, compared to Tests 2.1, and 2.2, is the same. However, light diffuser #2 sheet attached behind the TCP did not help in improving the daylight scattered into the test cubicle. However, the obtained illuminance (Lux) values were slightly higher than Test 2.2 by about 1%, but slightly lower by about 3% than Test 2.1, which was used as a reference.

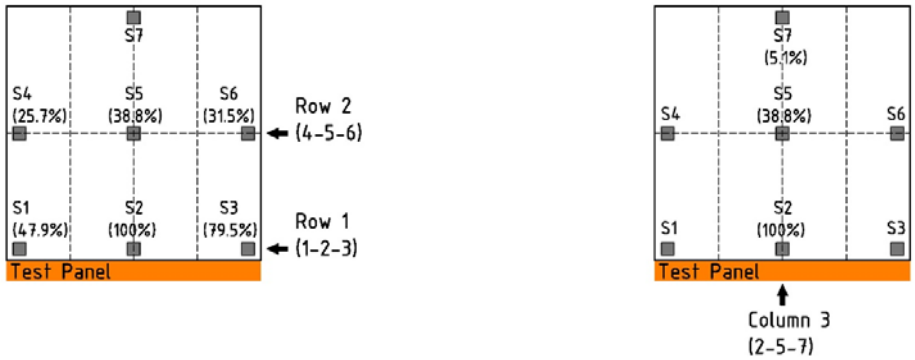


a. Sensors placed parallel to the face of the TCP



b. Sensors perpendicular to the face of the TCP

[3] The data obtained from the different test days, can be seen in Annex – Chapter 5.



c. Key results obtained from the sensors placed parallel to face of the TCP

d. Key results obtained from the sensors placed perpendicular to the face of the TCP

Figure 9. DDP of the TCP with diffuser #2. August 9th 2015. (Sunny day)

6.6 Test 3 – DDP of the TCP With Sensors Placed On The Walls Of The Test Cubicle

This test consisted on series of four tests[4] which parameters changed according to the positioning of the sensors on the side walls of the test box, as seen in **Figure 5b.** In this test series sensors (1-2-3) and (4-5-6) were distributed in two columns placed perpendicular to the test panel, **Figure 5c**. The test parameters are shown in **Table 1**.

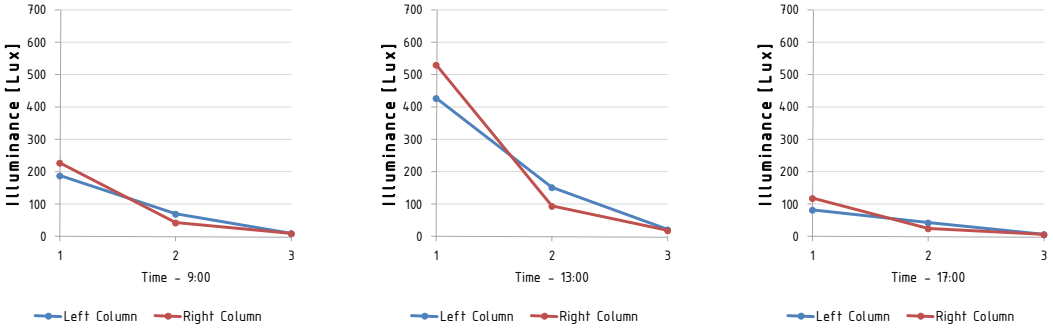
In Test 3.1, the sensors were placed on the base of the cubicle. In **Figure 10a**, the obtained results were proportional during the test hours, confirming that the OFs of the TCP kept the same daylight transmission behavior during the day of the test, with only one variation which came from the illuminance intensity (Lux) by capturing the peak around noon. In addition, based on the average of the total amount of illuminance (Lux) obtained during the solar hours of the test day, the right column obtained about 7% higher than the left one. From the left column, compared to sensor 1, sensor 2 captured only about 38% of illuminance, while sensor 5 captured only 18% compared to sensor 4. This confirmed that the daylight scattered into the cubicle decreased drastically before getting to the middle point of the test box, as observed also in Test 2. The differences between the columns of sensors come from the orientation of the TCP, which was facing south. In addition, the sensors placed at the back of the test box got low but constant values during the test days, without observing too much variations.

In Test 3.2, the sensors were distributed in the same way as Test 3.1 but in this case they were placed on the front side of the test box. In addition, this test obtained the same daylight scattering and diffusion behavior as explained in the previous test. From **Figure 10b**, based on the average of the total amount of illuminance (Lux) obtained during the solar hours of the test day, the right column obtained about 25% higher illuminance values as compared to the left column. Sensors 2 and 5, the ones that were placed in the middle of their columns, recorded about 36% and 21% more illuminance values compared to the averages that were taken from the respective three sensors of their columns. Again, the differences between the values assessed from the two columns of sensors came from the orientation of the TCP, which was facing south. Moreover, the sensors placed close to the ceiling and the base of the test box got low but constant values during the test days, without observing too much variations. There was more daylight intensity captured at the center of the cubicle due to the absence of walls surrounding the BiB sensors.

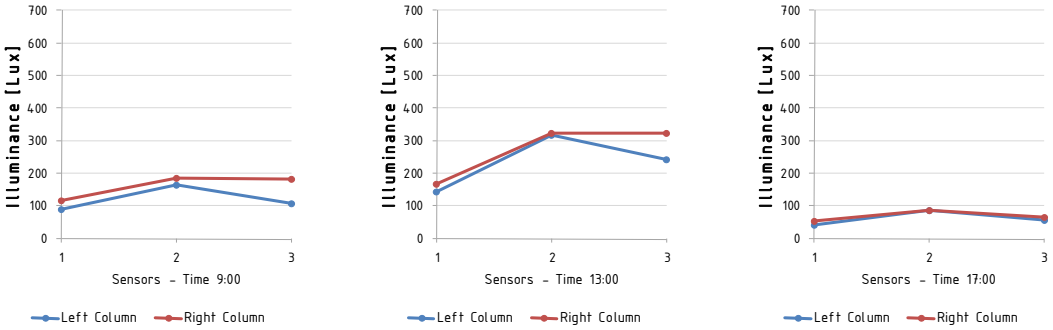
[4] The data obtained from the different test days, can be seen in Annex – Chapter 5.

In Test 3.3, the sensors were distributed in the same way as Test 3.1 but in this case they were placed on the lateral right side of the test box. This test obtained the same daylight scattering and diffusion behavior as was observed in the previous tests. As seen in **Figure 10c**, based on the average of the total amount of illuminance (Lux) obtained during the solar hours of the test day, the values recorded by the left column on average were about 8% lower in comparison with the right column. Sensors 2 and 5, the ones that were placed in the middle of their columns, obtained about 39% and 117% more illuminance values compared to the averages that were taken from the respective three sensors of their columns. Again, the differences between the values assessed from the two columns of sensors came from their position with respect to the TCP, obtaining more daylight. Moreover, the sensors placed close to the ceiling and the base of the test box got low but constant values during the test days, without observing too much variations. There was more daylight intensity captured at the center of the cubicle due to the absence of walls surrounding the BiB sensors.

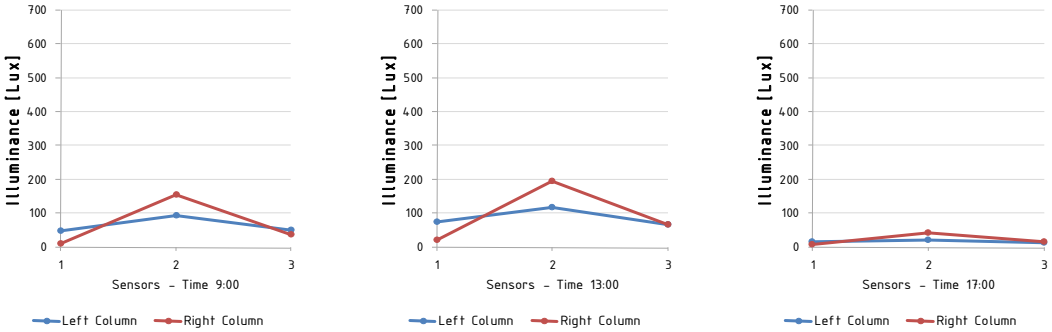
In Test 3.4, The sensors were distributed in the same way as Test 3.1 but in this case they were placed on the lateral left side of the test box. In the present test, we obtained the same daylight scattering and diffusion behavior as was observed in Test 3.3. As seen in **Figure 10d**, based on the average of the total amount of illuminance (Lux) obtained during the solar hours of the test day, the values recorded by the left column on average were about 14% higher in comparison with the right column. Sensors 2 and 5, the ones that were placed in the middle of their columns, obtained about 111% and 61% more illuminance values compared to the averages that were taken from the respective three sensors of their columns. Again, the differences between the values assessed from the two columns of sensors came from their position with respect to the TCP, obtaining more daylight. Moreover, the sensors placed close to the ceiling and the base of the test box got low but constant values during the test days, without observing too much variations.



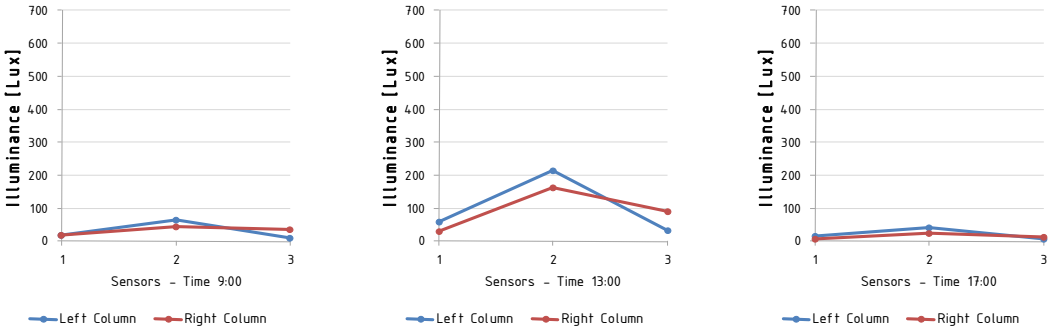
a. Test 3.1 – Sensors placed on the base of the test box. (August 26th 2015. Sunny day)



b. Test 3.2 – Sensors placed on the front of the test box (opposite to the TCP).
(September 26th 2015. Partial sunny day)



c. Test 3.3 – Sensors placed on the lateral right side of the test box. (October 3rd 2015. Sunny day)



d. Test 3.4 – Sensors placed on the lateral left side of the test box. (October 14th 2015. Partial sunny day)

Figure 10. DDP of the TCP with sensors placed on the walls of the test cubicle.

7. CONCLUDING REMARKS

The present research assesses the outdoor DDP of a non-scaled small prototype of the TCP embedded with OF 6 mm. From the conducted tests, it is concluded that the distribution of the OFs embedded in the test specimen provide constant daylight distribution. From the obtained results, the variations came from the illuminance intensities of the daylight that changed over the day, with a peak attained around noon time. In addition, the obtained results of the DDP together with the visual images, confirmed that daylight transmission by the OFs used in the specimens, do not undergo variations with sun path. The OFs scatter and diffuse the transmitted daylight homogeneously on the walls of the test box. On the other hand, the daylight reduces linearly along the depth of the test box. However, the conducted tests demonstrate that the OFs used in the specimens, do not spread too much daylight in the interior space of the test cubicle. This can be confirmed by the fact that the sensors placed in the center of the box captured about 40% of the illuminance intensity obtained from the front part of the TCP. Therefore, the OFs of the TCP provide a permanent interior daylight without too much variations along the day compared to a transparent glass. Nevertheless, from this conclusion, the present research speculates that the heat distributed into the test cubicle coming from the TCP must remain constant on the walls considering that the TCP does not trace the sun path. In addition, the test specimen was also tested together with two different light diffusers with the aim to observe if they could improve the daylight scattered and diffused. However, the obtained results have not been positive, transmitting only about 6% and 3% less daylight compared with the TCP without the light diffusers. Therefore, in the future, it is necessary to: 1) assess the surface temperature distribution of the walls and compare the results with transparent material, e.g. glass, 2) improve the daylight scattering of the TCP by modifying the OFs parameters, i.e. density, spacing, diameter, etc., and 3) explore the use of other diffusers than the two ineffective ones used in this study.

In addition, with the conducted tests presented in this study, it can be corroborated that the design of the SPTB is versatile to conduct preliminary scaled or non-scaled tests in an easy and fast manner using wireless sensors which facilitate the recording of accurate data under real outdoor conditions.

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CHAPTER 6

Conclusions

1. GENERAL DISCUSSION, CONCLUDING REMARKS AND FUTURE PERSPECTIVES

This chapter summarizes and highlights the most important contributions of the present Thesis together with the significant results obtained from the conducted research. In fact, part of the research resulted in a patent concerning the manufacturing of the Translucent Concrete Panel (U.S provisional application 62/240,859 / UCB ref: BK-2015-159). At the end of this chapter, in Section 1.4, there are suggested future lines of research focused on how to continue validating and improving the new building envelope technologies, and also the daylight transmission of the introduced Translucent Concrete Panel (TCP) into the building's interior in order to obtain energy savings. For this reason, both the conclusions and the future perspectives of the research, are presented according to the objectives previously defined in Chapter 1. After the introduction, the structure of this chapter is divided into general and specific conclusions, Sections 1.2 and 1.3 respectively, which provide answers to the objectives defined in the introduction of the Thesis.

1.1 Introduction

Currently, most of the world population is gathered in buildings mainly placed in urban areas. Unfortunately, a big part of these buildings are badly constructed without or with unsuitable insulation on the building envelope, and without any heating system. After some decades in use, these buildings suffer from an unacceptable interior living environment due to the unappropriated building envelope solution. This practice causes energy losses through the façades and roofs while producing low interior comfort inside the building, as well as health problems to the occupants. Therefore, nowadays the building industry is concerned with designing new construction solutions with novel components and geometries which are able to face the current energy inefficiency in buildings. The TCP is a novel energy efficient building envelope construction solution which is capable of channeling the sunlight through the opaque part of the walls. Its versatility is based on its capacity for concentrating and scattering daylight into the building's interior while achieving energy savings, i.e. reducing dependence on artificial lighting and also improving the occupant's interior comfort. The complexity of this novel construction solution comes from the physical behavior and geometry of its components, i.e. the Compound Parabolic Concentrator (CPC) and the Optical Fiber (OF). Currently, there is no software in the market that can simulate the daylight transmission of the CPCs and the OFs. In addition, there are no daylight metrics able to properly assess the daylight performance of the TCP. In this sense, this research considered this TCP innovative to give answers to the aforementioned problems.

1.2 General Conclusions

In the last decades, the building technology has experienced great advances regarding energy efficiency. However, the obtained results in the present Thesis state that there are still many topics to look at which require deeper research focused on energy efficiency through the building envelope in order to obtain energy savings. Based on the main objective already explained in Chapter 1, the present research has looked at two issues:

- The first one sought to see the viability how to save in energy consumption through the building envelope, i.e. façades and roofs, while improving the interior living environment and also reducing consumption of the heat system of an existing residential building used as a case study. Nevertheless, the assessed building stated the some of the common existing problems on the envelopes after some years in use, followed by the energy savings obtained after the energy retrofit of the façades and roofs.

- The second issue of the research was to assess and improve the daylight performance of a novel energy efficient building envelope namely TCP, in order to be used in the future as an energy efficient solution for daylighting for façades and roofs. Promising results were obtained from the different tests conducted outdoors. These results confirmed the viability of using the TCP as part of the opaque part of the building envelope for daylight transmission. This statement suggests that the TCP construction solution can be beneficial for the construction industry while improving energy savings, integration and cost.

In summary, the present research demonstrates the relationship between an energy efficient building envelope and the energy savings, which can be achieved through the envelope while improving interior comfort. The study also demonstrates the possibilities of the TCP to be implemented in the construction

industry as a novel energy efficient passive construction solution for daylighting. Nevertheless, further research is still required.

1.3 Specific Conclusions

For each of the two general issues studied in the present research, specific results and improvements have been detailed into the different chapters. However, the most significant conclusions are described in this section in order to give answers to the specific objectives already established in Chapter 1.

1.3.1 Energy Retrofit OF An Existing Building Envelope

- After the diagnosis of the building envelope case study, it was demonstrated that poorly or badly construction solutions of the façades and roofs result in energy loss and consequently result in tenant's higher running cost. In addition, the study stressed the importance of doing active maintenance on the building envelope thorough the years as a way to expand its lifespan and avoid future problems.

- The collected data from the monitored apartments of the building case study, explained the thermal energy behavior of apartments occupied by tenants with low income and that suffer from energy poverty. Only when the exterior weather conditions were extreme, then the tenants chose to make use of the heating system. Therefore, it was concluded that health and comfort are more important parameters than saving money under these extreme conditions for the case study.

- From the building case study, apartment AP1 was the one that provided accurate results regarding the energy retrofit work conducted on the building envelope. AP1 obtained a reduction of its thermal energy consumption by about 12%. Thus, the retrofit work indeed improved the interior thermal comfort while also improving the energy savings. However, this achievement could have been higher if the project had had enough budget to replace the exterior fenestrations for new ones with thermal brake and insulated glass.

1.3.2 Daylight Performance Assessment Of The Translucent Concrete Panel

- From the preliminary outdoor tests of the TCP components, i.e. CPCs and the OFs working independently or together, the obtained results confirmed that they could capture, channel and scatter daylight within a room. The first set of results was positive enough to start envisioning the TCP as a future novel passive building envelope construction solution used in daylighting.

- The CPC facing the outside with a large half acceptance angle, i.e. Θ_{max}>30°, was more effective to capture and transmit sunlight throughout the year in comparison to cones with smaller angles. Initially, the results seemed inconsistent. However, it is necessary for maximum efficiency that the rays of sunlight fall within the numerical aperture (NA) of the OF. In addition, the CPCs were more effective with high sunlight incidence angles (summer time) by improving the light transmission of the OFs specimens. However, with low sunlight incidence angles (winter time) the CPCs did not give optimal results. The CPC that worked better was the one whose smaller diameter (d_2) matched the OF diameter.

- The outdoor tests confirmed that the OFs provided more light transmission in comparison to Acrylic Rods (AR). However, both elements had similar daylight transmission behavior. In addition, it was confirmed that the distribution and separation edge-to-edge of the fibers were important in order to obtain larger light transmission through the panels, instead of using OFs with larger diameters or densities in terms of the ratio between the surface area of the OFs' cross-sections with respect to the area of the panel.

- OFs with a modified geometry of the tip helped capture and scatter more light compared to a flat tip. As observed from in the obtained results, the OF shapes (with or without a CPC), had the capability of increasing the number of hours of sunlight effectiveness. Thus, the proposed OF tip shapes are a solution to enhance the amount of sunlight captured and daylight channeled into a room. In addition, from the conducted tests, independently of the solar concentrator, it was confirmed that the cone shaped tip with an angle of 45° for OFs, worked very well with low sunlight incidence angles, i.e. during the winter. On the other hand, the hemispherical OF tip obtained the best results with high sunlight incidence angles, i.e. during the summer. However, the OF tip cone shaped with an angle of 56° gave results of less effectiveness compared to the other two specimens, and its light behavior was kept constant throughout the different sunlight incidence angles. Therefore, it was concluded that both ends of OFs embedded into the TCP should be modified as either cones or hemispheres as a way to transmit and scatter more sunlight within an interior space.

- From the conducted tests using a Dynamic Daylight Performance (DDP) metric, the assessed OFs embedded in a panel provided constant daylight properties throughout the day. The only parameter that changed during the day was the illuminance intensity. This statement derived from the fact that during the tests, the OFs daylight transmission did not undergo variations regarding the sunlight tracking. They have the property to cause a constant projection on the walls of the test box of the scattered and diffused transmitted daylight. In addition, the conducted tests demonstrated that the OFs did not spread too much the daylight in an interior space. The sensors placed in the center of the test box captured only by about 30% of illuminance intensity from the light obtained directly at of the test panel.

- From the conducted tests, the present study corroborated that the design of the Small Portable Test Box (SPTB) was versatile enough to conduct preliminary tests in an easy and fast manner with wireless sensors which facilitated obtaining accurate data under real outdoor conditions.

2. SUGGESTIONS AND FUTURE PERSPECTIVES

The present research has achieved an important progress in the daylight performance assessment of the TCP case study. In fact, this is the first time that this evaluation has been conducted on the TCP. Therefore, these preliminary daylight outdoor tests helped understand the TCP daylight behavior. However, there are still many issues to resolve before implementing the TCP solution into the building market. Therefore, this section presents some suggestions for future lines of research, development and innovation which aim at the continuation of the obtained results.

- Based on the obtained results explained in the present research, the next step would be to develop a computer program which can simulate the CPC and the OF light transmission behavior. Then, computational models of the TCP construction solution would be able to simulate real conditions while speeding up its optimization process by considering different variables such as: geometry of the CPCs and OFs, location and time of the year of the case study, compass orientation, skylight conditions, and so on.

- There is a need to continue doing research on OF properties in terms of material specifications and light transmission. The fibers of the TCP will be permanently placed outdoors. Therefore, it is important to make sure that they will tolerate the concentration of high temperatures without damaging its core.

- The success of the TCP will be based on the possibility of implementing it into the construction market. Therefore, studies regarding the TCP constructability should be focused on reducing the cost of the construction of the panels without a reduction of the final quality or the interior comfort. Recently, some concrete panels embedded with optical fibers have been manufactured in UC Berkeley with different concrete mixes. The idea was to see the complexity of mass production of the TCP and as a way to start working in this new area of research. In addition, this study should take into consideration different external indicators such as social, economic and cost aspects. For this reason, it is suggested to develop a modular solution capable to be used in any type of building. It is suggested also to seek new materials that can replace the concrete while improving the thermal interior comfort of the building and reducing cost of the material during the mass production process. Finally, it is important to extend the research to consider the Life Cycle Analysis (LCA) of the material, as a way to validate the durability and viability of the TCP in a real building construction.

- Not all the daylight metrics options provide consistent outputs. Basically, the professionals have a lack of knowledge on how to use the daylight metrics and which one is more appropriate for each use. In order to resolve this general problem, it is suggested to continue the research to specify in the building codes what light metrics should be enforced for different measurements. In addition, it is recommended to improve the different building codes contents regarding multifunctional building envelopes and daylight transmission.

- As it is commented in some of the chapters of this research, there is a general belief based on common sense on the potential of saving energy through an effective daylighting design. It is supposed that a proper daylighting solution can reduce energy consumption of the building. On the other side, as aforementioned, the professionals usually confuse which daylight metrics are more appropriate for their purposes. For this reason, it is recommended to evaluate the total amount of energy savings (thermal and daylighting) that can be obtained in real buildings with the implementation of the TCP.

PUBLICATIONS

Scientific Papers

Casquero-Modrego, N., Goñi-Modrego, M., Mosalam, K. M., "Energy Retrofit Of An Existing Affordable Building Envelope in Spain," *Journal of Building Engineering,* 2015. (In review)

Mosalam, K. M., Casquero-Modrego, N., "Experimental Investigation of Sunlight Permeability by Translucent Concrete Panels as an Energy Efficient Building Envelope," *Journal of Architectural Engineering*, 2015. (In review)

Casquero-Modrego, N., Mosalam, K. M., "Optical Fiber Light Scattering Outdoor Tests For Interior Daylighting," *Journal of Architectural Engineering*, 2015. (In review)

Conference Proceedings

Mosalam, K. M., Casquero-Modrego, N., Armengou, J., Ahuja, A., Zohdi, T. I., and Huang, B., "Anidolic Day-Light Concentrator in Structural Building Envelope." In *First Annual International Conference on Architecture and Civil Engineering*, Singapore, 2013.

Ahuja, A., Casquero-Modrego, N., Mosalam, K. M., "Evaluation of Translucent Concrete Using ETTV-Based Approach." In *IEEE International Conference on Building Energy Efficiency and Sustainable Technologies (ICBEST 2015)*, Singapore, 2015.

Patents

Mosalam, K.M., N. Casquero-Modrego, A. Ahuja and B. Huang, "BRIGHT – Building with Radiant and Insulated Green Harvesting Technology," U.S provisional application 62/240,859 (UCB ref: BK-2015-159)

ANNEX – Chapter 2 Results

1. Apartment 1 (AP1)

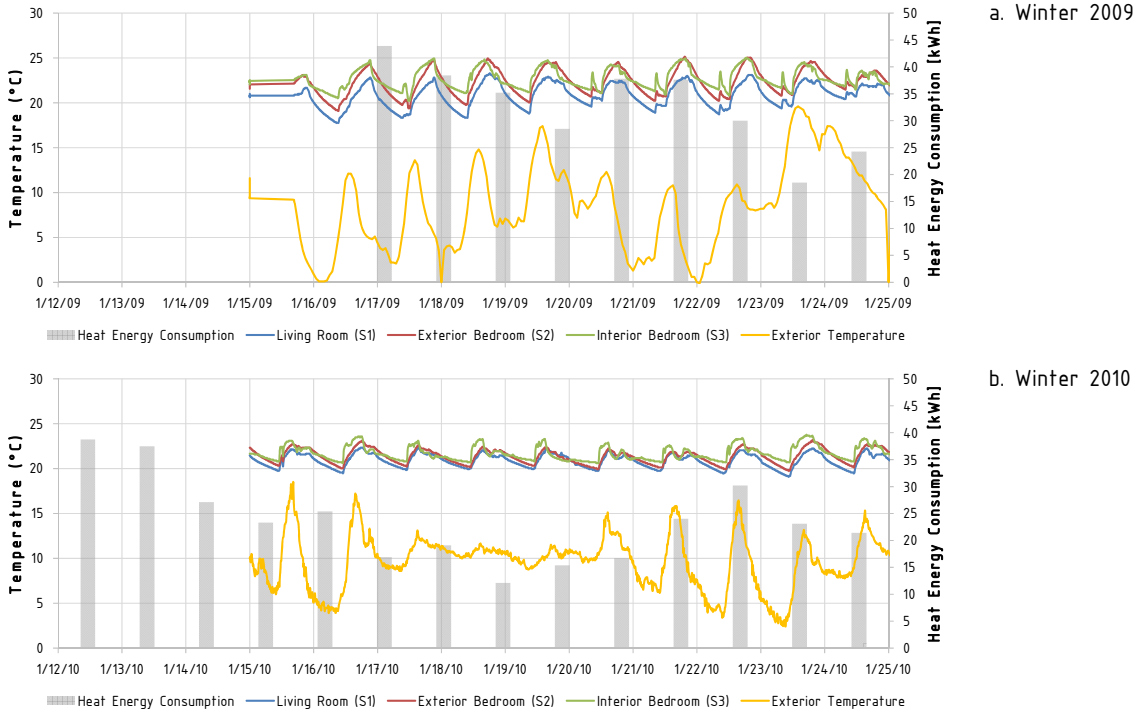

Figure 1. From January 12th to January 25th – AP1 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

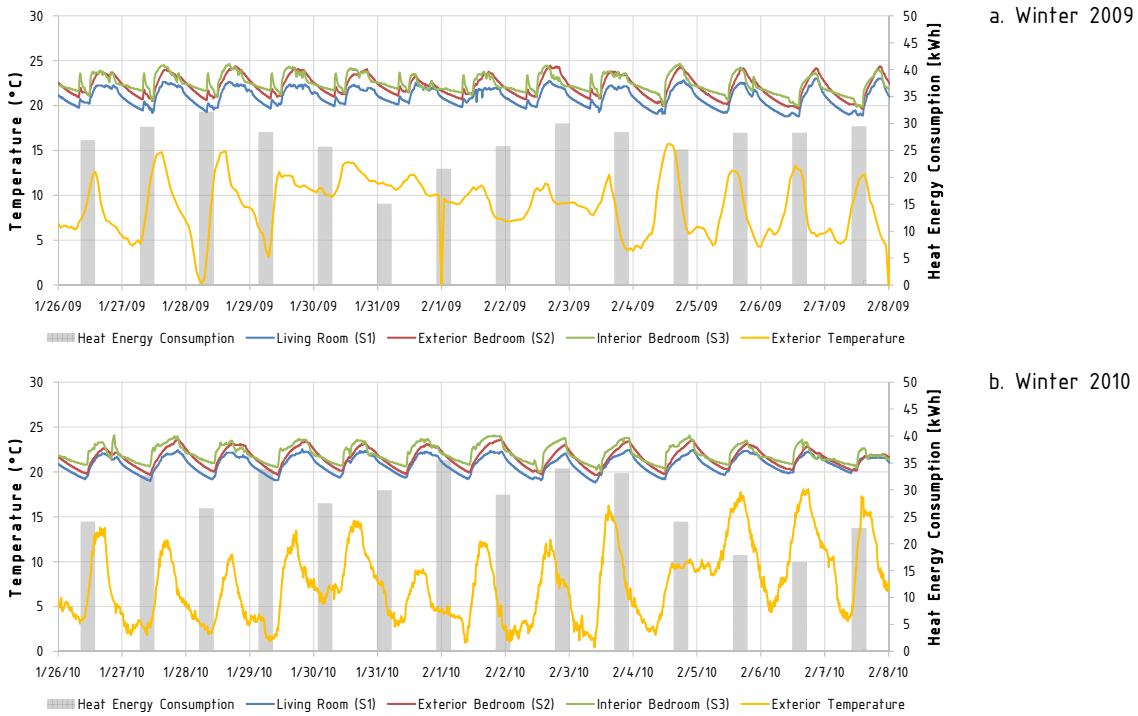

Figure 2. From January 26th to February 8th – AP1 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

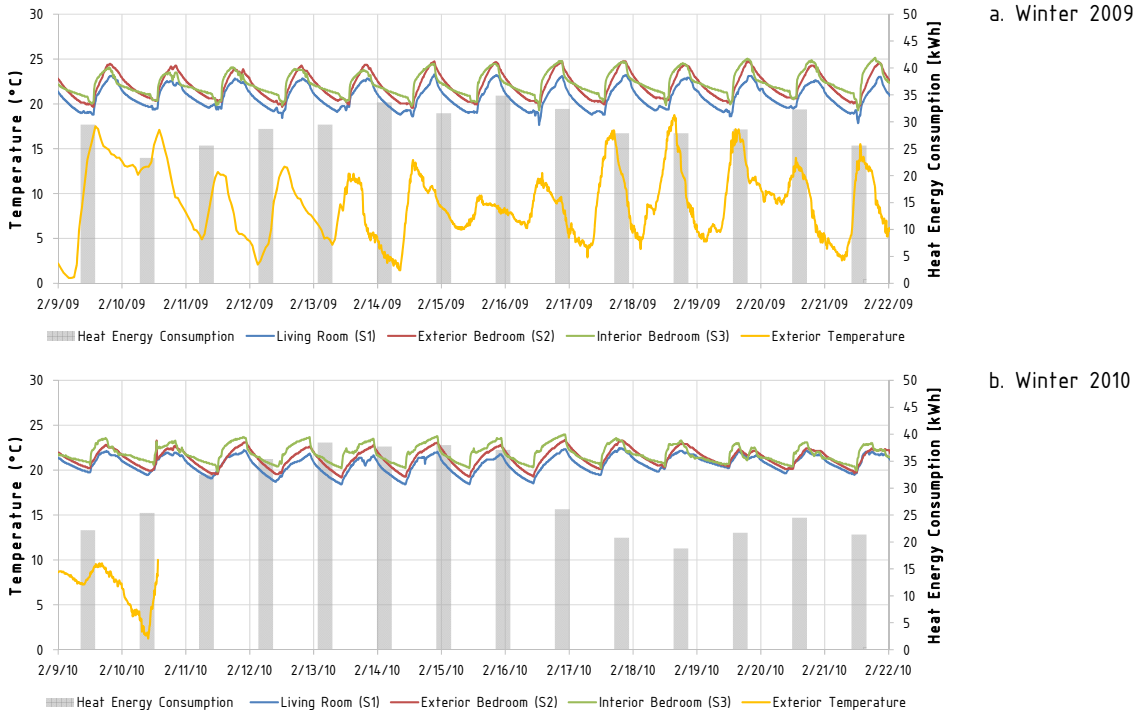

Figure 3. From February 9th to February 22nd – AP1 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

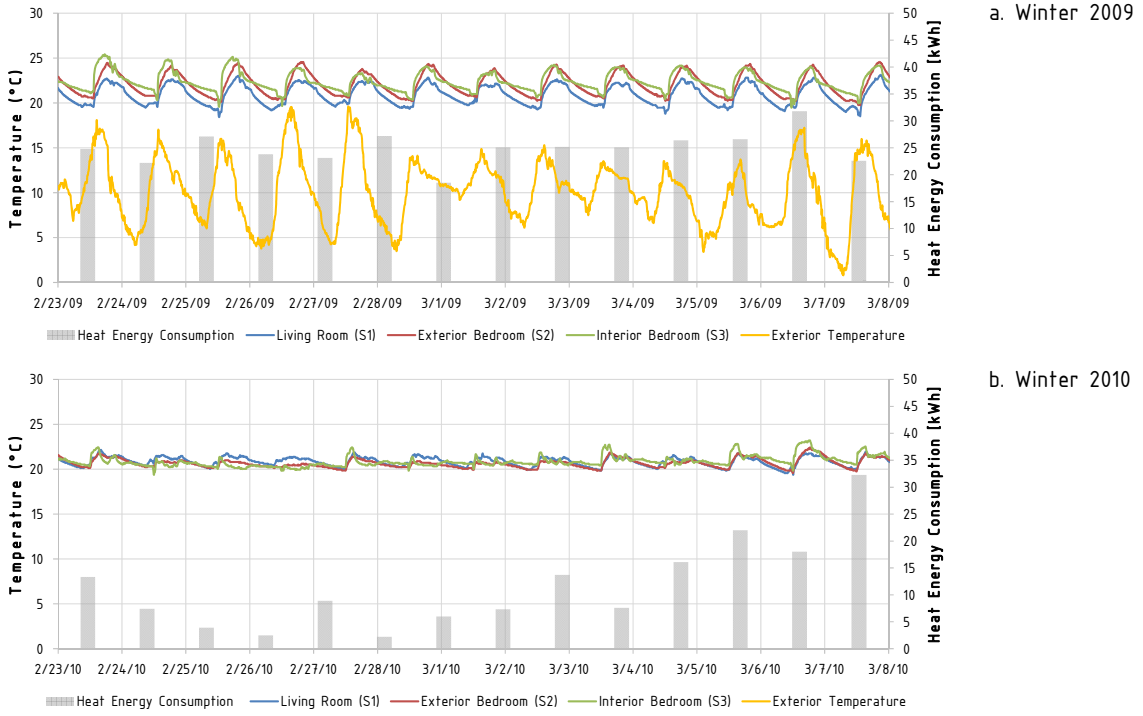

Figure 4. From February 23rd to March 8th – AP1 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

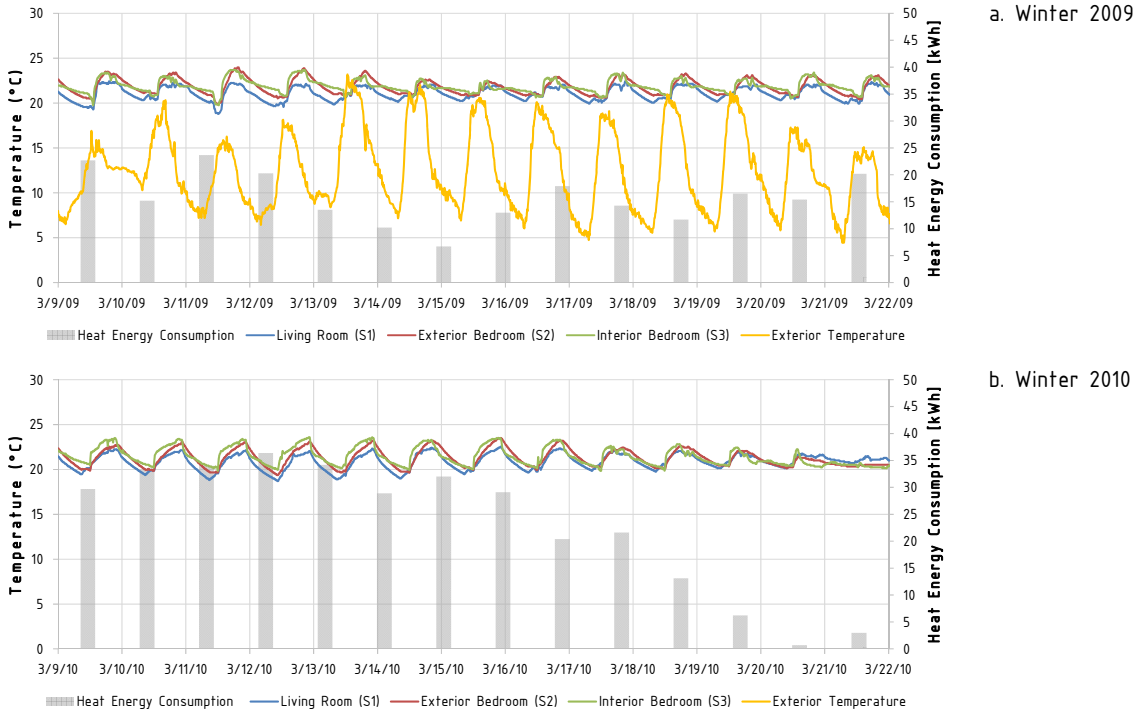

Figure 5. From March 9th to March 22nd – AP1 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

2. Apartment 2 (AP2)

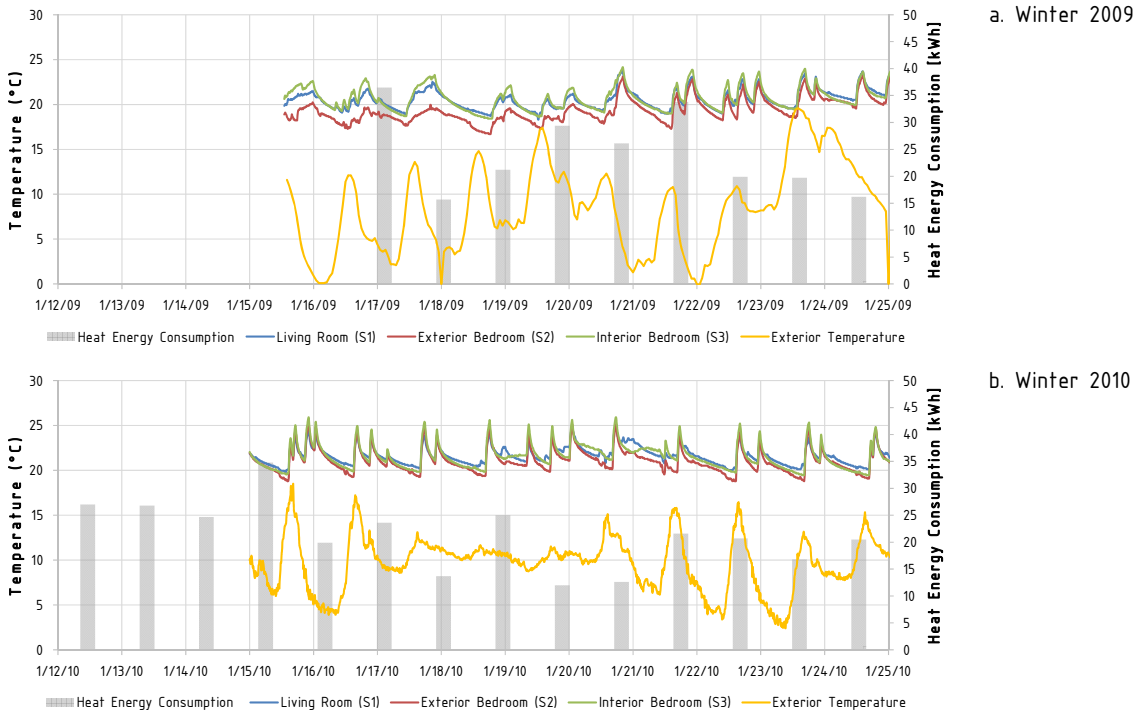

Figure 6. From January 12th to January 25th – AP2 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

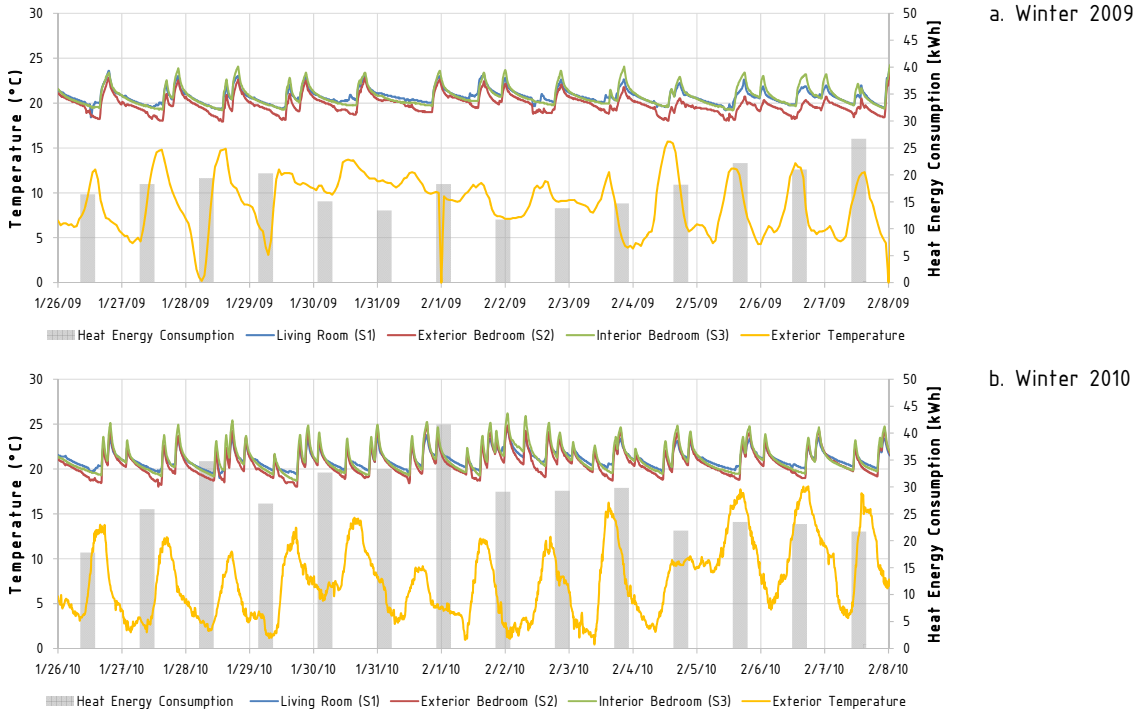

Figure 7. From January 26th to February 8th – AP2 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

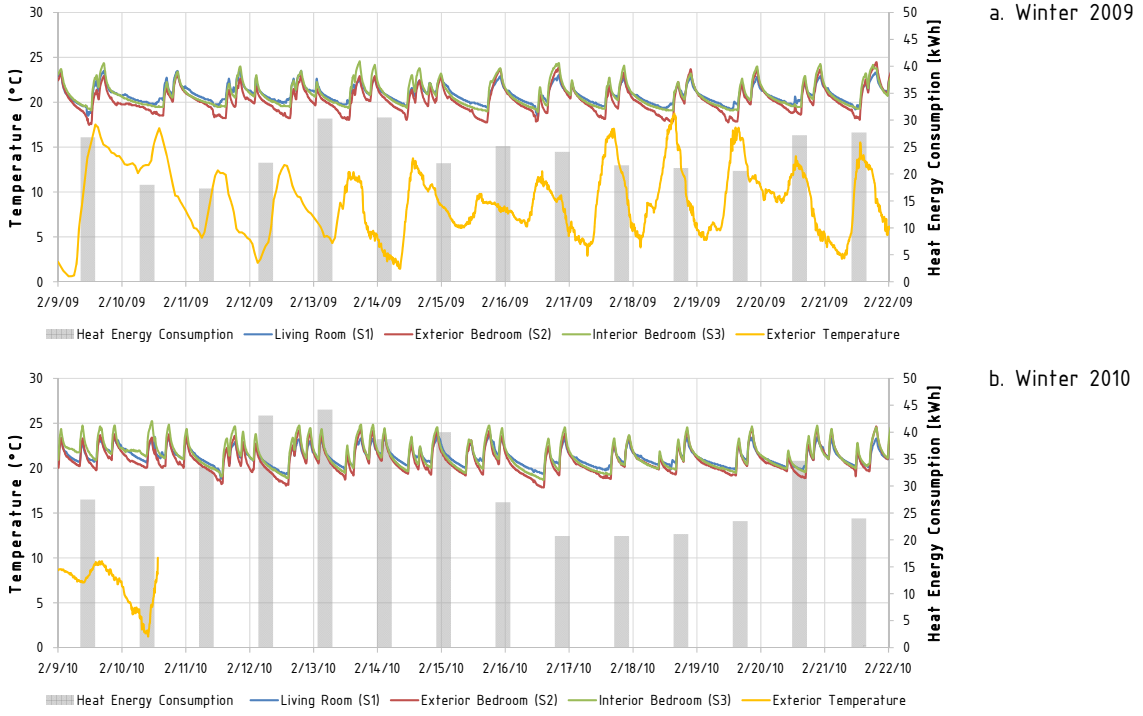

Figure 8. From February 9th to February 22nd – AP2 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

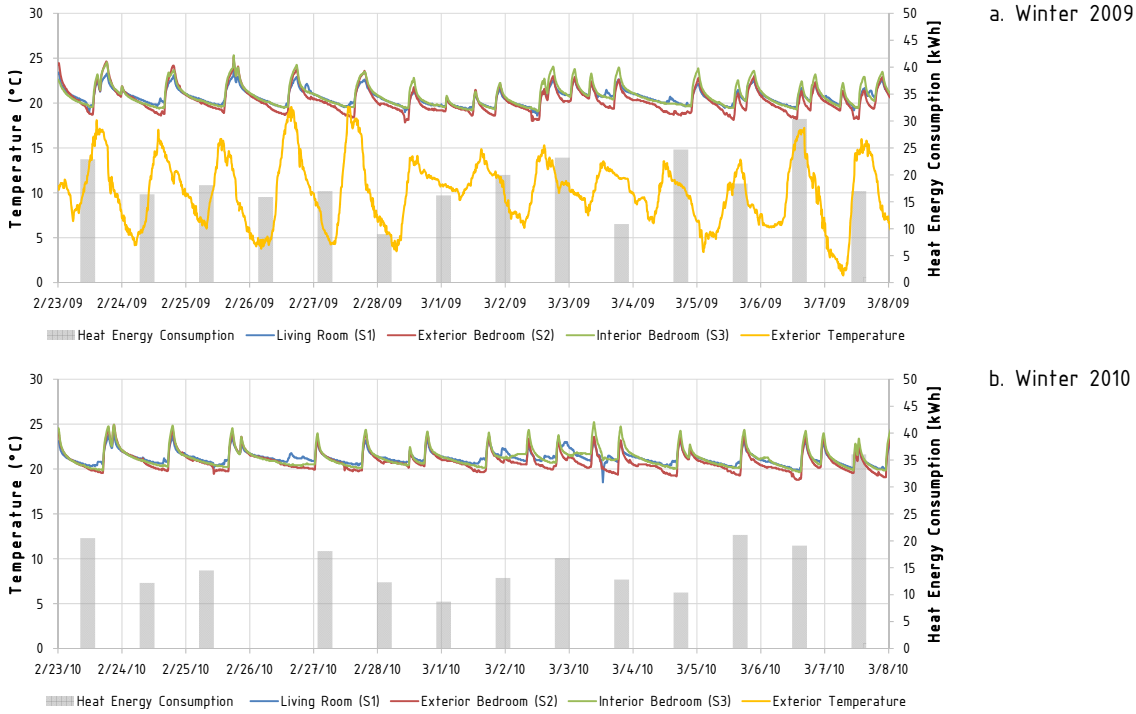

Figure 9. From February 23rd to March 8th – AP2 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

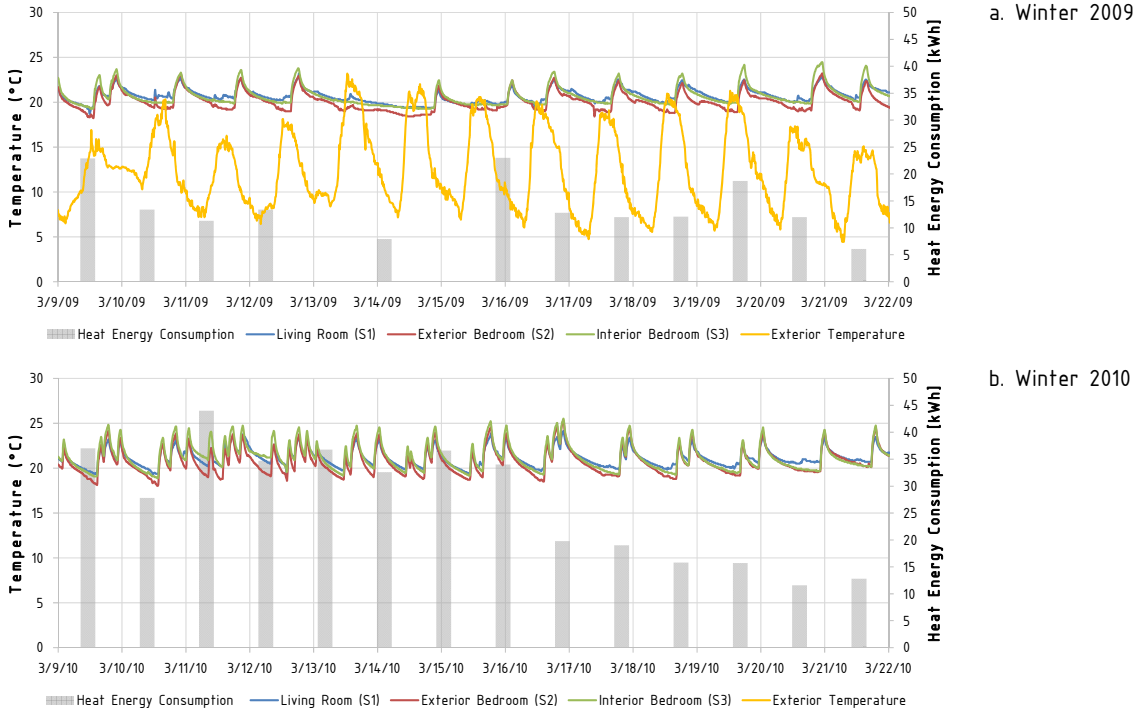

Figure 10. From March 9th to March 22nd – AP2 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

3. Apartment 3 (AP3)

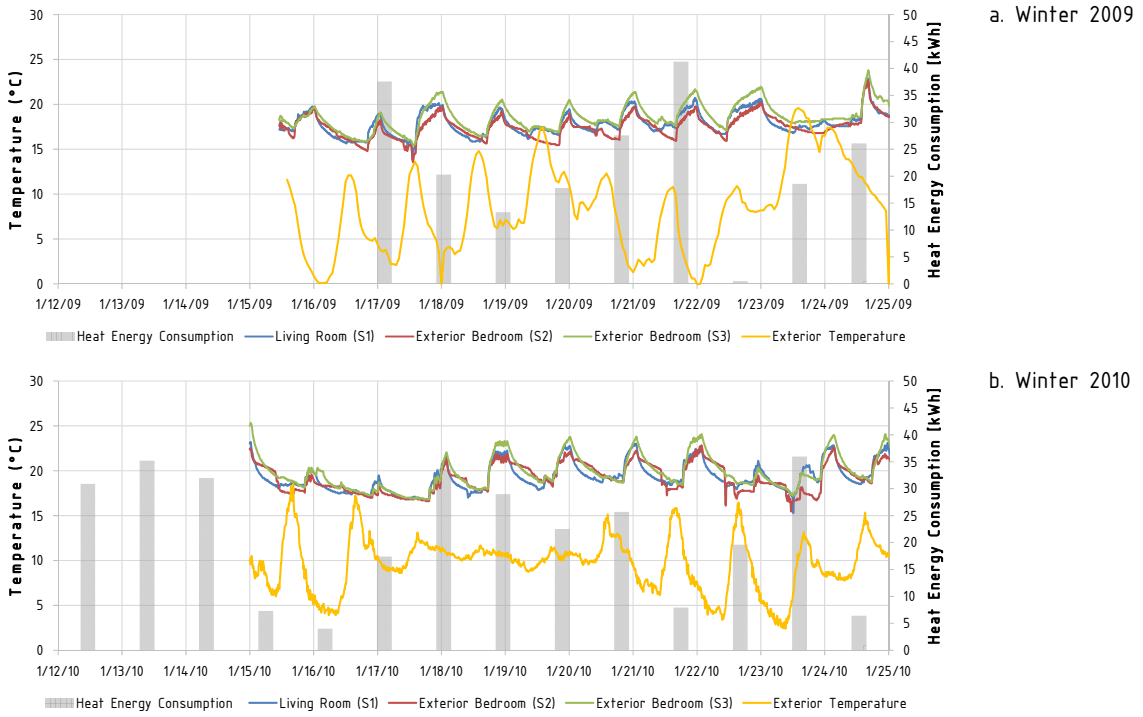

Figure 11. From January 12th to January 25th – AP3 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

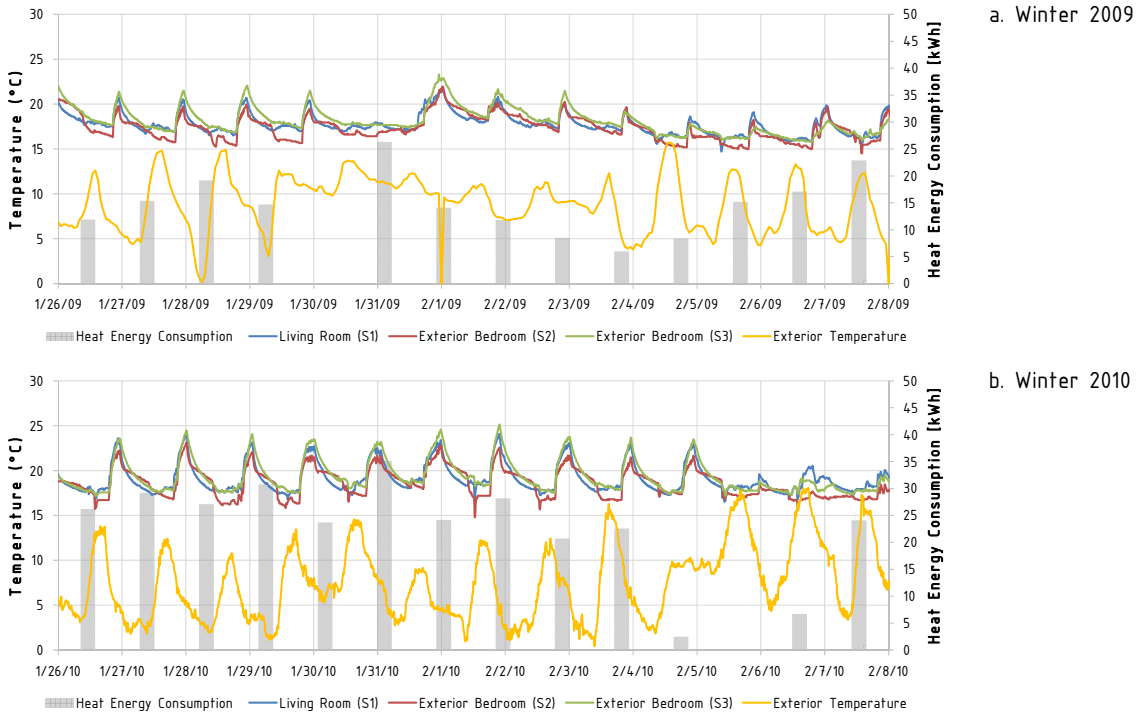

Figure 12. From January 26th to February 8th – AP3 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

Figure 13. From February 9th to February 22nd – AP3 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

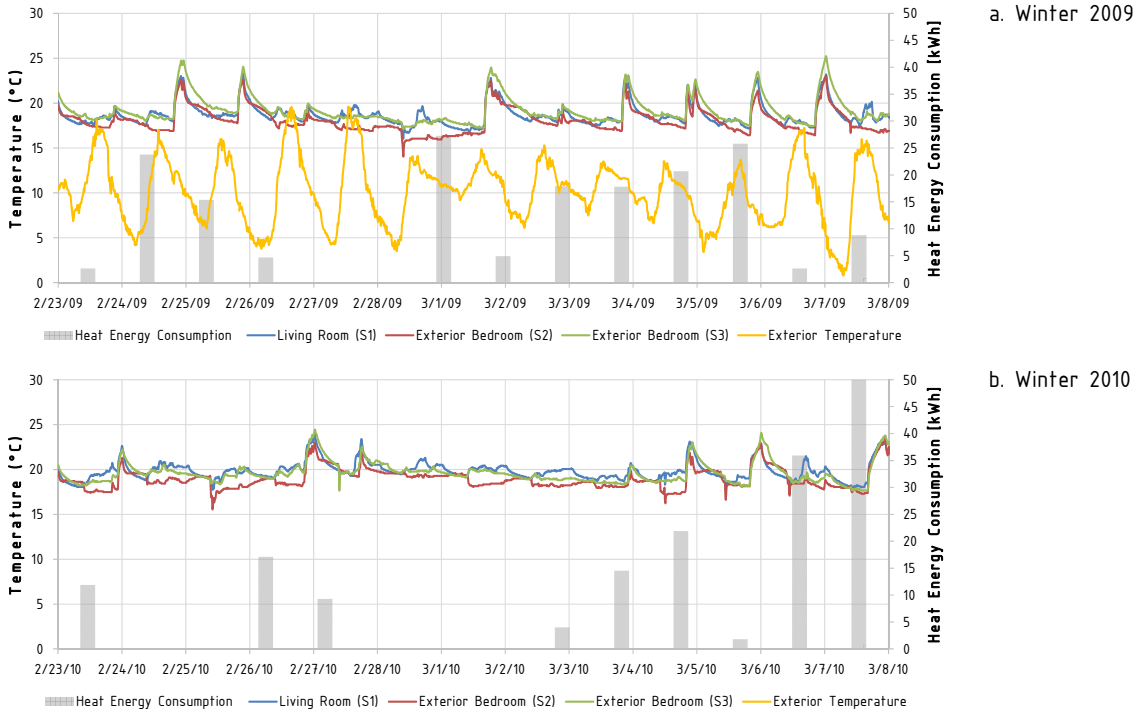

Figure 14. From January 23rd to March 8th – AP3 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

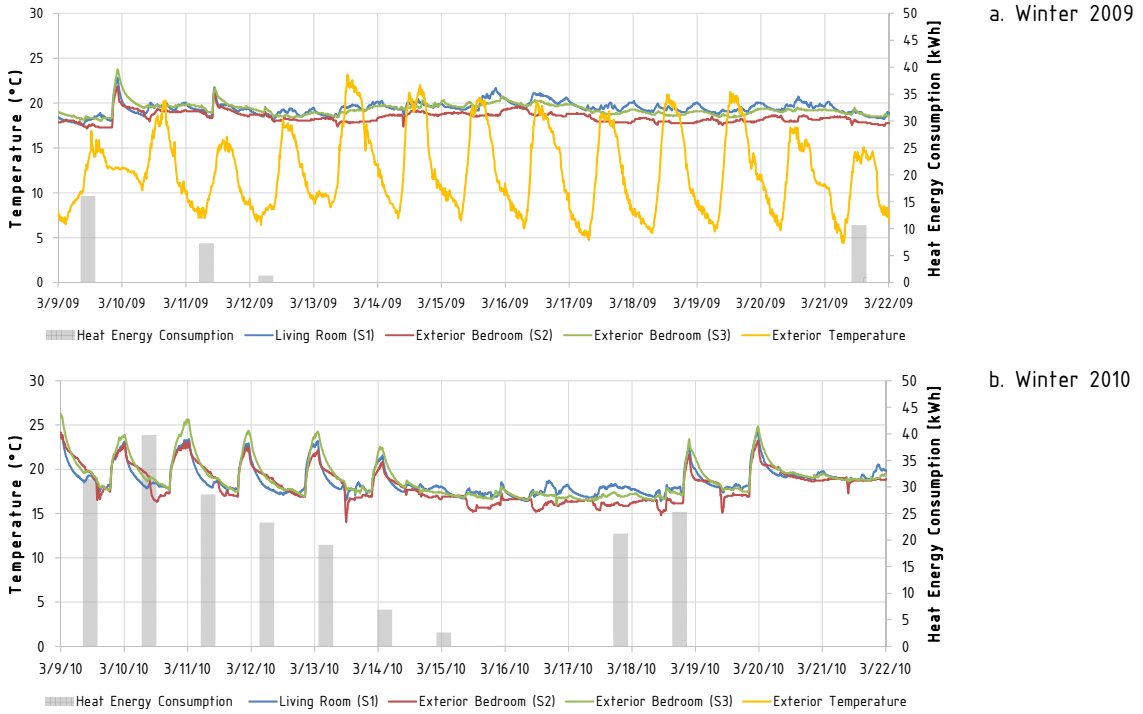

Figure 15. From March 9th to March 22nd – AP3 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

4. Apartment 4 (AP4)

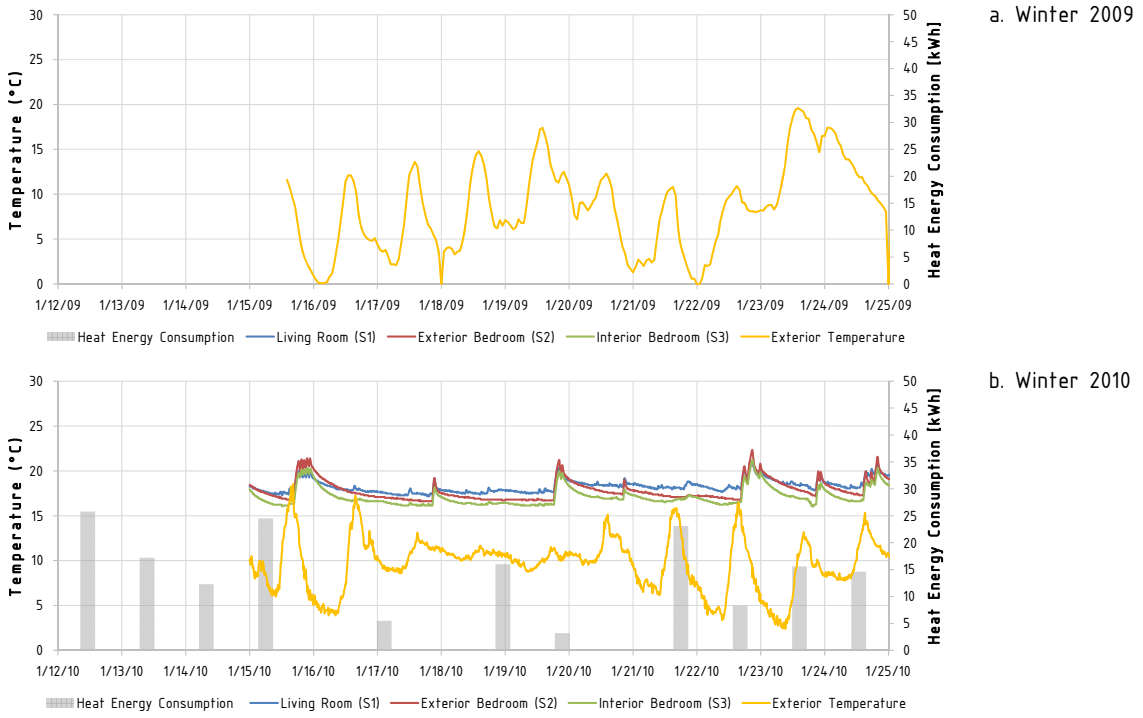

Figure 16. From January 12th to January 25th – AP4 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

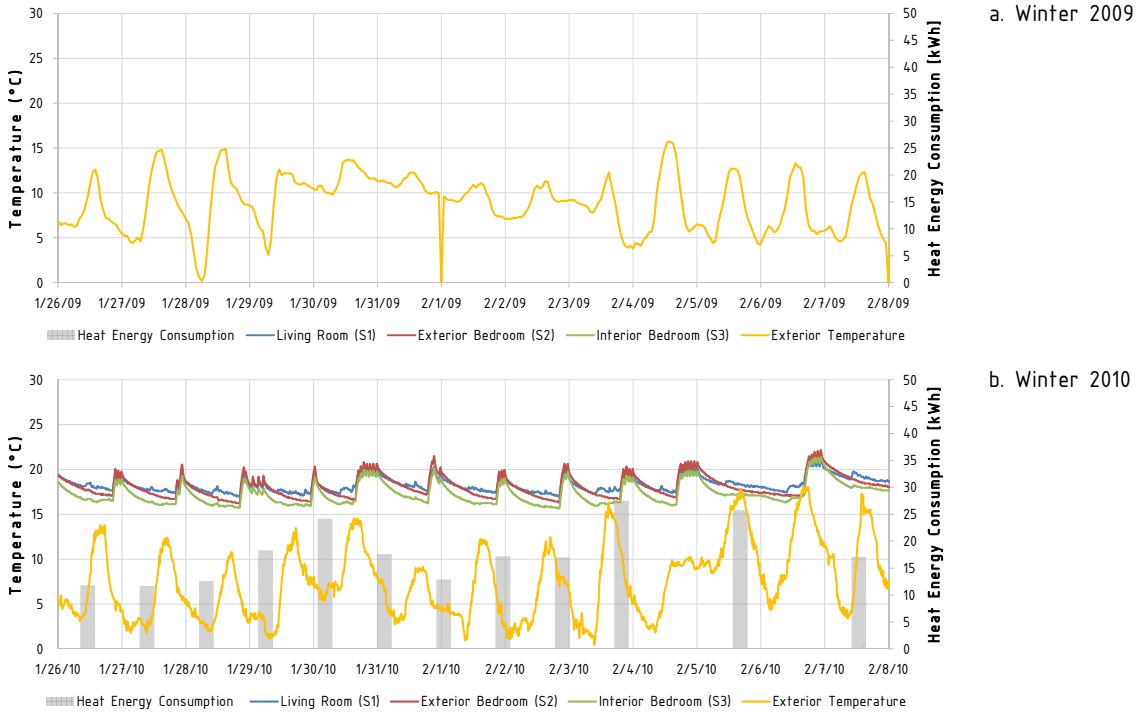

Figure 17. From January 26th to February 8th – AP4 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

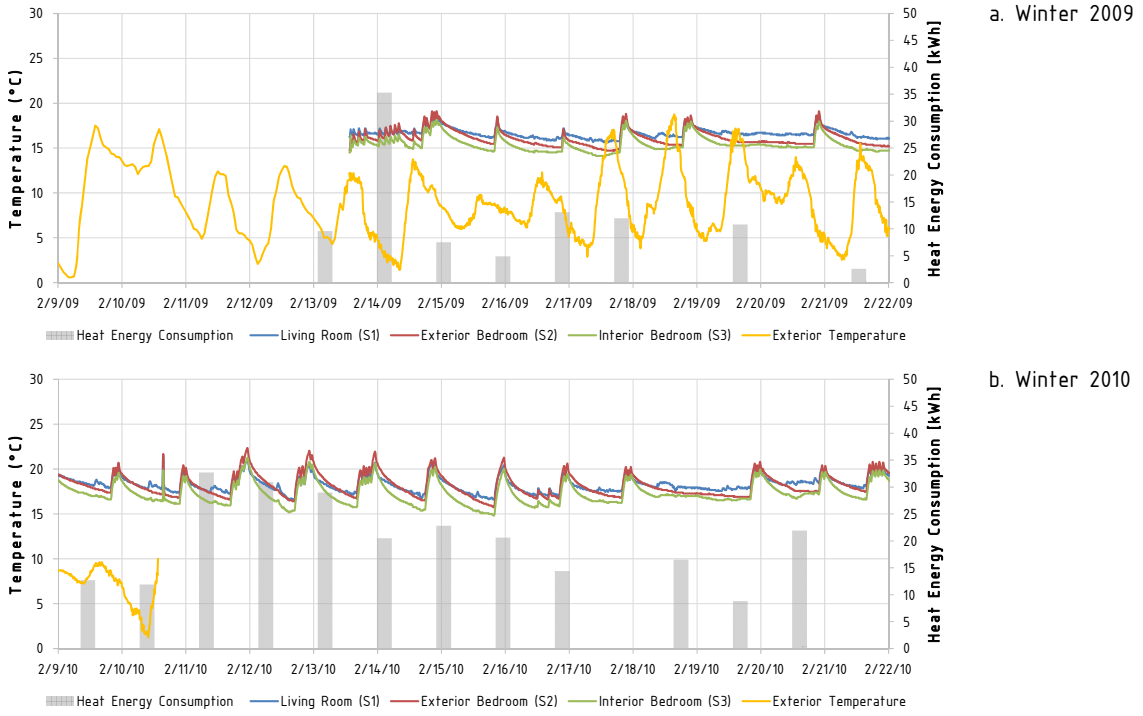

Figure 18. From February 9th to February 22nd – AP4 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

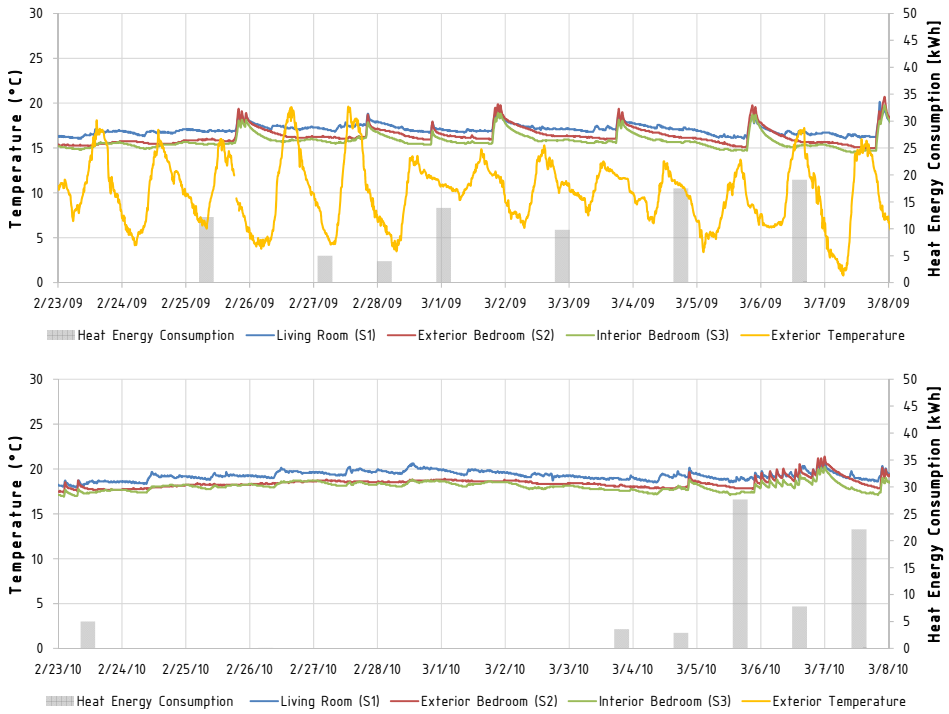

Figure 19. From February 23rd to March 8th – AP4 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

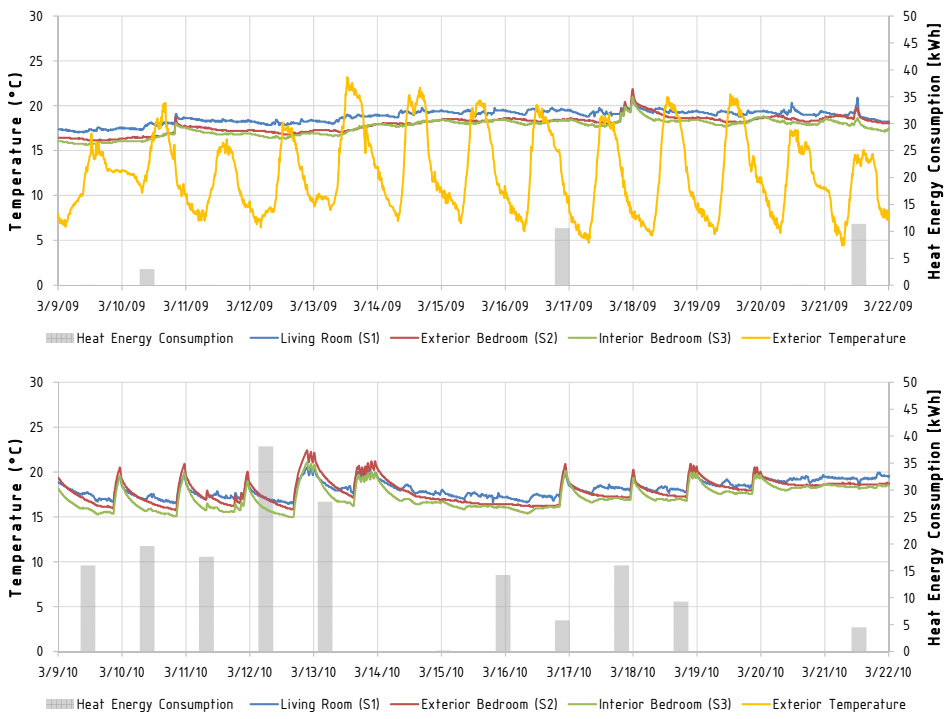

Figure 20. From March 9th to March 22nd – AP4 interior temperature (°C), exterior temperature (°C), and heat energy consumption (kWh) during: a) Winter 2009, and b) Winter 2010.

ANNEX - Chapter 4 Results

1. Test 1 - OF Tip Shapes Facing The Outside

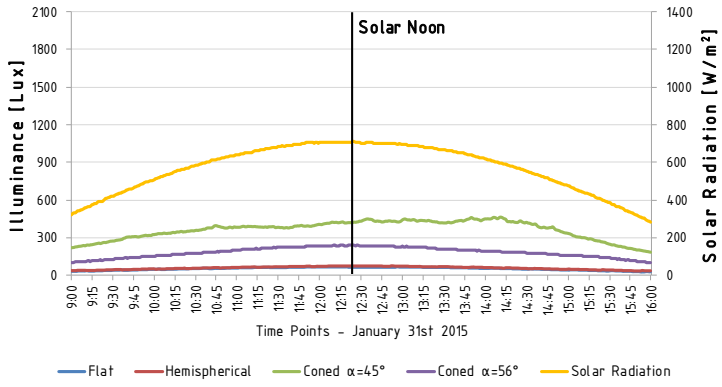

Figure 1. January 31st 2015. Sunny day with a Sunlight Incidence Angle at 35.13°. Solar Radiation Average from 10:00 to 15:00 was 635.02 W/m².

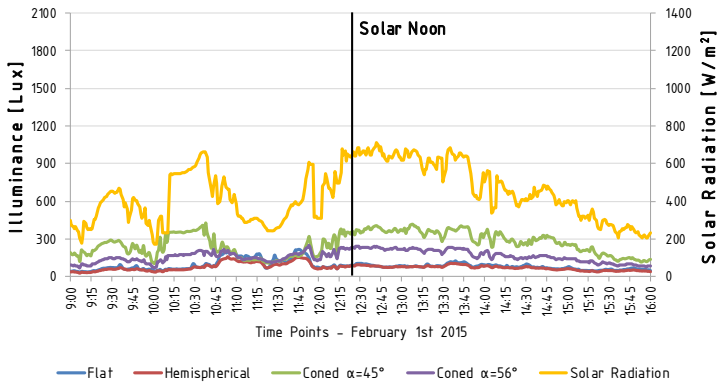

Figure 2. February 1st 2015. Partial sunny day with a Sunlight Incidence Angle at 35.42°. Solar Radiation Average from 10:00 to 15:00 was 490.29 W/m².

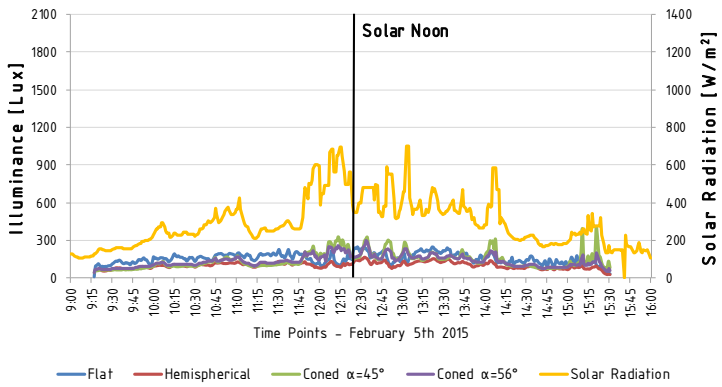

Figure 3. February 5th 2015. Cloudy day with a Sunlight Incidence Angle at 36.60°. Solar Radiation Average from 10:00 to 15:00 was 340.03 W/m². Data rejected.

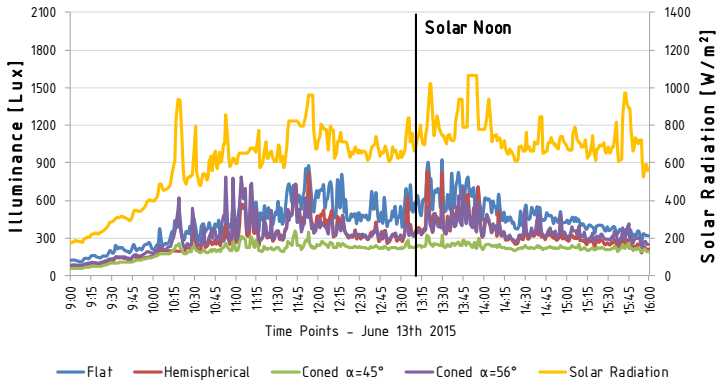

Figure 4. June 13th 2015. Cloudy day with a Sunlight Incidence Angle at 75.64°. Solar Radiation Average from 10:00 to 15:00 was 700.19 W/m². Data rejected.

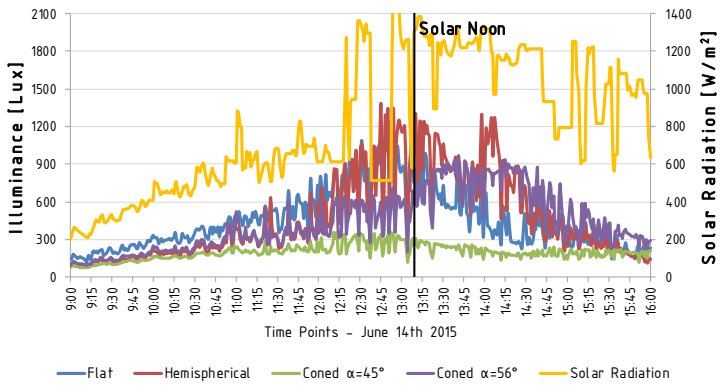

Figure 5. June 14th 2015. Partial sunny day with a Sunlight Incidence Angle at 75.69°. Solar Radiation Average from 10:00 to 15:00 was 864.09 W/m².

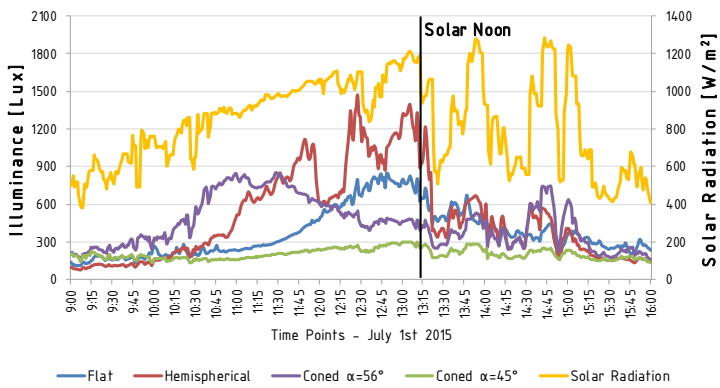

Figure 6. July 1st 2015. Partial sunny day with a Sunlight Incidence Angle at 75.50°. Solar Radiation Average from 10:00 to 15:00 was 923.91 W/m².

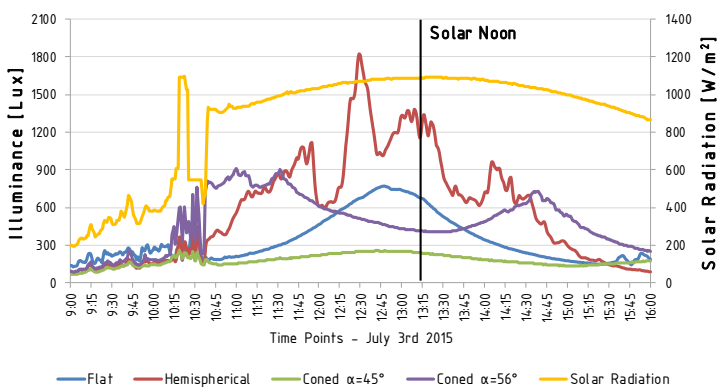

Figure 7. July 3rd 2015. Partial sunny day with a Sunlight Incidence Angle at 75.34°. Solar Radiation Average from 10:00 to 15:00 was 977.65 W/m².

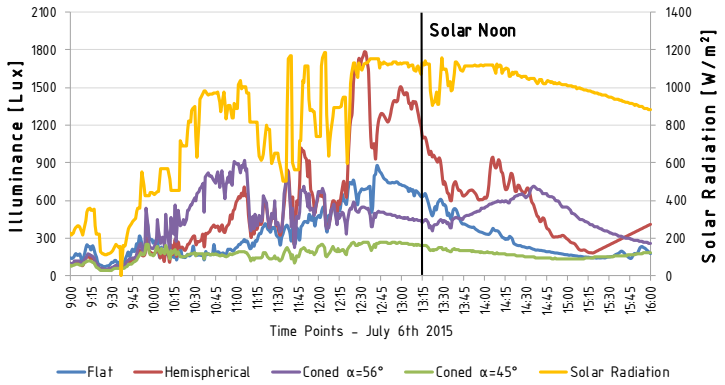

Figure 8. July 6th 2015. Partial sunny day with a Sunlight Incidence Angle at 75.07°. Solar Radiation Average from 10:00 to 15:00 was 945.28 W/m².

2. Test 2 - OF Tip Shapes Facing The Inside Of The Test Box

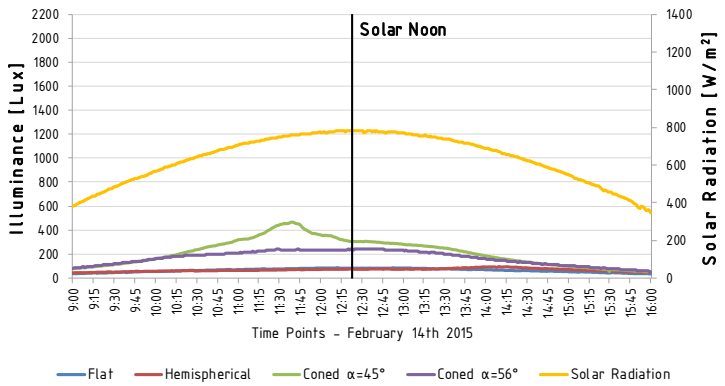

Figure 9. February 14th 2015. Sunny day with a Sunlight Incidence Angle at 39.51°. Solar Radiation Average from 10:00 to 15:00 was 703.74 W/m².

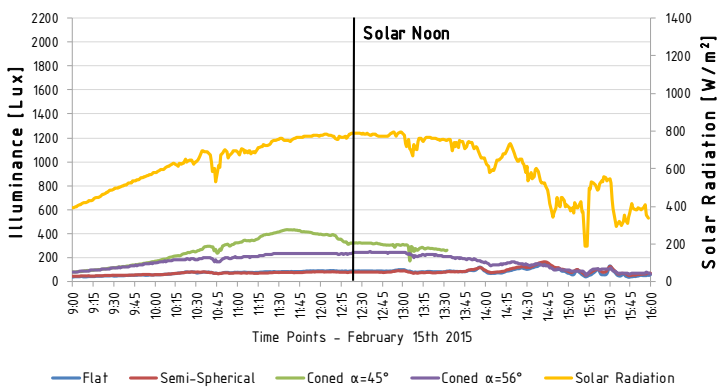

Figure 10. February 15th 2015. Sunny day with a Sunlight Incidence Angle at 39.85°. Solar Radiation Average from 10:00 to 15:00 was 691.44 W/m². Data rejected due to technical problems with one sensor.

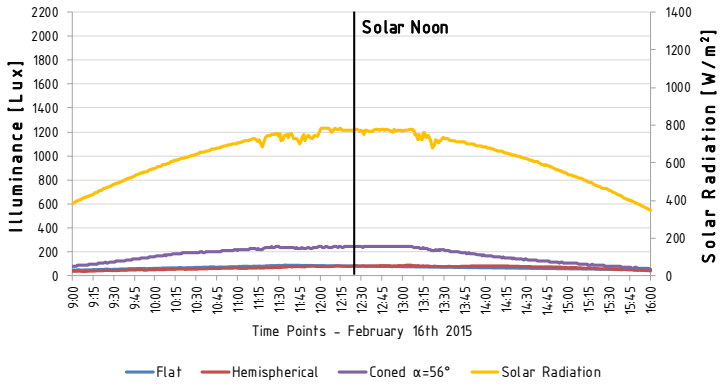

Figure 11. February 16th 2015. Sunny day with a Sunlight Incidence Angle at 40.20°. Solar Radiation Average from 10:00 to 15:00 was 697.47 W/m². Data rejected due to technical problems with one sensor.

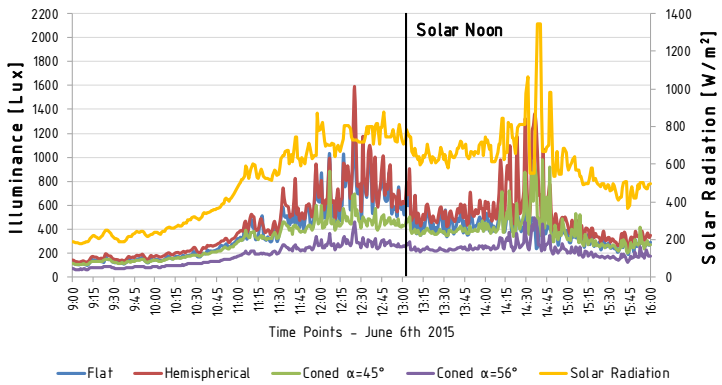

Figure 12. June 6th 2015. Cloudy day with a Sunlight Incidence Angle at 75.09°. Solar Radiation Average from 10:00 to 15:00 was 541.13 W/m². Data rejected.

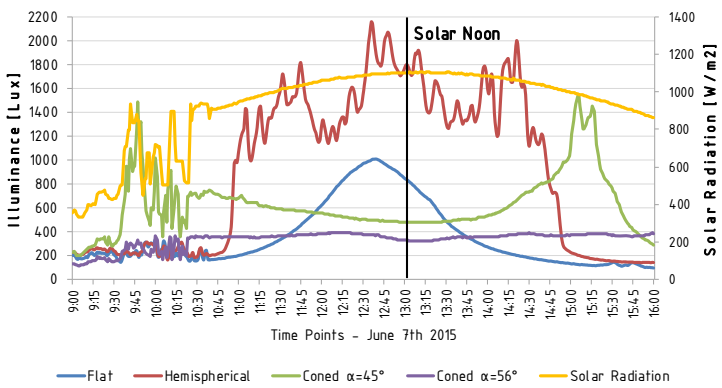

Figure 13. June 7th 2015. Partial sunny day with a Sunlight Incidence Angle at 75.19°. Solar Radiation Average from 10:00 to 15:00 was 928.01 W/m².

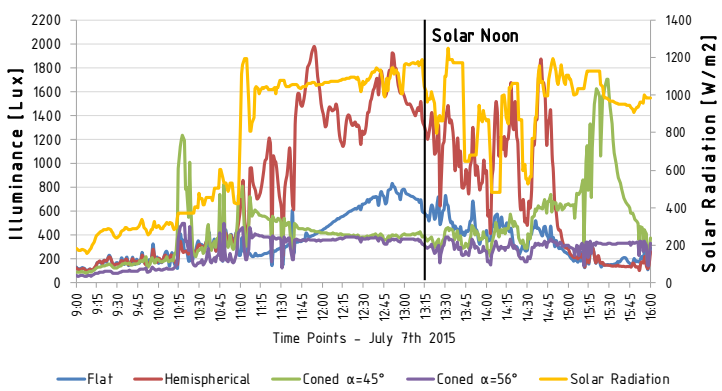

Figure 14. July 7th 2015. Partial sunny day with a Sunlight Incidence Angle at 74.96°. Solar Radiation Average from 10:00 to 15:00 was 885.54 W/m².

3. Test 3.1 – CPCs Aligned With OF Tip Shapes Facing The Outside

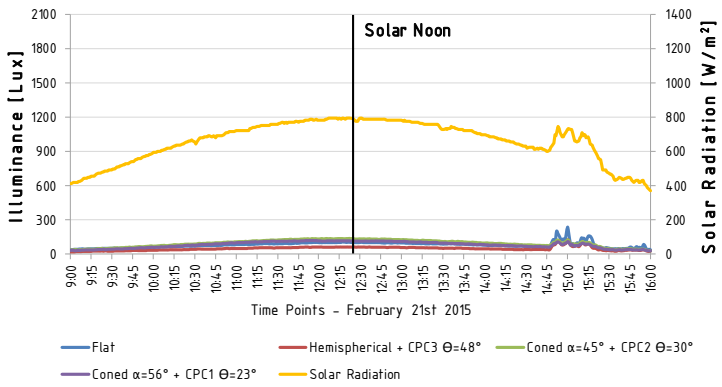

Figure 15. February 21st 2015. Sunny day with a Sunlight Incidence Angle at 41.98°. Solar Radiation Average from 10:00 to 15:00 was 720/10 W/m².

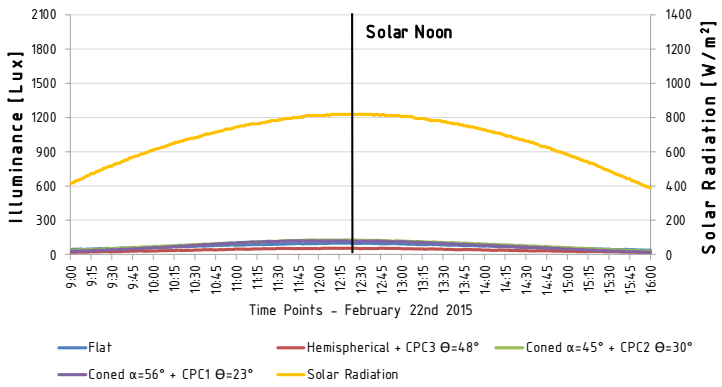

Figure 16. February 22nd 2015. Sunny day with a Sunlight Incidence Angle at 42.34°. Solar Radiation Average from 10:00 to 15:00 was 742.10 W/m².

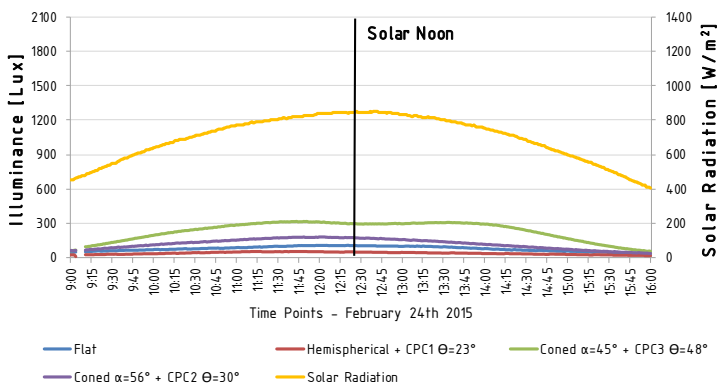

Figure 17. February 24th 2015. Sunny day with a Sunlight Incidence Angle at 43.08°. Solar Radiation Average from 10:00 to 15:00 was 766.60 W/m².

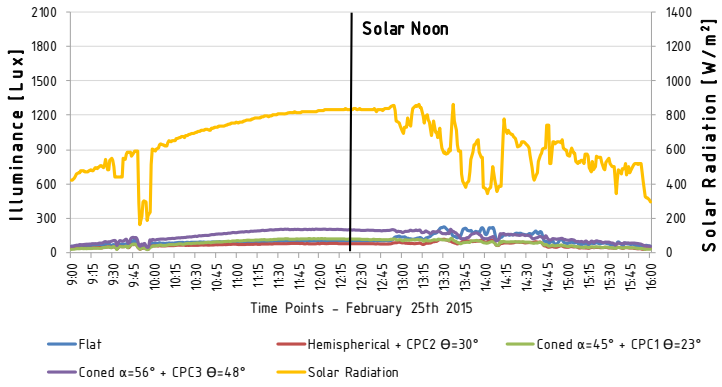

Figure 18. February 25th 2015. Partial sunny day with a Sunlight Incidence Angle at 43.45°. Solar Radiation Average from 10:00 to 15:00 was 710.80 W/m².

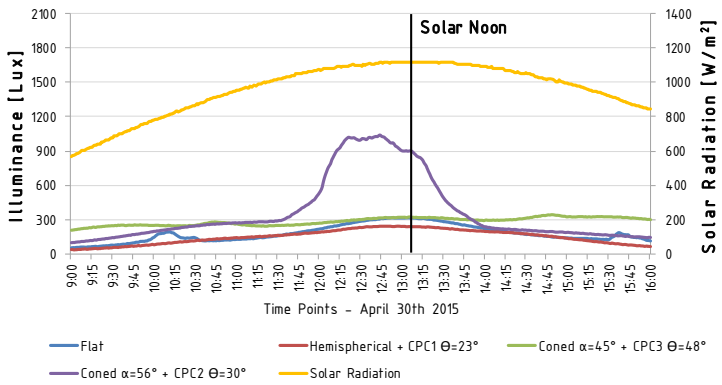

Figure 19. April 30th 2015. Sunny day with a Sunlight Incidence Angle at 67.28°. Solar Radiation Average from 10:00 to 15:00 was 1027.70 W/m².

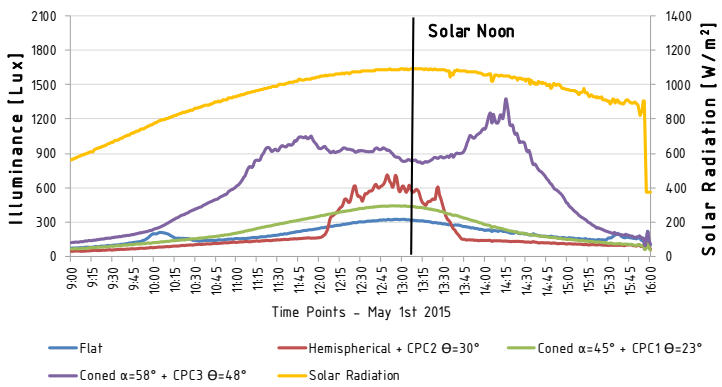

Figure 20. May 1st 2015. Sunny day with a Sunlight Incidence Angle at 67.58°. Solar Radiation Average from 10:00 to 15:00 was 1005.90 W/m².

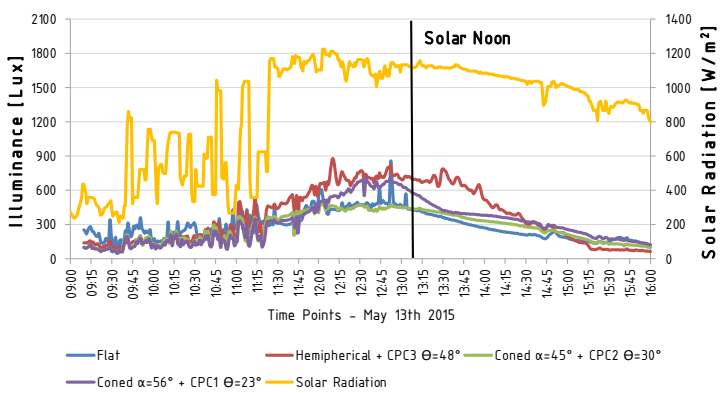

Figure 21. May 13th 2015. Partial sunny day with a Sunlight Incidence Angle at 70.87°. Solar Radiation Average from 10:00 to 15:00 was 954.90 W/m².

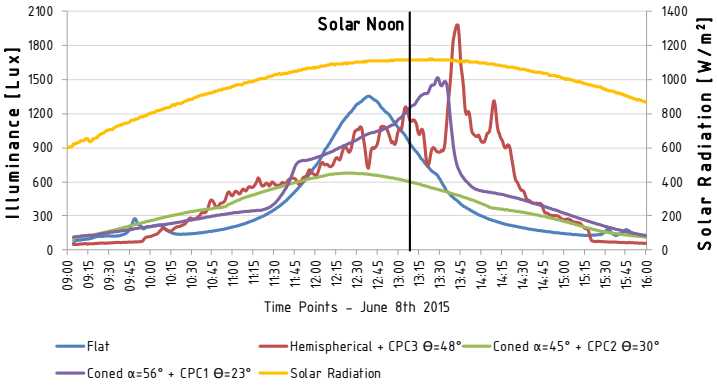

Figure 22. June 8th 2015. Sunny day with a Sunlight Incidence Angle at 75.28°. Solar Radiation Average from 10:00 to 15:00 was 1031.40 W/m².

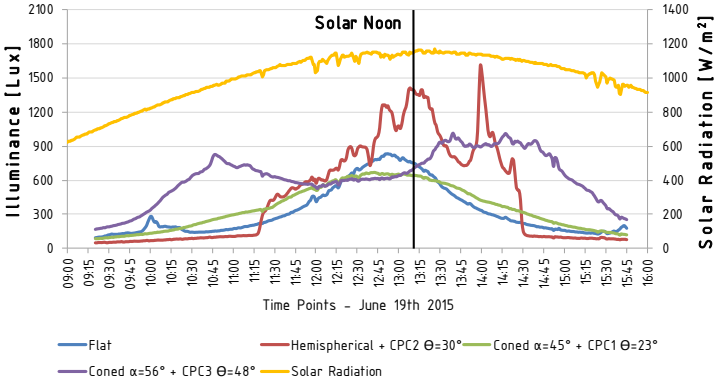

Figure 23. June 19th 2015. Sunny day with a Sunlight Incidence Angle at 75.84°. Solar Radiation Average from 10:00 to 15:00 was 1064.70 W/m².

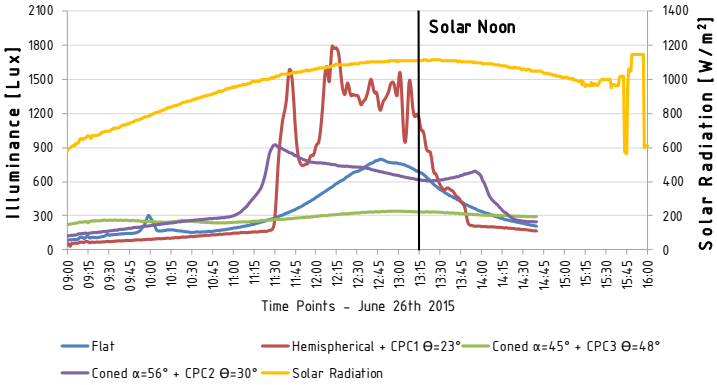

Figure 24. June 26th 2015. Sunny day with a Sunlight Incidence Angle at 76.79°. Solar Radiation Average from 10:00 to 15:00 was 1026.30 W/m².

4. Test 3.2 – CPCs With The Same Half Acceptance Angle But With Different Smaller Diameter

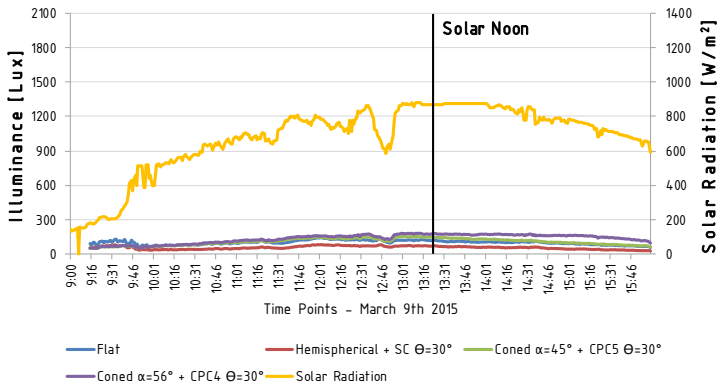

Figure 25. March 9th 2015. Partial sunny day with a Sunlight Incidence Angle at 48.04°. Solar Radiation Average from 10:00 to 15:00 was 749.40 W/m².

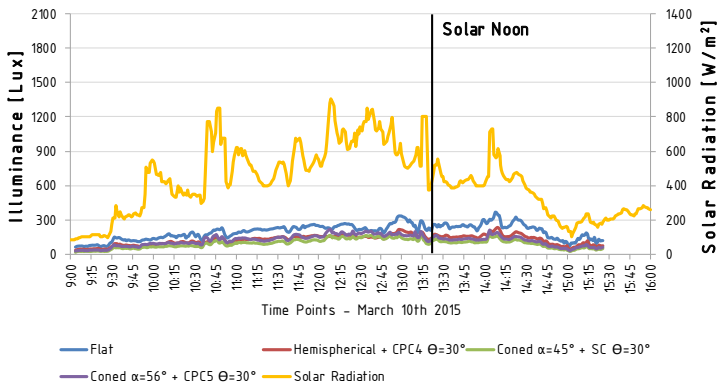

Figure 26. March 10th 2015. Partial sunny day with a Sunlight Incidence Angle at 48.43°. Solar Radiation Average from 10:00 to 15:00 was 509.90 W/m².

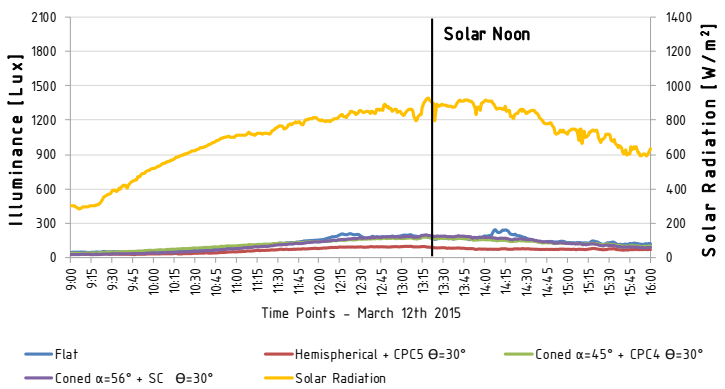

Figure 27. March 12th 2015. Sunny day with a Sunlight Incidence Angle at 49.22°. Solar Radiation Average from 10:00 to 15:00 was 783.90 W/m².

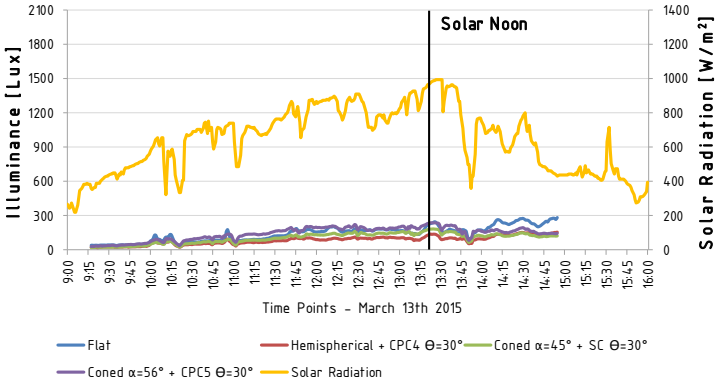

Figure 28. March 13th 2015. Partial sunny day with a Sunlight Incidence Angle at 49.61°. Solar Radiation Average from 10:00 to 15:00 was 728.70 W/m². Data rejected due to technical problems with the sensors.

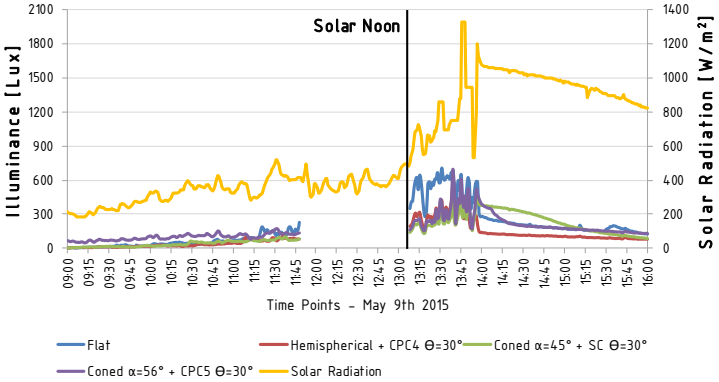

Figure 29. May 9th 2015. Cloudy day with a Sunlight Incidence Angle at 69.85°. Solar Radiation Average from 10:00 to 15:00 was 575.90 W/m². Data rejected.

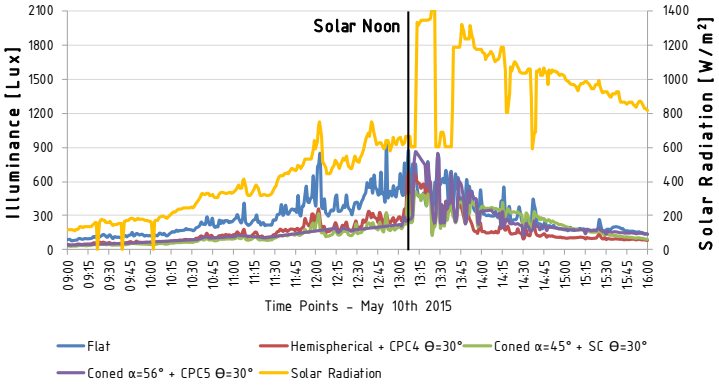

Figure 30. May 10th 2015. Cloudy day with a Sunlight Incidence Angle at 70.11°. Solar Radiation Average from 10:00 to 15:00 was 660.00 W/m². Data rejected.

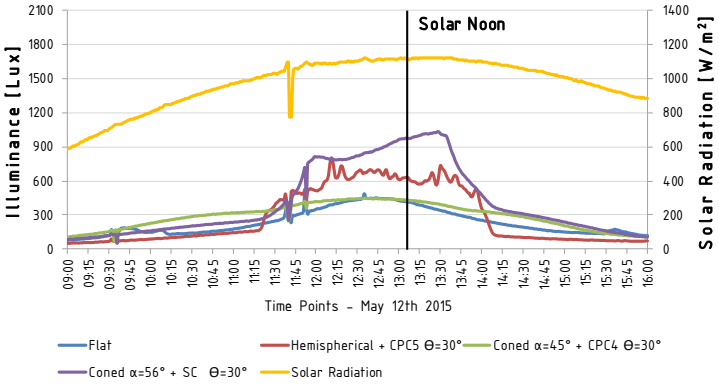

Figure 31. May 12th 2015. Sunny day with a Sunlight Incidence Angle at 70.62°. Solar Radiation Average from 10:00 to 15:00 was 1034.80 W/m².

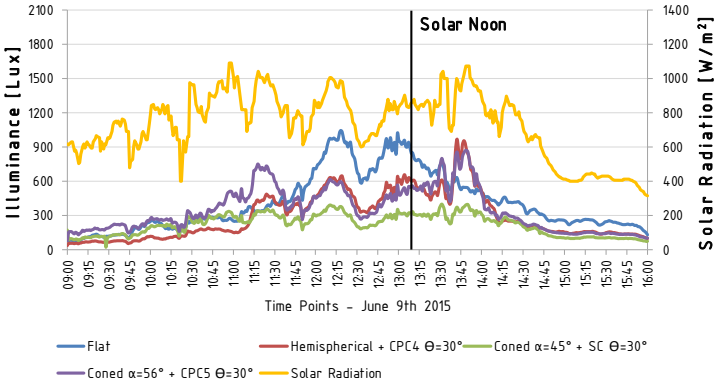

Figure 32. June 9th 2015. Cloudy day with a Sunlight Incidence Angle at 75.37°. Solar Radiation Average from 10:00 to 15:00 was 809.50 W/m². Data rejected.

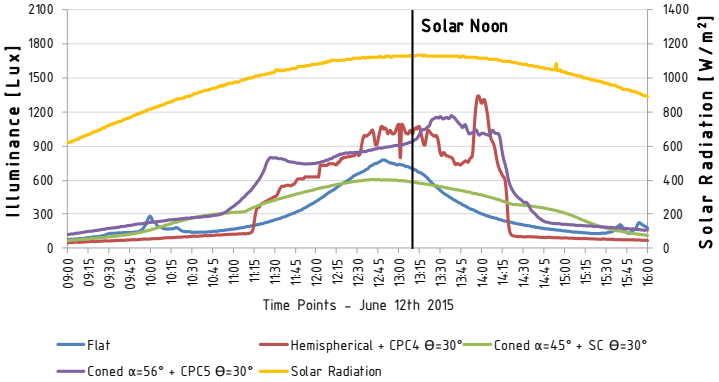

Figure 33. June 12th 2015. Sunny day with a Sunlight Incidence Angle at 75.58°. Solar Radiation Average from 10:00 to 15:00 was 1046.90 W/m².

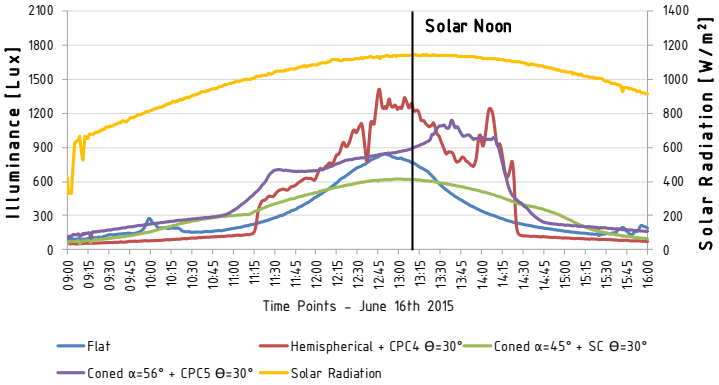

Figure 34. June 16th 2015. Sunny day with a Sunlight Incidence Angle at 75.76°. Solar Radiation Average from 10:00 to 15:00 was 1055 W/m².

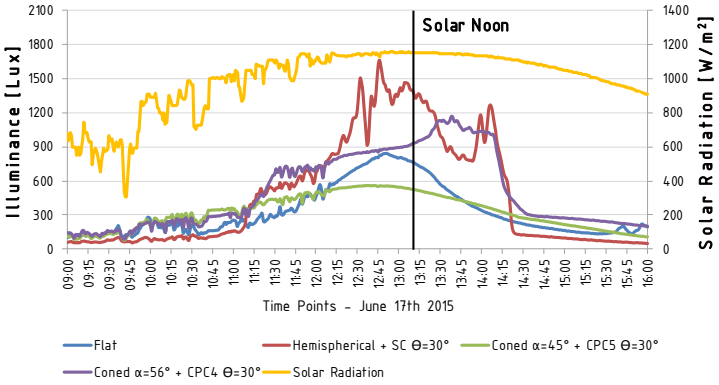

Figure 35. June 17th 2015. Partial sunny day with a Sunlight Incidence Angle at 75.80°. Solar Radiation Average from 10:00 to 15:00 was 1063.40 W/m².

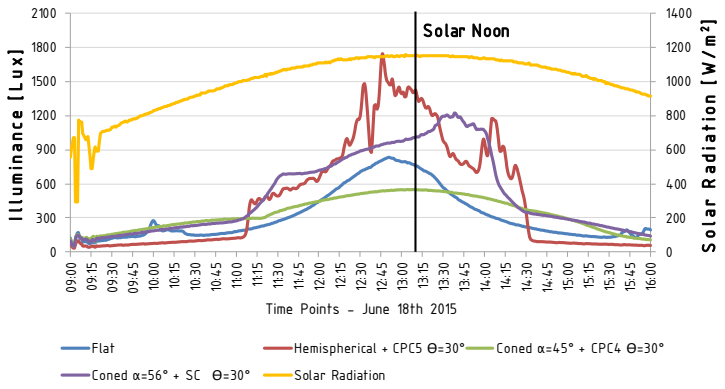

Figure 36. June 18th 2015. Sunny day with a Sunlight Incidence Angle at 75.82°. Solar Radiation Average from 10:00 to 15:00 was 1067.20 W/m².

5. Test 4 – CPCs Facing The Outside And Aligned With OF Tip Shapes Facing The Inside Of The Test Box

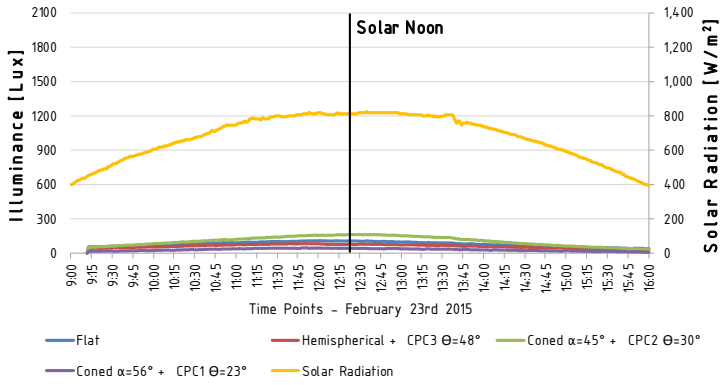

Figure 37. February 23rd 2015. Sunny day with a Sunlight Incidence Angle at 42.71°. Solar Radiation Average from 10:00 to 15:00 was 747.00 W/m².

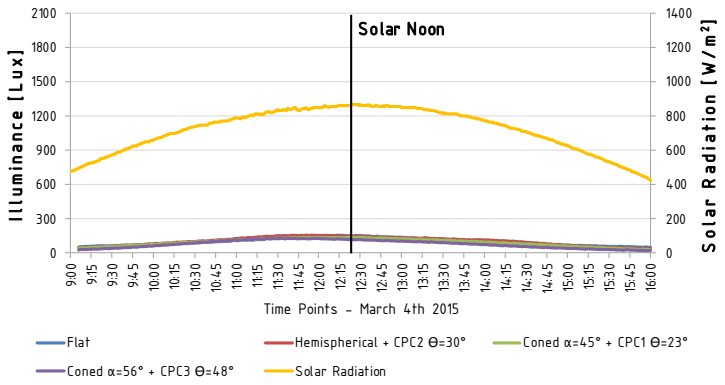

Figure 38. March 4th 2015. Sunny day with a Sunlight Incidence Angle at 46.10°. Solar Radiation Average from 10:00 to 15:00 was 786.10 W/m².

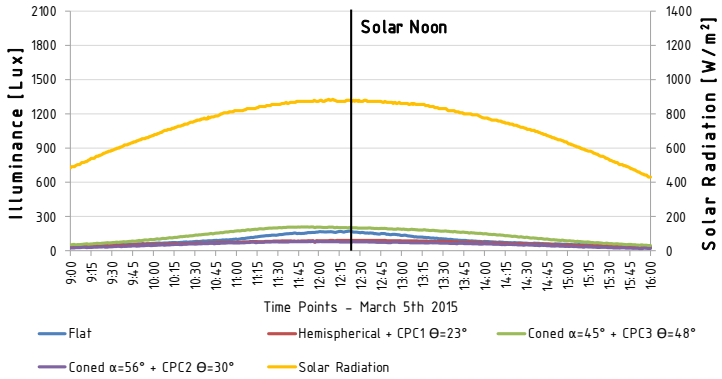

Figure 39. March 5th 2015. Sunny day with a Sunlight Incidence Angle at 46.49°. Solar Radiation Average from 10:00 to 15:00 was 802.40 W/m².

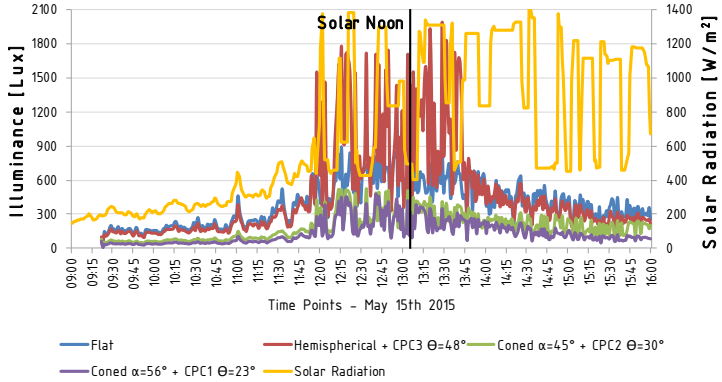

Figure 40. May 15th 2015. Cloudy day with a Sunlight Incidence Angle at 71.35°. Solar Radiation Average from 10:00 to 15:00 was 680.50 W/m². Data rejected.

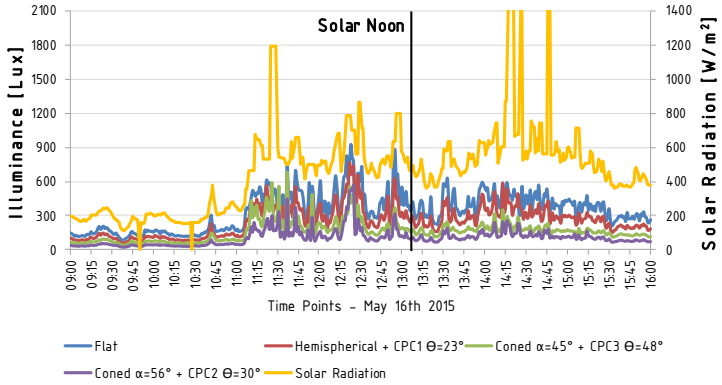

Figure 41. May 16th 2015. Cloudy day with a Sunlight Incidence Angle at 71.58°. Solar Radiation Average from 10:00 to 15:00 was 516.40 W/m². Data rejected.

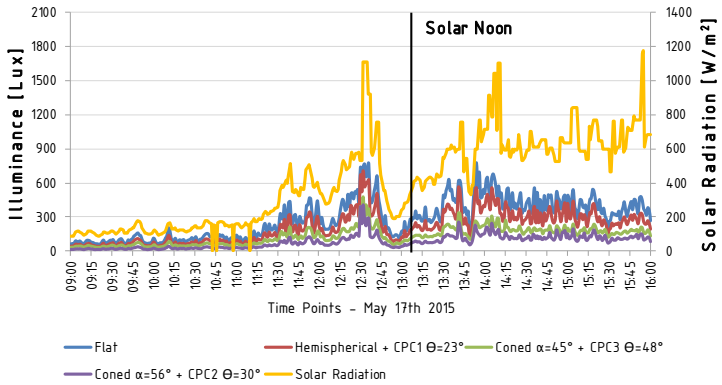

Figure 42. May 17th 2015. Cloudy day with a Sunlight Incidence Angle at 71.81°. Solar Radiation Average from 10:00 to 15:00 was 411.90 W/m². Data rejected.

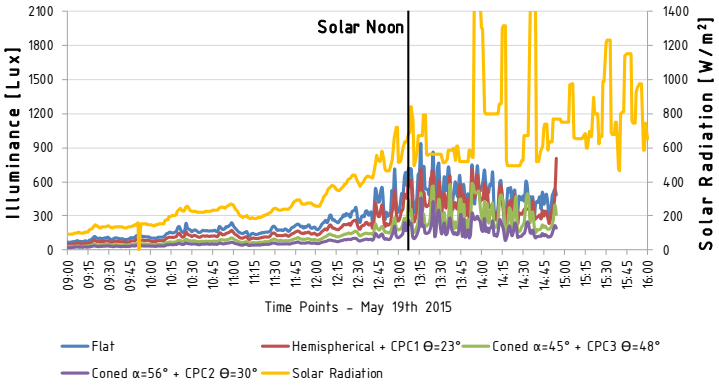

Figure 43. May 19th 2015. Cloudy day with a Sunlight Incidence Angle at 72.24°. Solar Radiation Average from 10:00 to 15:00 was 456.40 W/m². Data rejected.

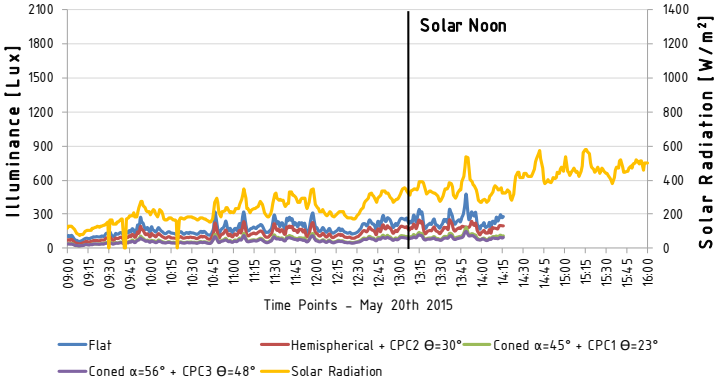

Figure 44. May 20th 2015. Cloudy day with a Sunlight Incidence Angle at 72.52°. Solar Radiation Average from 10:00 to 15:00 was 267.70 W/m². Data rejected.

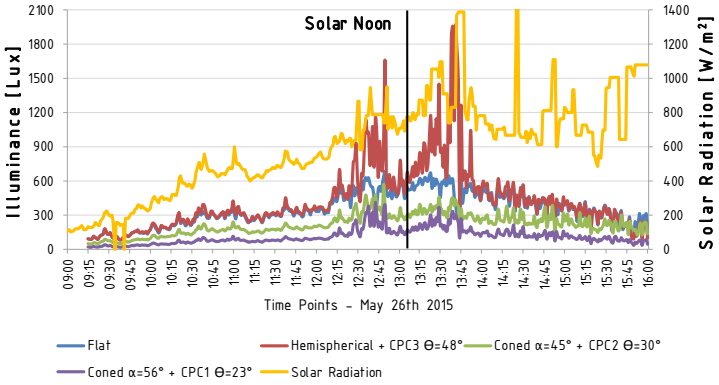

Figure 45. May 26th 2015. Cloudy day with a Sunlight Incidence Angle at 73.59°. Solar Radiation Average from 10:00 to 15:00 was 641.00 W/m². Data rejected.

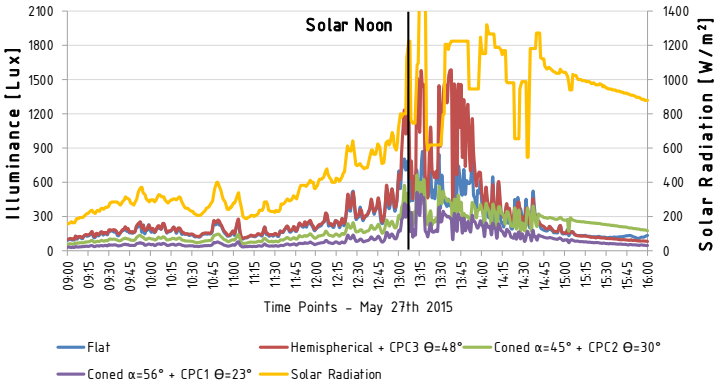

Figure 46. May 27th 2015. Cloudy day with a Sunlight Incidence Angle at 73.76°. Solar Radiation Average from 10:00 to 15:00 was 627.70 W/m². Data rejected.

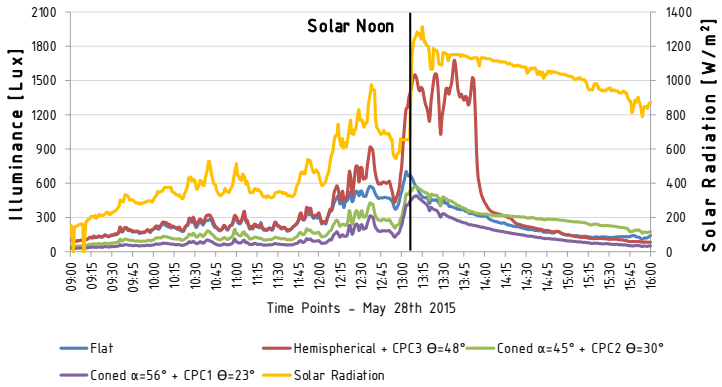

Figure 47. May 28th 2015. Partial sunny day with a Sunlight Incidence Angle at 73.92°. Solar Radiation Average from 10:00 to 15:00 was 758.30 W/m².

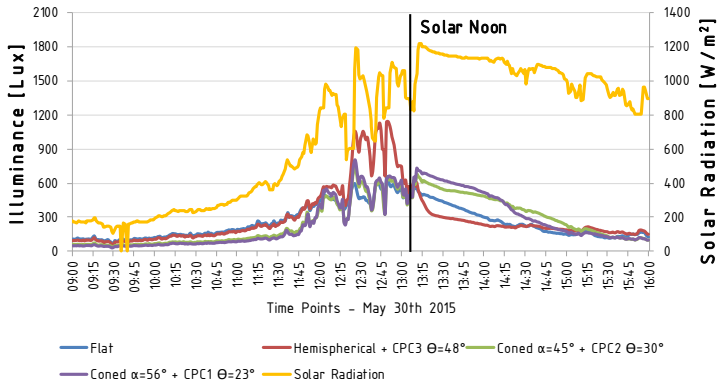

Figure 48. May 30th 2015. Partial sunny day with a Sunlight Incidence Angle at 74.22°. Solar Radiation Average from 10:00 to 15:00 was 755.70 W/m².

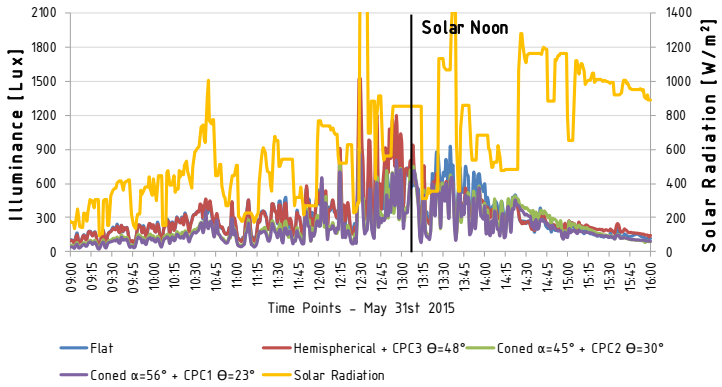

Figure 49. May 31st 2015. Cloudy day with a Sunlight Incidence Angle at 74.37°. Solar Radiation Average from 10:00 to 15:00 was 648.90 W/m². Data rejected.

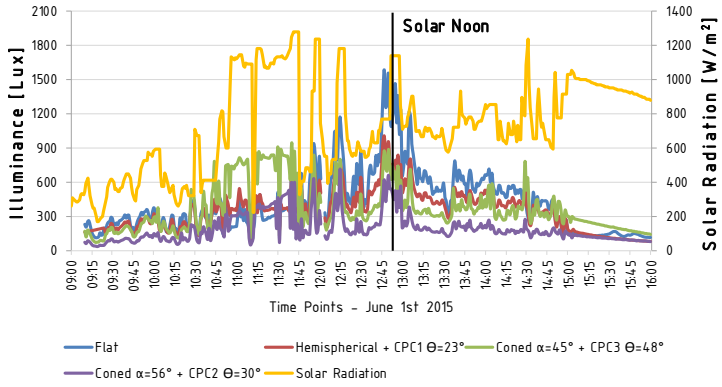

Figure 50. June 1st 2015. Partial sunny day with a Sunlight Incidence Angle at 74.51°. Solar Radiation Average from 10:00 to 15:00 was 752.00 W/m².

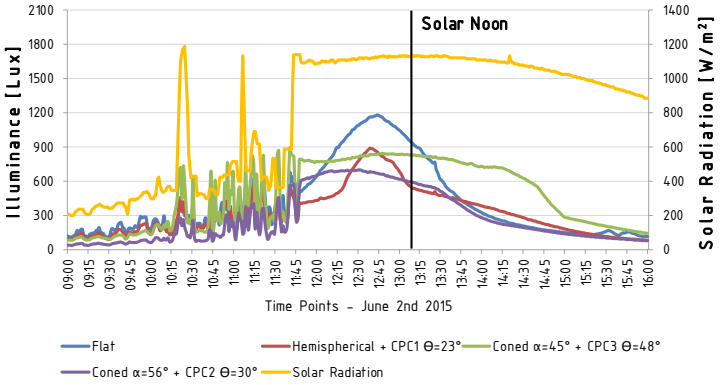

Figure 51. June 2nd 2015. Partial sunny day with a Sunlight Incidence Angle at 74.64°. Solar Radiation Average from 10:00 to 15:00 was 890.00 W/m².

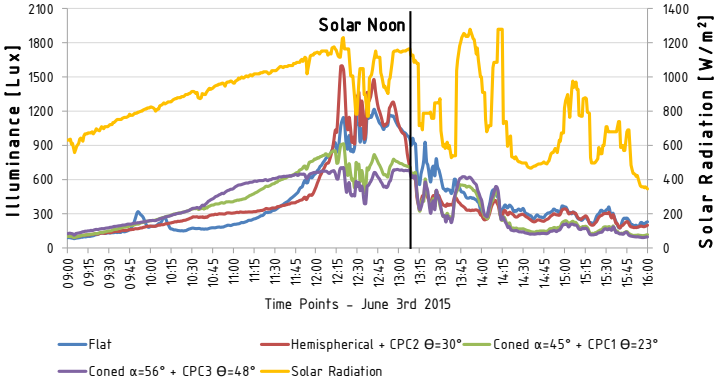

Figure 52. June 3rd 2015. Partial sunny day with a Sunlight Incidence Angle at 74.76°. Solar Radiation Average from 10:00 to 15:00 was 924.20 W/m².

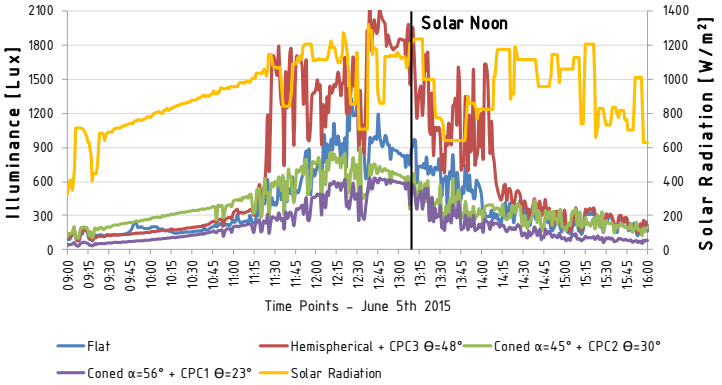

Figure 53. June 5th 2015. Partial sunny day with a Sunlight Incidence Angle at 74.99°. Solar Radiation Average from 10:00 to 15:00 was 1060 W/m².

6. Test 5 – OF Tip Shapes Embedded In CPCs Facing The Inside Of The Test Box

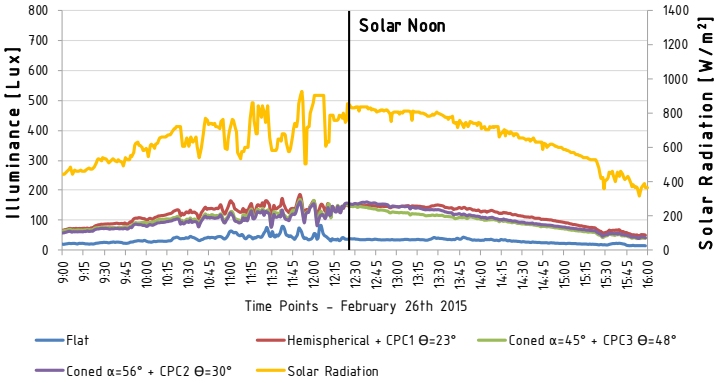

Figure 54. February 26th 2015. Partial sunny day with a Sunlight Incidence Angle at 43.82°. Solar Radiation Average from 10:00 to 15:00 was 721.50 W/m².

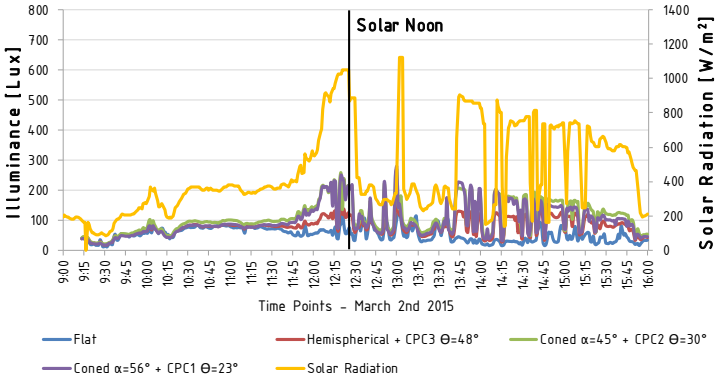

Figure 55. March 2nd 2015. Partial sunny day with a Sunlight Incidence Angle at 45.33°. Solar Radiation Average from 10:00 to 15:00 was 482.60 W/m².

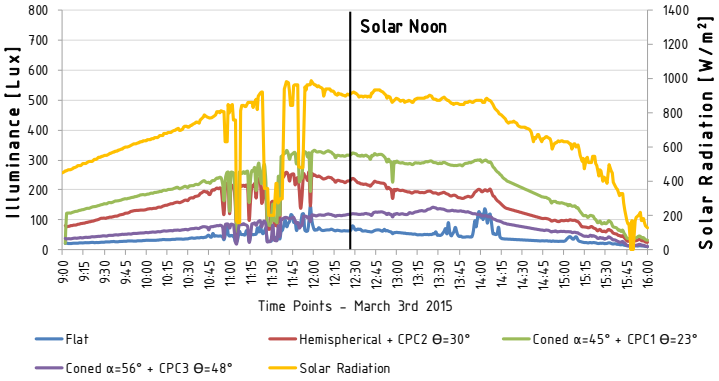

Figure 56. March 3rd 2015. Partial sunny day with a Sunlight Incidence Angle at 45.72°. Solar Radiation Average from 10:00 to 15:00 was 783.70 W/m².

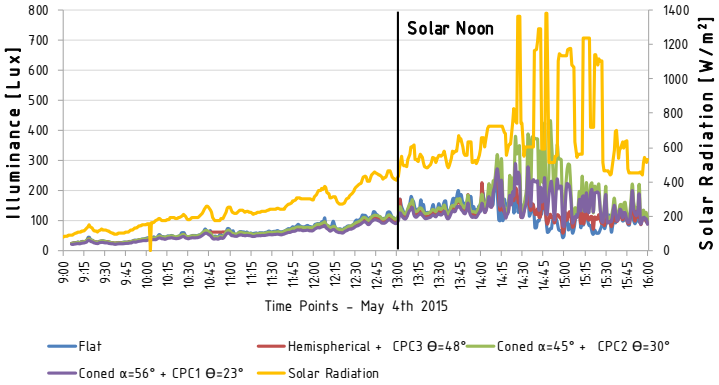

Figure 57. May 4th 2015. Cloudy day with a Sunlight Incidence Angle at 68.47°. Solar Radiation Average from 10:00 to 15:00 was 430.20 W/m². Data rejected.

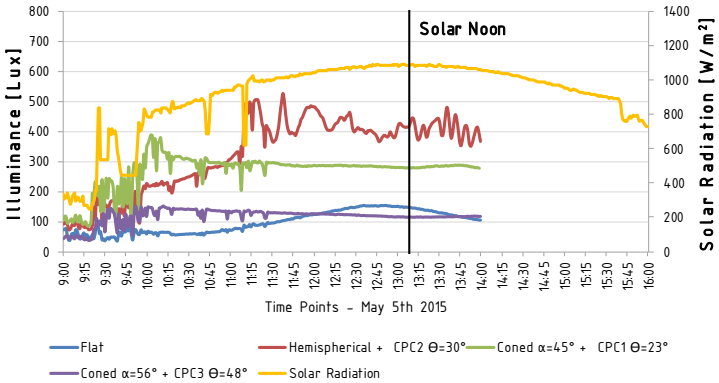

Figure 58. May 5th 2015. Partial sunny day with a Sunlight Incidence Angle at 68.75°. Data rejected due to a problem with the sensors.

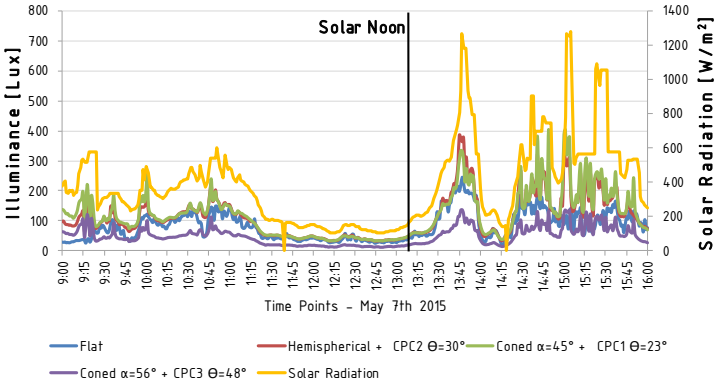

Figure 59. May 7th 2015. Cloudy day with a Sunlight Incidence Angle at 69.31°. Solar Radiation Average from 10:00 to 15:00 was 339.80 W/m². Data rejected.

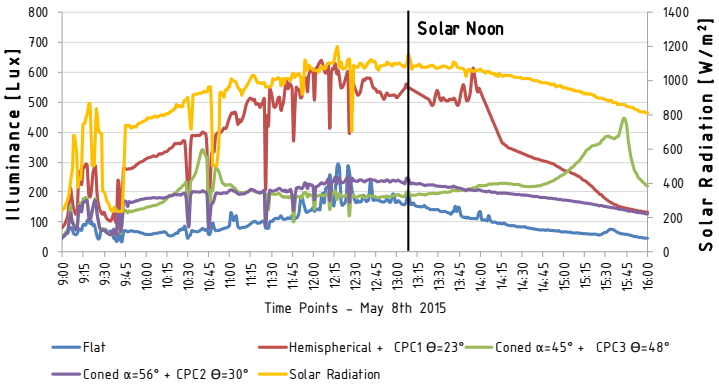

Figure 60. May 8th 2015. Partial sunny day with a Sunlight Incidence Angle at 69.58°. Solar Radiation Average from 10:00 to 15:00 was 1001.40 W/m².

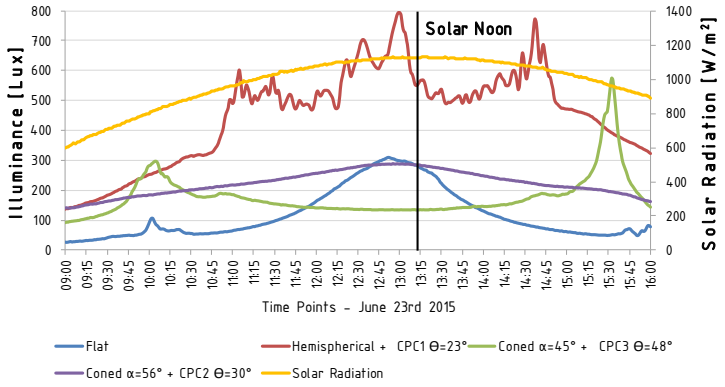

Figure 61. June 23rd 2015. Sunny day with a Sunlight Incidence Angle at 75.83°. Solar Radiation Average from 10:00 to 15:00 was 1043.10 W/m².

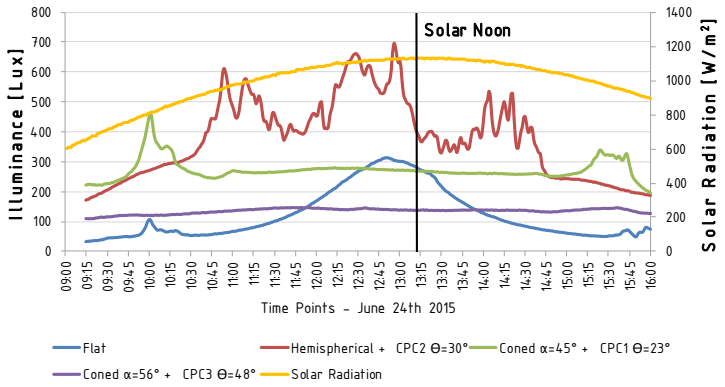

Figure 62. June 24th 2015. Sunny day with a Sunlight Incidence Angle at 75.81°. Solar Radiation Average from 10:00 to 15:00 was 1046.40 W/m².

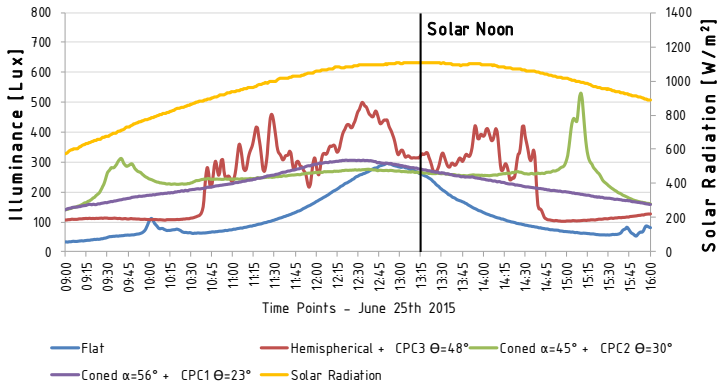

Figure 63. June 25th 2015. Sunny day with a Sunlight Incidence Angle at 75.79° Solar Radiation Average from 10:00 to 15:00 was 1025.50 W/m².

ANNEX - Chapter 5 Results

1. Test 2.1 - Base

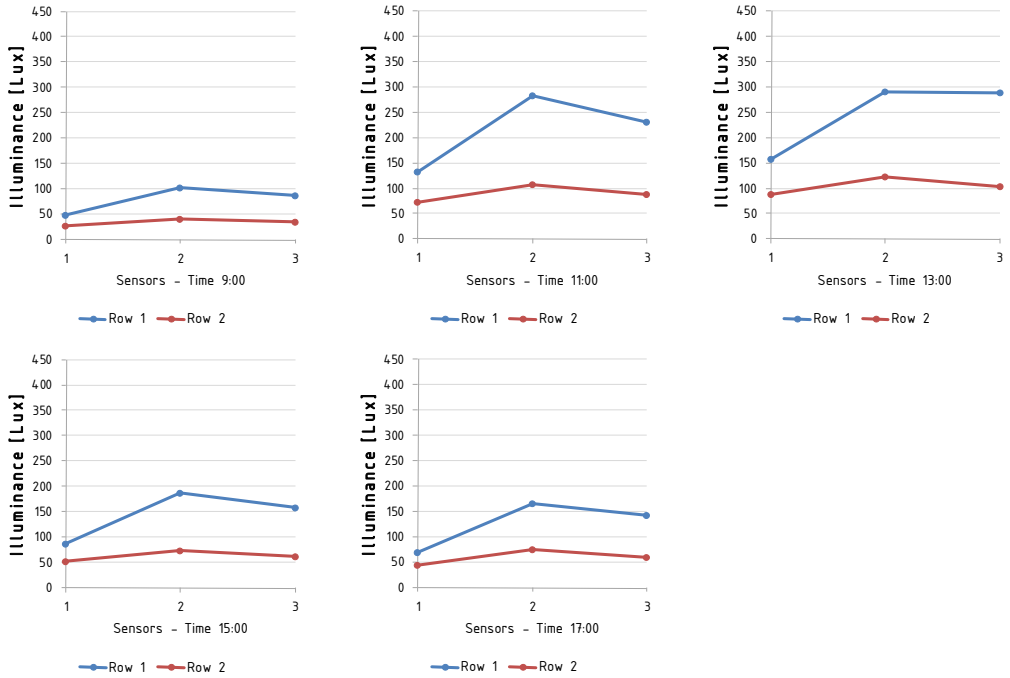

Figure 1. August 6th 2015. Cloudy day with a Sunlight Incidence Angle at 69.02°. Solar Radiation Average from 9:00 to 17:00 was 518.71 W/m². (Sensors parallel to the TCP)

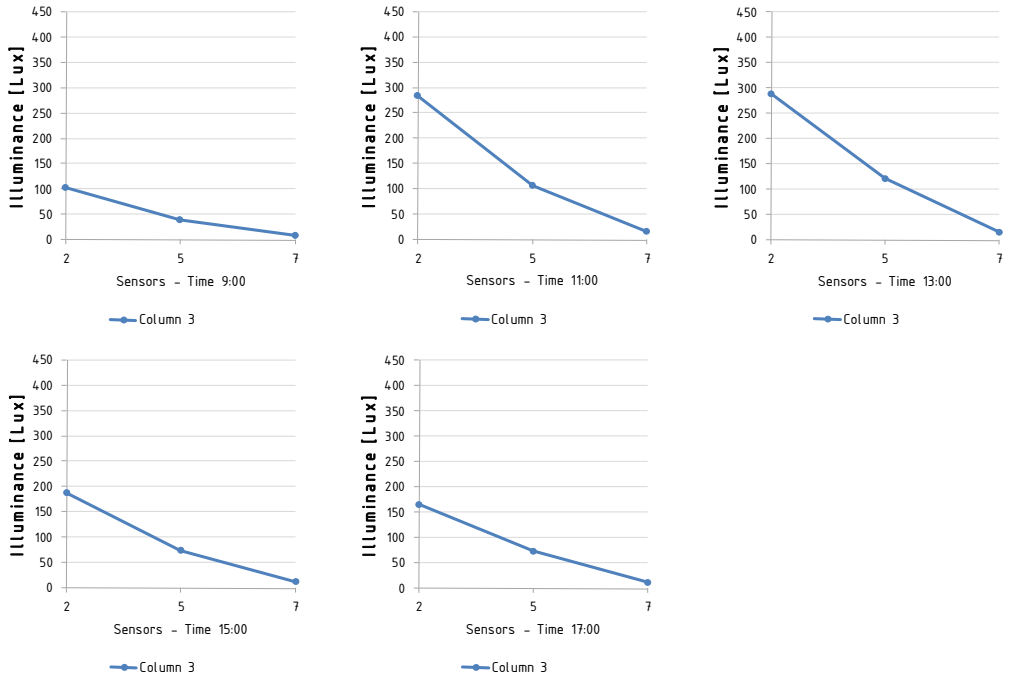

Figure 2. August 6th 2015. Cloudy day with a Sunlight Incidence Angle at 69.02°. Solar Radiation Average from 9:00 to 17:00 was 518.71 W/m². (Sensors perpendicular to the TCP)

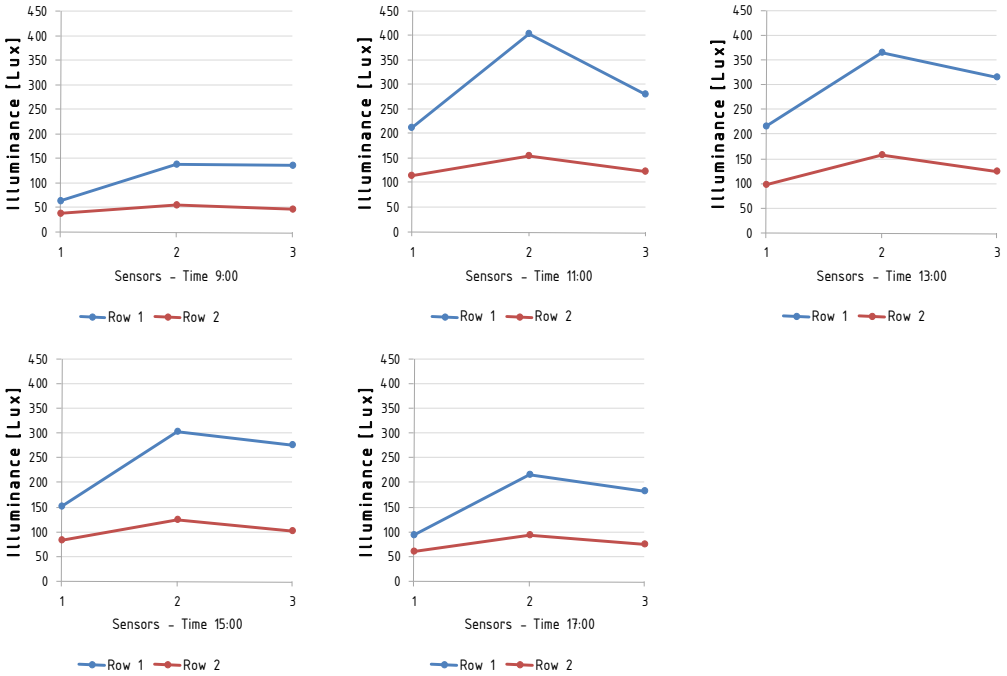

Figure 3. August 7th 2015. Partial sunny day with a Sunlight Incidence Angle at 68.74°. Solar Radiation Average from 9:00 to 17:00 was 787.30 W/m². (Sensors parallel to the TCP)

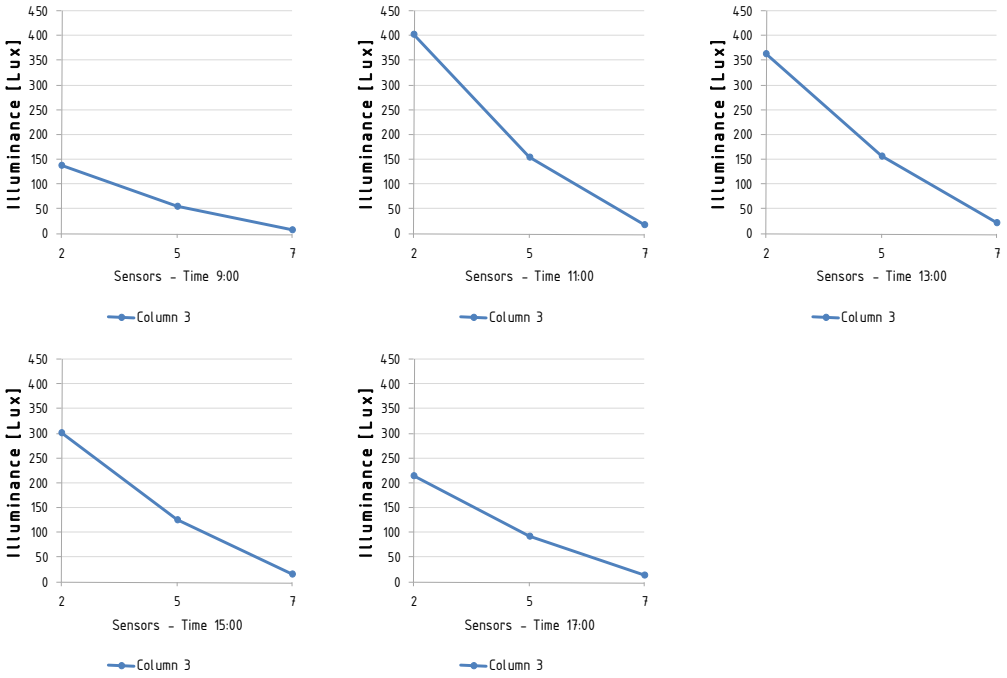

Figure 4. August 7th 2015. Partial sunny day with a Sunlight Incidence Angle at 68.74°. Solar Radiation Average from 9:00 to 17:00 was 787.30 W/m². (Sensors perpendicular to the TCP)

2. Test 2.2 – Diffuser 1

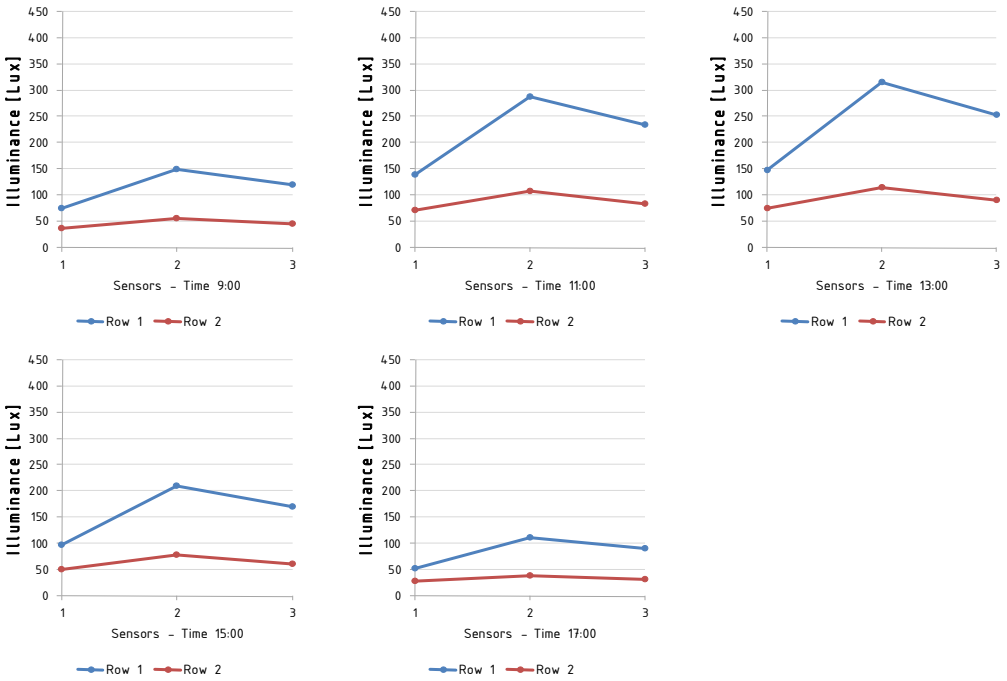

Figure 5. August 12th 2015. Sunny day with a Sunlight Incidence Angle at 67.29°. Solar Radiation Average from 9:00 to 17:00 was 886.09 W/m². (Sensors parallel to the TCP)

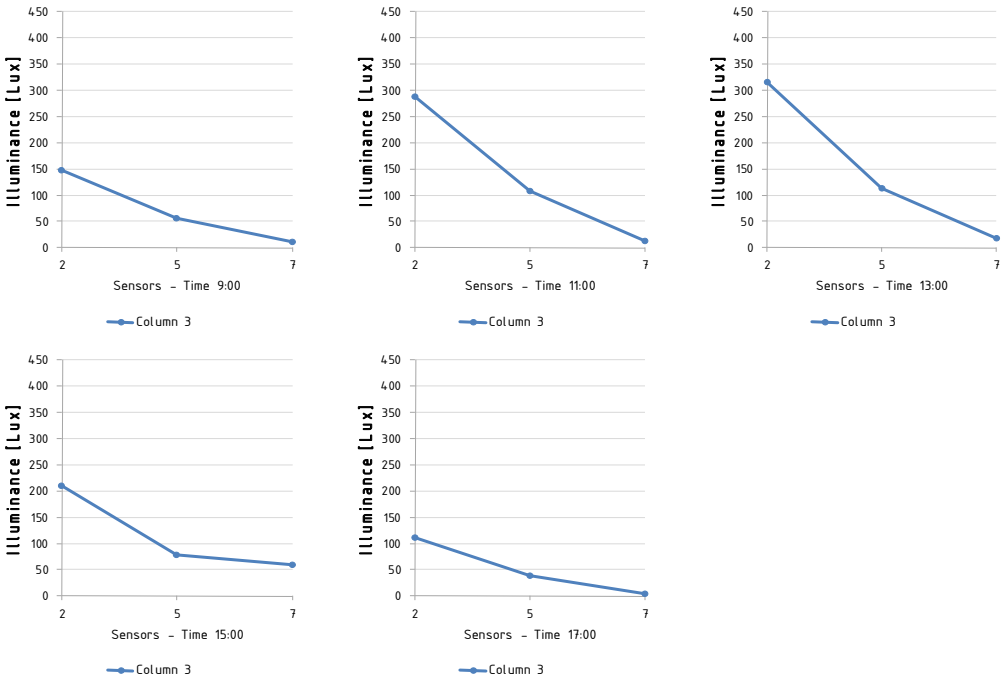

Figure 6. August 12th 2015. Sunny day with a Sunlight Incidence Angle at 67.29°. Solar Radiation Average from 9:00 to 17:00 was 886.09 W/m². (Sensors perpendicular to the TCP)

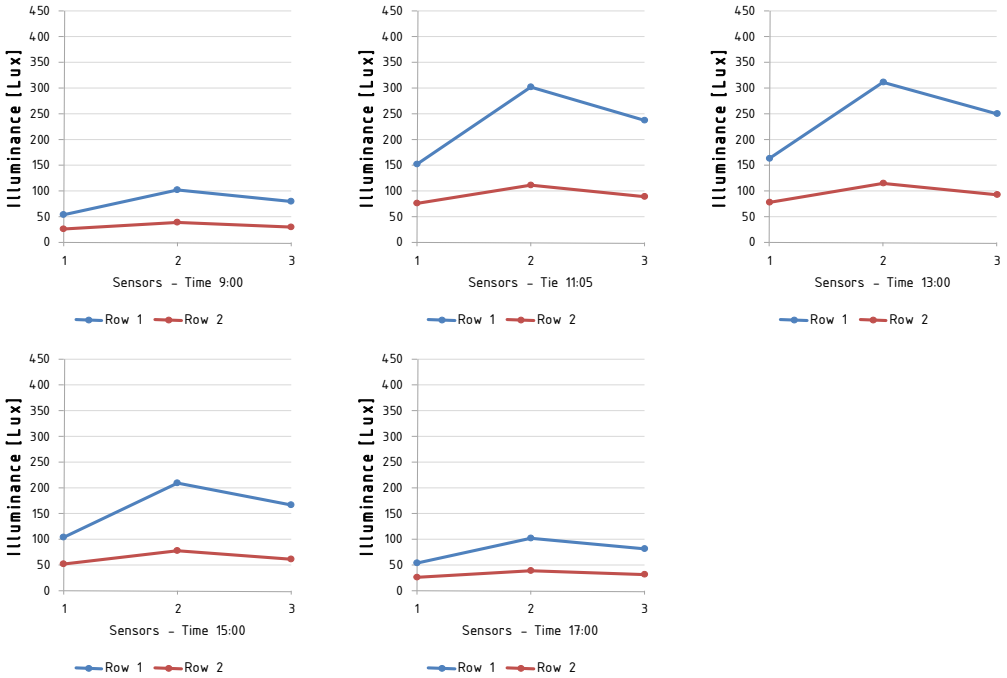

Figure 7. August 14th 2015. Sunny day with a Sunlight Incidence Angle at 66.68°. Solar Radiation Average from 9:00 to 17:00 was 850.02 W/m². (Sensors parallel to the TCP)

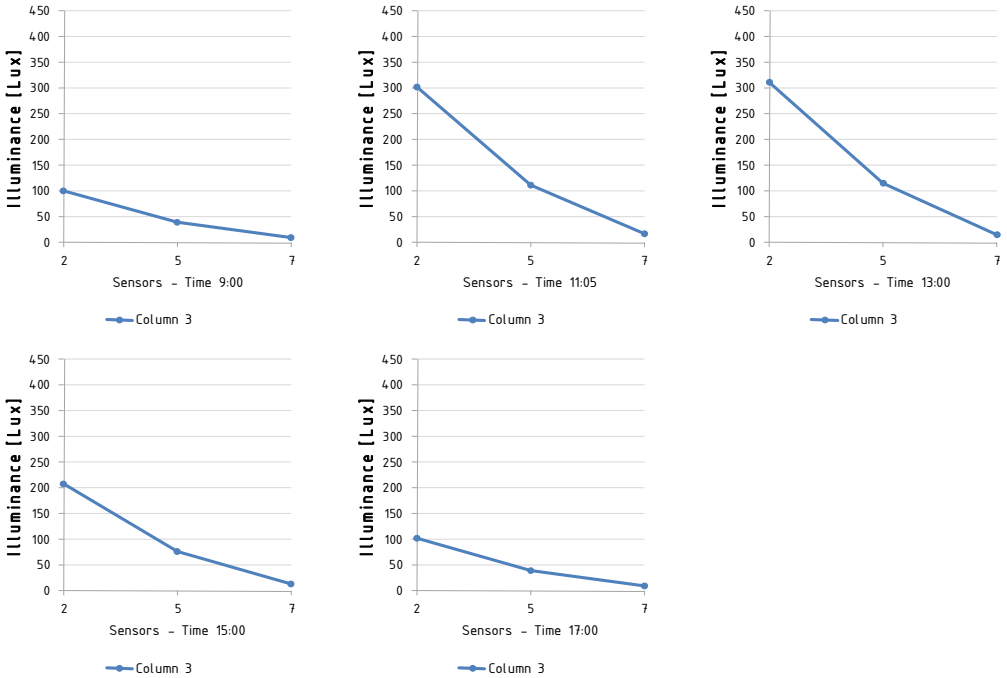

Figure 8. August 14th 2015. Sunny day with a Sunlight Incidence Angle at 66.68°. Solar Radiation Average from 9:00 to 17:00 was 850.02 W/m². (Sensors perpendicular to the TCP)

3. Test 2.3 – Diffuser 2

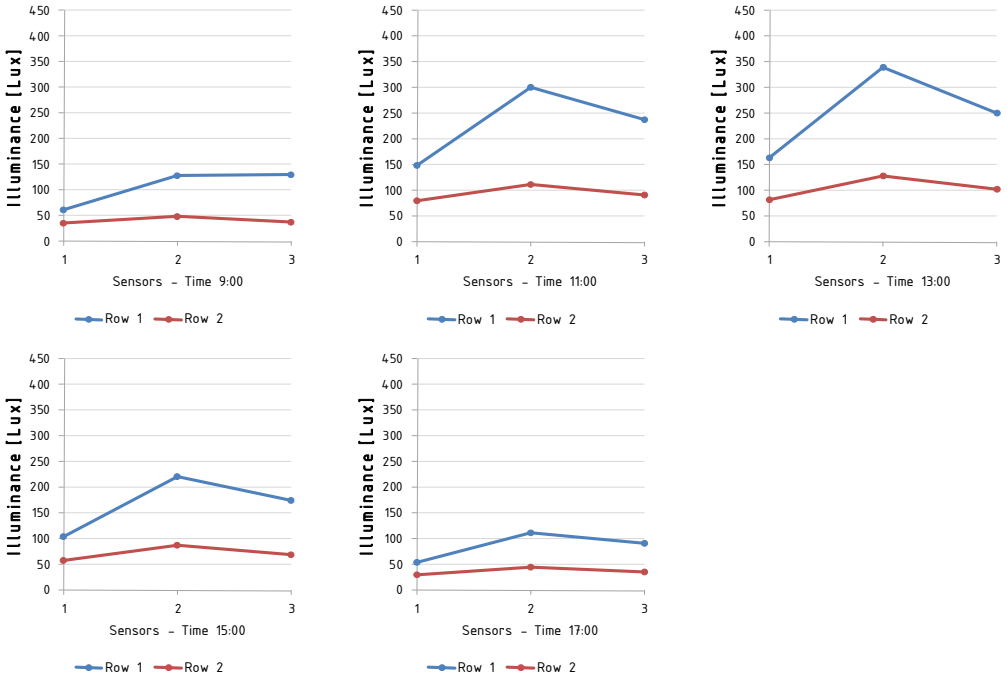

Figure 9. August 9th 2015. Sunny day with a Sunlight Incidence Angle at 68.17°. Solar Radiation Average from 9:00 to 17:00 was 893.55 W/m². (Sensors parallel to the TCP)

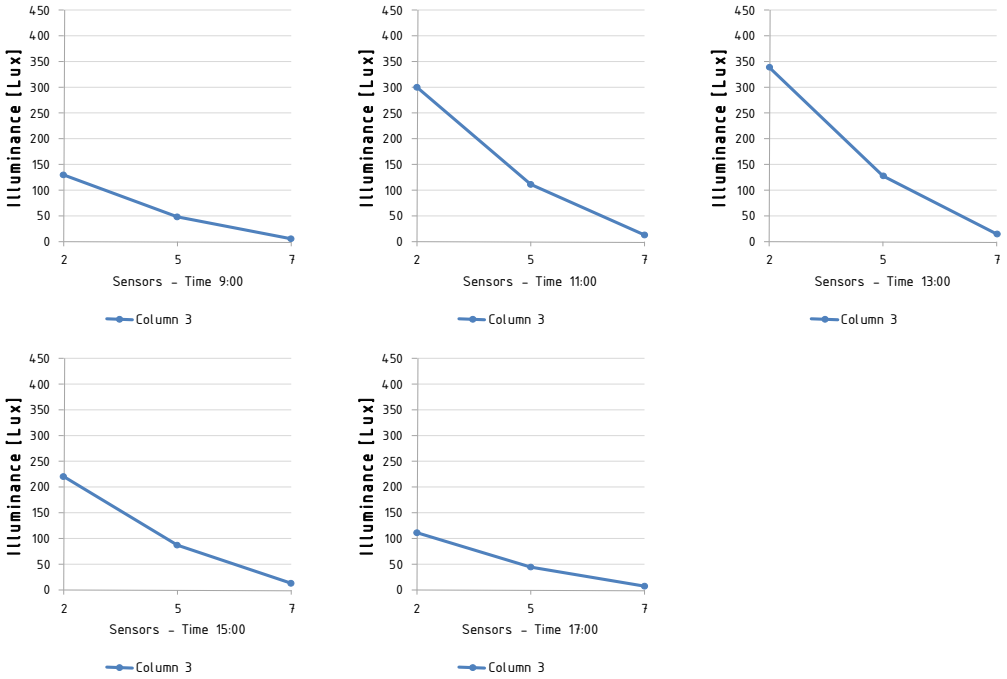

Figure 10. August 9th 2015. Sunny day with a Sunlight Incidence Angle at 68.17°. Solar Radiation Average from 9:00 to 17:00 was 893.55 W/m². (Sensors perpendicular to the TCP)

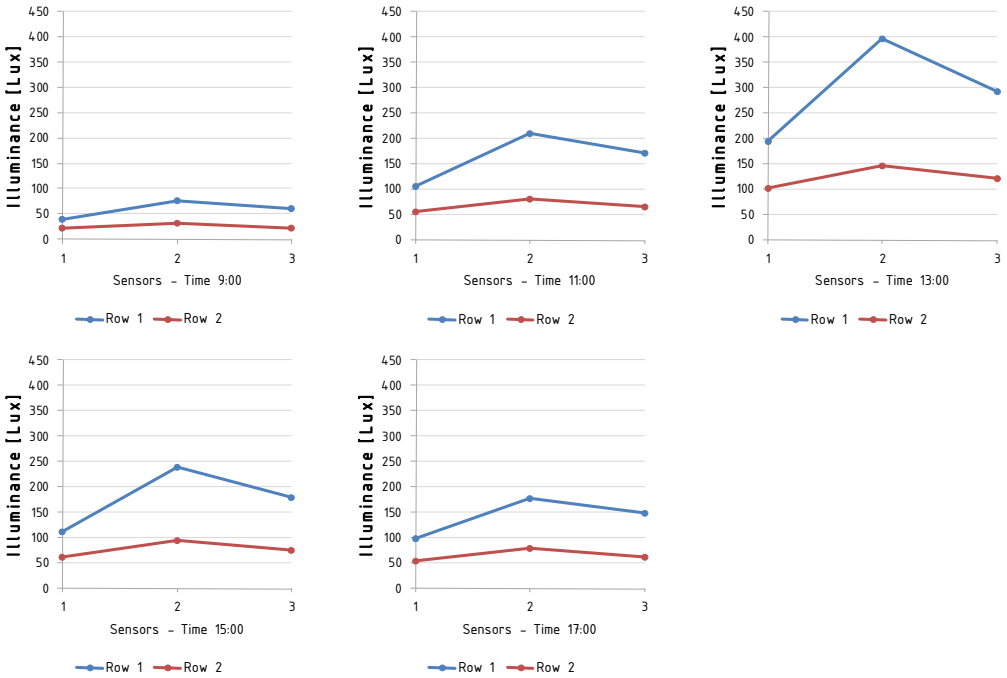

Figure 11. August 11th 2015. Partial sunny day with a Sunlight Incidence Angle at 67.59°. Solar Radiation Average from 9:00 to 17:00 was 763.67 W/m². (Sensors parallel to the TCP)

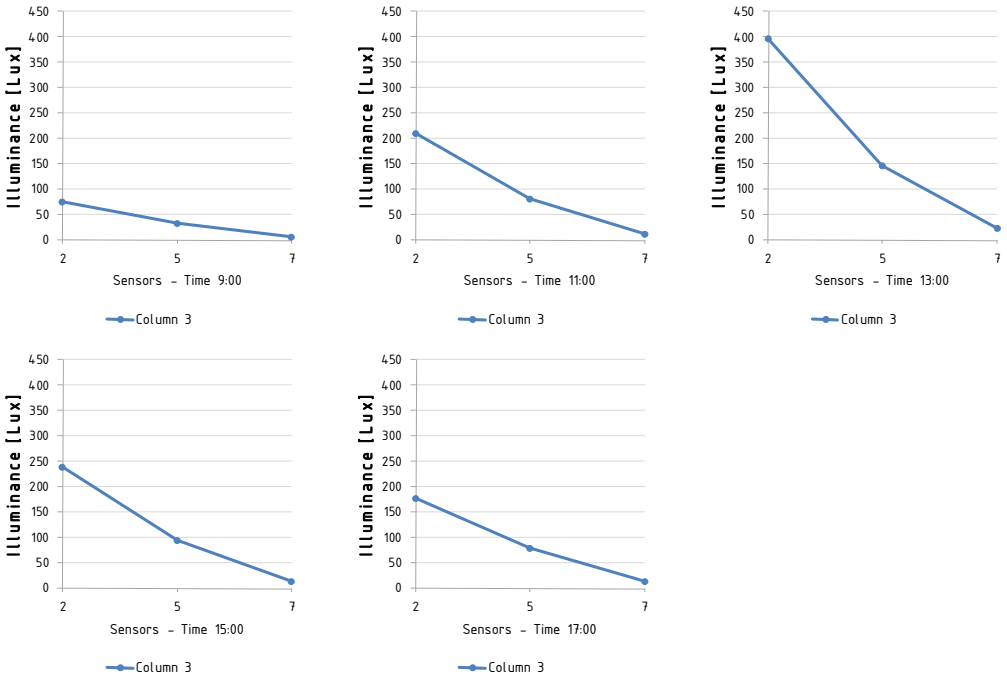

Figure 12. August 11th 2015. Partial sunny day with a Sunlight Incidence Angle at 67.59°. Solar Radiation Average from 9:00 to 17:00 was 763.67 W/m². (Sensors perpendicular to the TCP)

4. Test 3.1 – Base

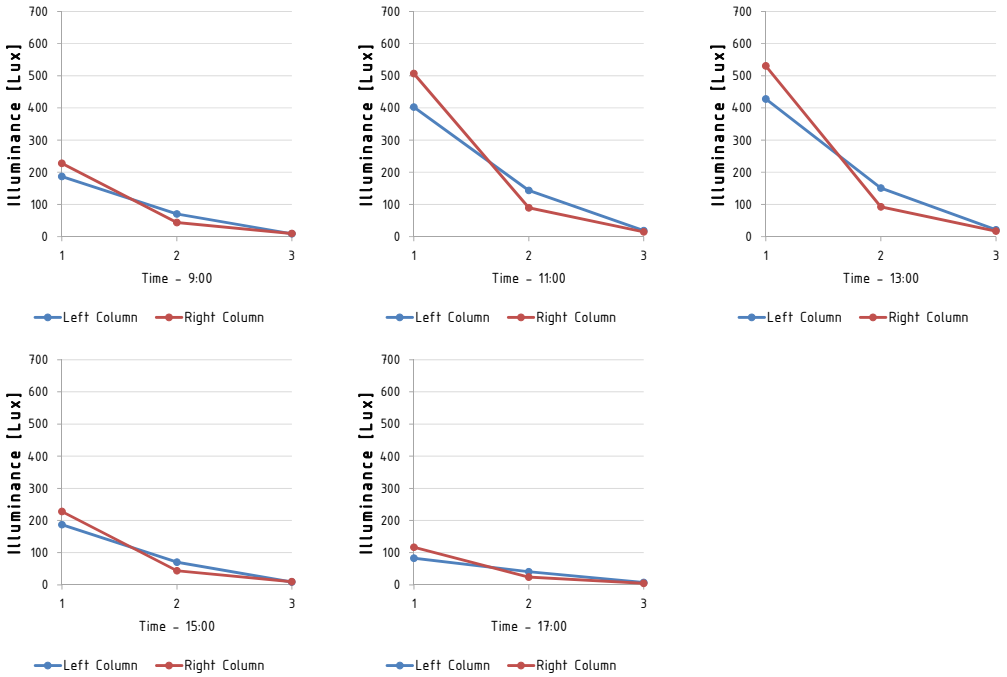

Figure 13. August 26th 2015. Sunny day with a Sunlight Incidence Angle at 62.72°. Solar Radiation Average from 9:00 to 17:00 was 816.35 W/m².

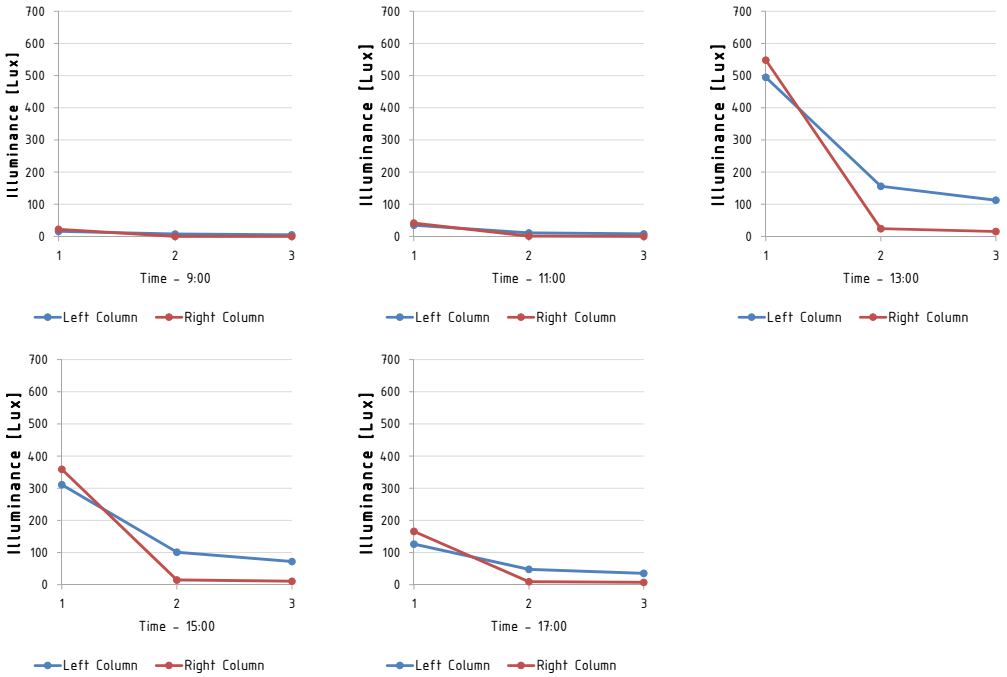

Figure 14. August 29th 2015. Cloudy day with a Sunlight Incidence Angle at 61.66°. Solar Radiation Average from 9:00 to 17:00 was 523.87 W/m².

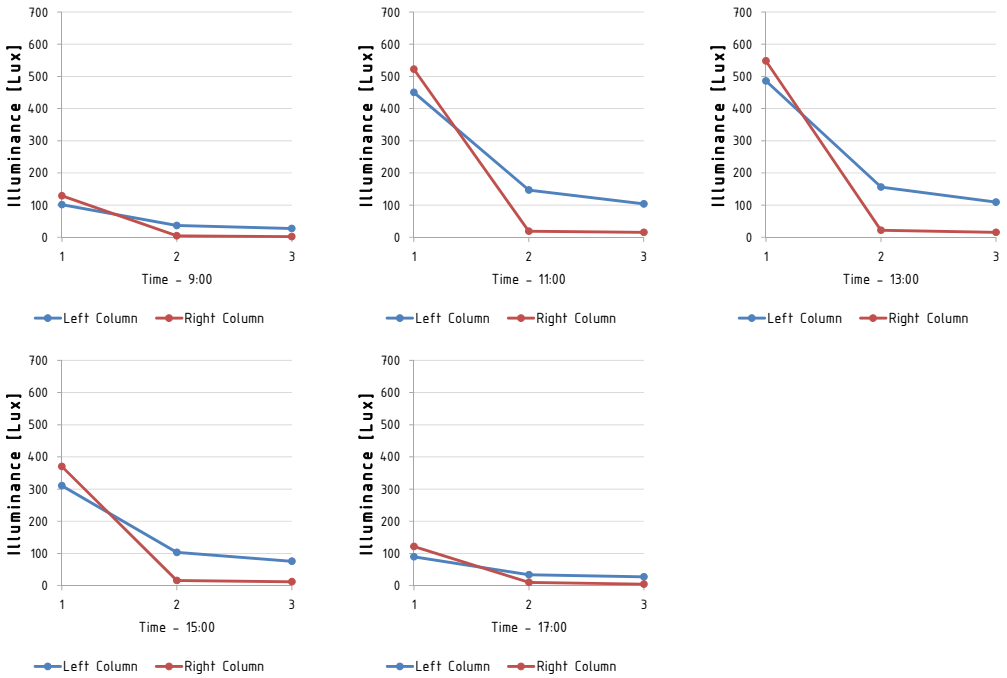

Figure 15. August 30th 2015. Partial sunny day with a Sunlight Incidence Angle at 61.30°. Solar Radiation Average from 9:00 to 17:00 was 746.30 W/m².

5. Test 3.2 – Frontal (Opposite To The TCP)

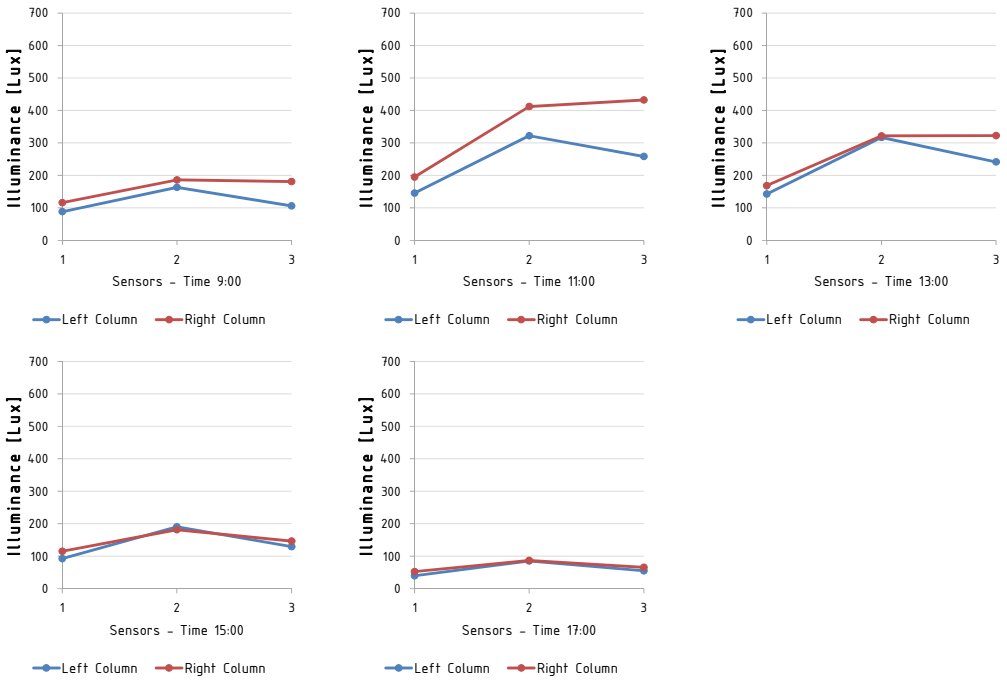

Figure 16. September 26th 2015. Partial sunny day with a Sunlight Incidence Angle at 51.06°. Solar Radiation Average from 9:00 to 17:00 was 710.32 W/m².

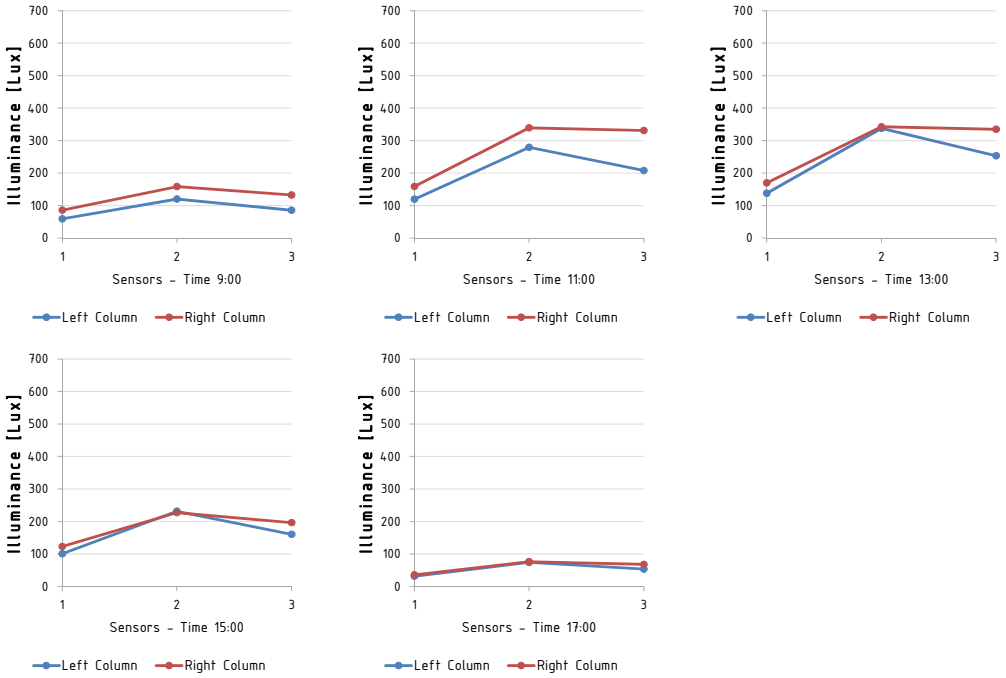

Figure 17. September 27th 2015. Cloudy day with a Sunlight Incidence Angle at 50.67°. Solar Radiation Average from 9:00 to 17:00 was 510.57 W/m².

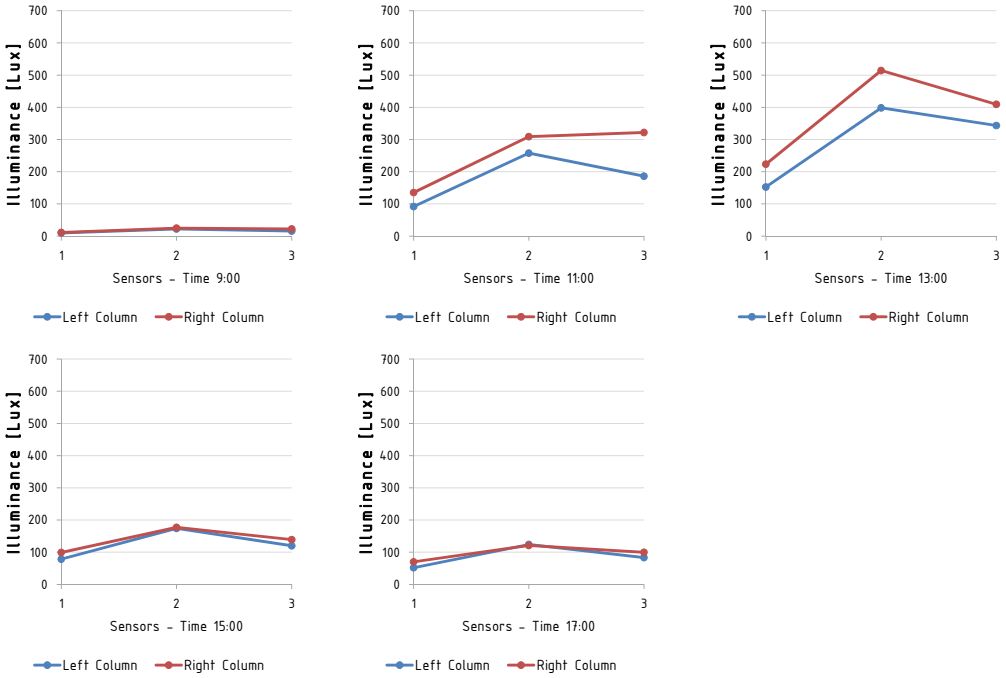

Figure 18. September 28th 2015. Cloudy day with a Sunlight Incidence Angle at 50.28°. Solar Radiation Average from 9:00 to 17:00 was 554.57 W/m².

6. Test 3.3 – Lateral Right

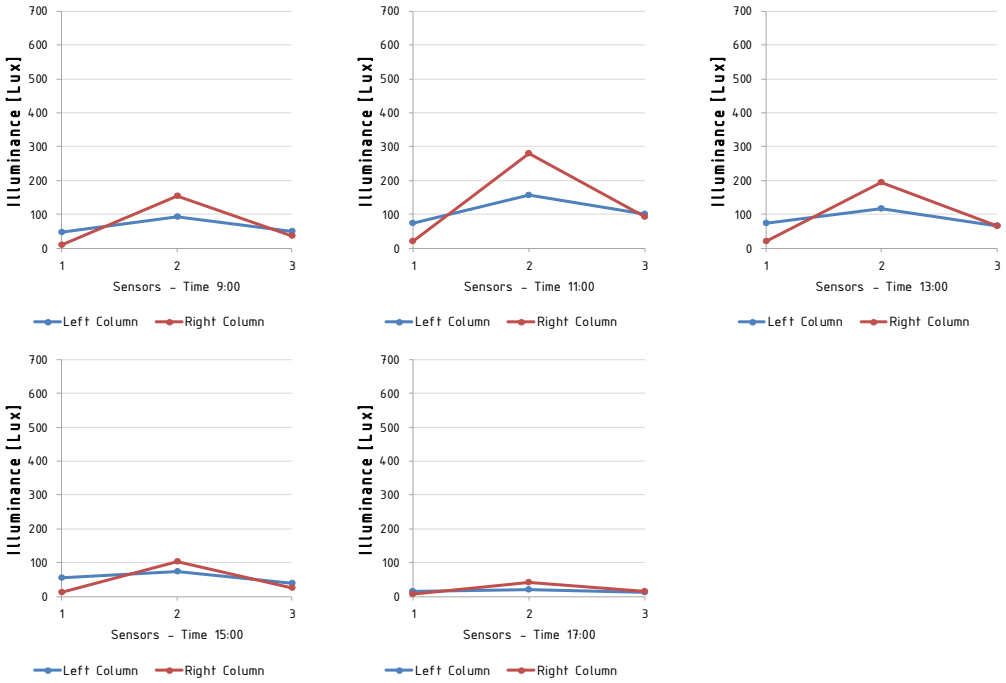

Figure 19. October 3rd 2015. Sunny day with a Sunlight Incidence Angle at 48.34°. Solar Radiation Average from 9:00 to 17:00 was 685.20 W/m².

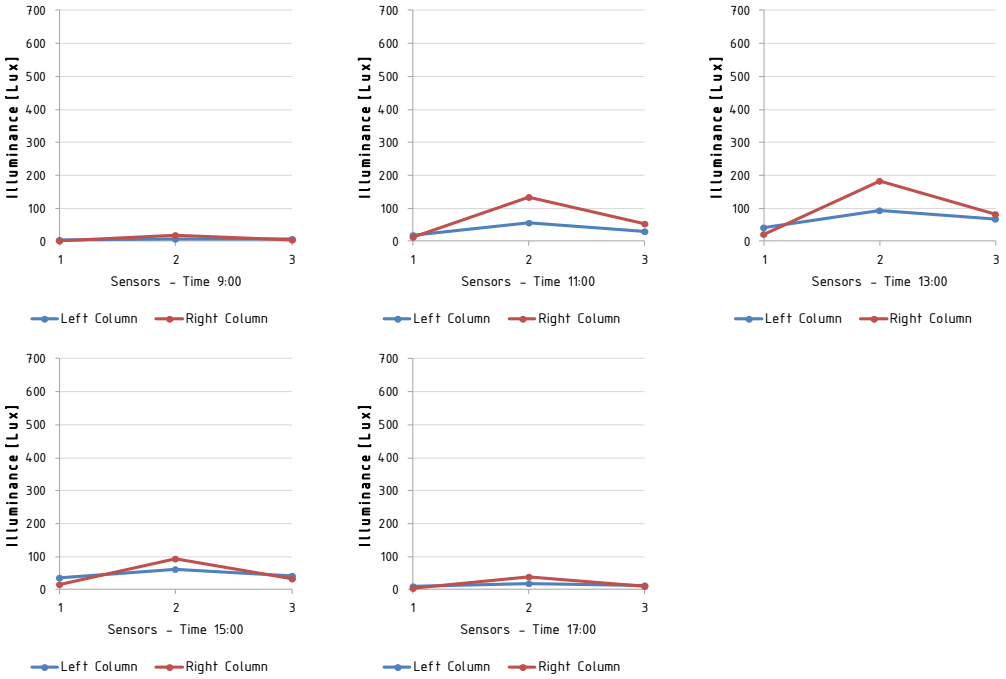

Figure 20. October 6th 2015. Partial sunny day with a Sunlight Incidence Angle at 47.19°. Solar Radiation Average from 9:00 to 17:00 was 578.33 W/m².

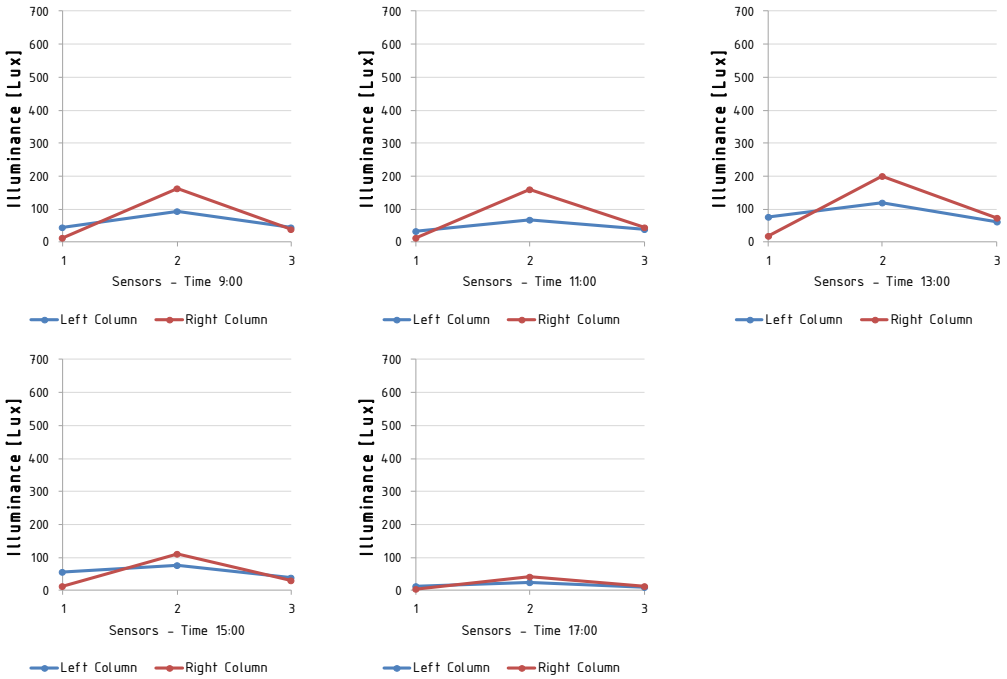

Figure 21. October 19th 2015. Partial sunny day with a Sunlight Incidence Angle at 42.34°. Solar Radiation Average from 9:00 to 17:00 was 564.35 W/m².

7. Test 3.4 – Lateral Left

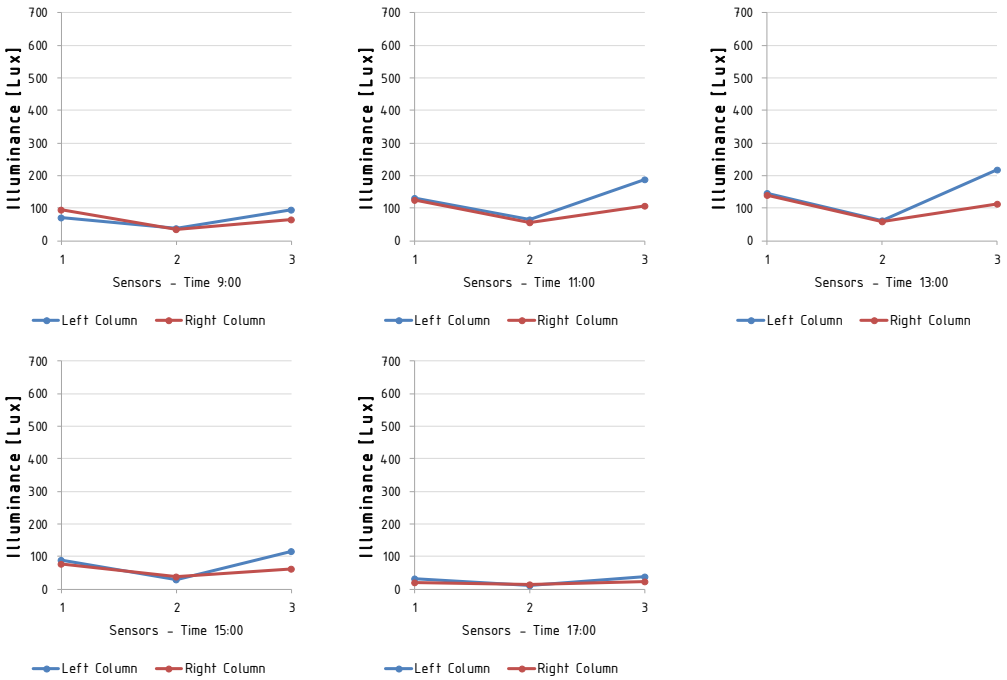

Figure 22. September 23rd 2015. Sunny day with a Sunlight Incidence Angle at 52.23°. Solar Radiation Average from 9:00 to 17:00 was 737.51 W/m².

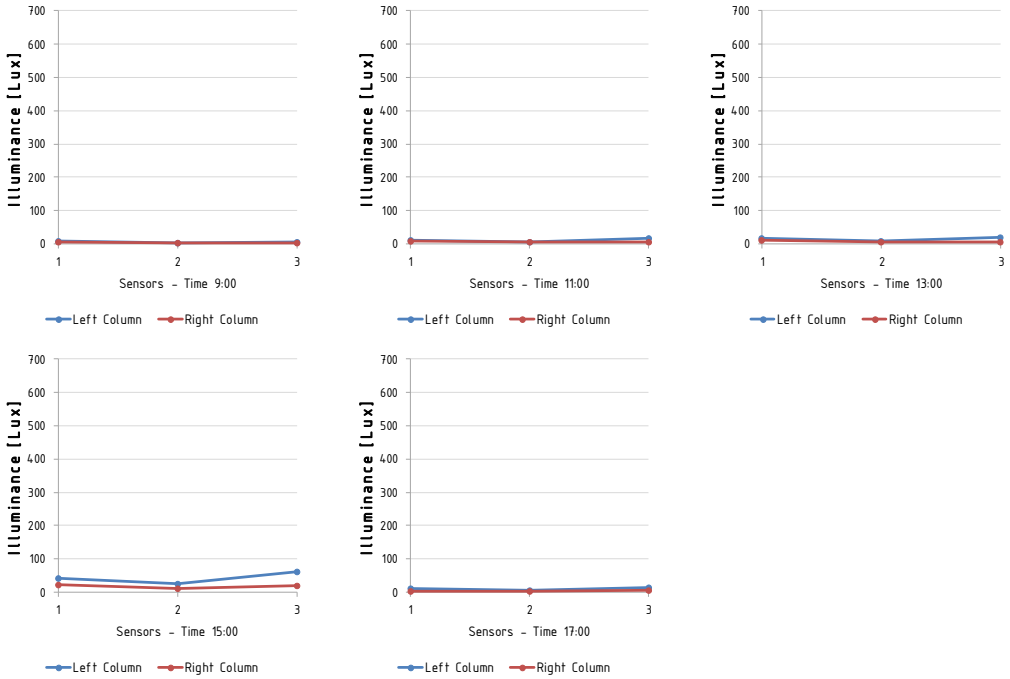

Figure 23. September 30th 2015. Cloudy day with a Sunlight Incidence Angle at 49.50°. Solar Radiation Average from 9:00 to 17:00 was 165.26 W/m².

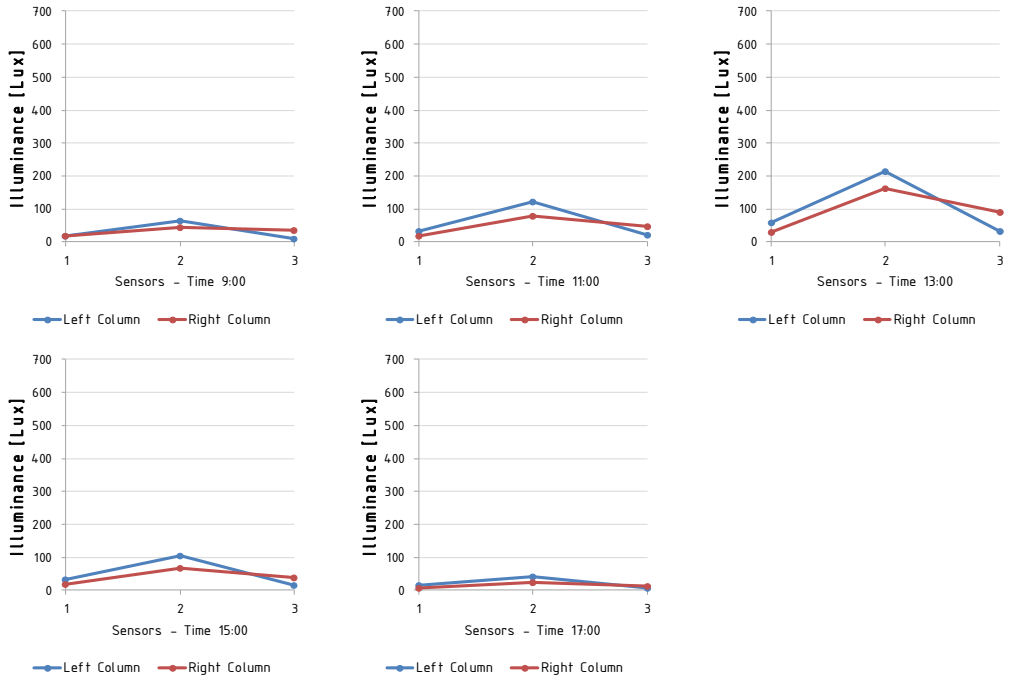

Figure 24. October 14th 2015. Partial sunny day with a Sunlight Incidence Angle at 44.17°. Solar Radiation Average from 9:00 to 17:00 was 542.16 W/m².