AN INNOVATIVE SYSTEM FOR DAYLIGHT COLLECTING AND TRANSPORT FOR LONG DISTANCES AND MIXING WITH ARTIFICIAL LIGHT COMING FROM HOLLOW LIGHT GUIDES

Authors ([1]):

Ph.D. eng Angelo Mingozzi
Eng. Sergio Bottiglioni

Ricerca & Progetto
Galassi, Mingozzi e associati
Ingegneria, architettura, ambiente
via di San Luca 11 - 40135 Bologna, Italia
Tel. + 39 051 6153800 – Fax. + 39 051 6156173
e-mail: studio@ricercaeprogetto.it

Arch. Roberto Casalone

A.L.C.S.
Advanced Lighting Consulting Services S.r.l.
Via Borgo 13 - 14034 Castello di Annone (AT), Italia
Tel. + 39 0141 401738 – Fax. + 39 0141 402728
e-mail: alcssrl@tin.it

Abstract (English):

Daylight is a basic element for visual comfort which is not a simple question of visual task performance satisfaction. As daylight is an irreplaceable source for life, health and human comfort, the possibility of conveying it into windowless spaces, or into spaces with inadequate traditional windows, opens up new potential for using places where the requirements for visual comfort are not completely satisfied. An innovative lighting system which combines daylight and artificial light, has been designed by Ricerca & Progetto - Bologna and A.L.C.S. – Asti, in the framework of the ARTHELIO project. The aim of this system, which is now installed in the 3M European Distribution Centre in Carpiano, near Milan, is to transport high quantities of daylight over long distances, at a good rate of efficiency, maintaining all its inherent positive properties and to combine it to artificial light, transported by hollow light guides and produced by an innovative sulphur lamp. The system focuses on visual comfort and, in the specific case of this application, it aims to restore visual comfort for the people who work in one of the distribution centre's storage areas whose only lighting is artificial, while also leading to a reduction in energy consumption.
Although it is very innovative, the system is based on the application of simple mechanical technology in order to reduce construction and maintenance costs. This is feasible because of the use of innovative materials which guarantee high collecting and transport efficiencies
The natural light is extracted separately from the artificial light in order to save daylight quality and ensure the positive physiological and psychological effects it has on people.
Overall system's performance is now under monitoring and people concerned has been interviewed in order to check system acceptance and comfort issues.
This solution is very suitable for applications in industrial building and has plenty of potential for use in all those types of buildings that have one dimension longer than the other and need daylight improvement and uniform artificial lighting to enable visual tasks to be performed throughout their interiors. Such building types, which include industrial and commercial buildings, car-parks and underground stations, are very common throughout Europe, this augurs very well for the possibility of replicating the system designed in other applications.

Sommaire (Français) :

La lumiere du jour est un élément de base pour le confort visuel qui n'est pas une simple question de quantité de lumière pour l'exécution d'une tâche, mais concerne aussi des aspects physiologiques et psychologiques, car le jour est une source fondamentale pour la vie, la santé et le confort. La possibilité de la transporter dans les espaces sans fenêtres, ou dans les espaces avec fenêtres traditionelles insatisfaisantes, ouvre un nouveau potentiel pour l'utilisation d'espaces où les conditions pour le confort visuel ne sont pas complètement satisfaisantes. Un

nouveau système d'éclairage, qui combine la lumière du jour et la lumière artificielle, a été conçu par Ricerca et Progetto - Bologna et A.L.C.S. Asti, dans le cadre du projet Européen Arthelio. Ce système, qui maintenant est installé chez 3M European Distribution Centre de Carpiano, près de Milan, est pensé pour transporter des quantités élevées de lumière naturelle sur de longues distances, de façon efficace et en conservant ses propriétés et, pour combiner la lumière naturelle avec la lumière artificielle, transportée par des guides optiques et produite par une lampe innovative au soufre. Le système se concentre sur le confort visuel et, dans le cas spécifique de cette application, il vise à restaurer le confort visuel pour les employés qui travaillent dans l'une des zones de stockage du centre de distribution dont le seul éclairage est artificiel, conduisant aussi à une réduction de consommation d'énergie. Bien qu'il soit très innovateur, le système est basé sur l'application de technologies mécaniques simples afin de réduire les coûts de construction et d'entretien. Ceci est possible en raison de l'utilisation de nouveaux matériaux qui garantissent de hautes performances de captage et de transport.
La lumière naturelle est éxtraite séparément de la lumière artificielle afin de sauvegarder la qualité de celle-ci et d'assurer les effets physiologiques et psychologiques positifs qu'elle a sur les personnes. Les performances du système sont à présent sous moniteur et les employés concernés ont été interviewés.
La solution adoptée est très appropriée aux applications dans les bâtiments industriels et a un potentiel élevé pour être utilisée dans tous ces types de bâtiments qui ont une difference importante entre la longueur et la largeur et ont besoin de lumière naturelle et d'un éclairage artificiel uniforme pour permettre d'exécuter les tâches visuelles dans tout l'espace. De tels types de bâtiments, qui incluent les bâtiments industriels, commerciaux, les parkings et les stations de métro, sont très communs dans l'ensemble de l'Europe.
Cette condition fait bien espérer sur la possibilité de reproduire le système conçu dans d'autres applications.

Zusammenfassung (Deutsch):

Das Naturallicht ist ein Grundelement fuer das visuelle Wohlbefinden, das sich nicht nur der Erfuellung von visuellen Aufgaben limitiert.
Da das Naturallicht eine unverzichtbare Bedingung fuer das Leben, die Gesundheit und das Wohlsein der Leuten ist, die Moeglichkeit, dasselbe in die Innenseite von eingegrabenen Raeumen oder mit traditionellen ungeneugenden Fenstern leiten zu koennen, gibt neue Wohnungsmoeglichkeiten und erlaubt, neue Raeume zur Verfuegung zu haben, wo ansonsten die Erfoerdernisse vom visuellen Wohlbefinden nich erfuellt werden koennten.
Im Rahmen der Aktivitaeten des Projektes „ARTHELIO" hat die Arbeitsgruppe – gebildet von Ricerca & Progetto – Bologna und A.L.C.S. – Asti – ein Erneuerungssystem von Beleuchtung eingestellt, welches das Naturallicht mit dem Kunstlicht zusammenstellt.
Das Ziel des System, welches z.Z. bei 3M European Distribution Centre in Carpiano (in der Naehe von Mailand) eingerichtet ist, ist :

- die Leitung grosser Mengen von Naturallicht fuer lange Entfernungen mit einem empfindlich hohen Ergebnis in der Beibehaltung seiner Qualitaet
- die Kombinierung desselben mit Kunstlicht aus Sulfidlampen mit Leitung durch optische Holschienen

Das System ist fuer das visuelle Wohlsein gedacht und im Falle der in Frage stehenden Einrichtungen hat als Ziel das Wohlsein der Arbeiter, die sich in einer Seite der Fabrik befinden, die z.Z. ausschliesslich mit Kunstlicht beleuchtet wird; somit wird man auch zur Energieersparnis beitragen. Obwohl es sich um ein stark Erneuerungsystem handelt, benutzt es relativ einfache mechanische Technologien, welche die Herstell- und die Betriebskosten einzuschraenken erlauben..Diese Bedingung ist durch die Benutzung von hoch innovativen Sondermaterialien ermoeglicht, welche ein hohes Ergebnis in der Sammlung und Leitung garantieren.
Das Naturallicht wird getrennt im Vergleich zum Kunstlist ausgezogen, um die Qualitaet unveraendert beizubehalten und dessen physiologische und psychologische Vorteile an Personen nicht zu limitieren. Die Ergebnisse und die Erwartungen dieses Systems werden z.Z. kontrolliert und die Arbeiter des Werkes sind interpelliert worden, um spezifische Informationen ueber die Genehmigung des eingerichteten Systems und die Vorteile des visuellen Wohlbefindens zu sammeln.
Das eingestellte System hat erhebliche Benuetzungsmoeglichkeiten in allen industriellen Gebaeuden mit den gleichen Eigenschaften wie bei 3M European Distribution Centre in Carpiano sowohl in Gebaeuden wo die Bautypologie eine anpassende naturelle Beleuchtung in den zentralen Raeumen nicht garantiert.
Solche Gebaeude, die auch diejenigen fuer Handelszentren – Industrie – Parkplaetze – eingegrabene Bahnhofe fuer Zuege oder U-Bahn usw einschliessen, sind in Europa sehr gewoehnlich; dies laesst demzufolge interessante Moeglichkeiten vorsehen, dieses System in anderen Anwendungen wiederholen zu koennen.

1. FOREWORDS

Daylight is a basic element for visual comfort which is not a simple question of visual task performance. Daylight has several positive influences on human physiology and psychology and provides an important means of receiving several environmental stimuli [1]. As daylight is an irreplaceable source of visual comfort, the possibility of conveying it into windowless spaces or into spaces with inadequate traditional windows opens up new potential for using places where the requirements for visual comfort are not completely satisfied.
The application of daylight transportation systems with high efficiency and low maintenance costs may have manifold applications in windowless spaces, creating great potential for using such spaces and for innovation in building typologies [2].
These systems may be used in all kind of spaces that do not communicate directly with the exterior. These spaces can be found in underground constructions, such as underground railway stations, or in buildings with a deep plan, like some building typologies for offices, multi-storey car parks, department stores and trading centres, etc..
In addition to meeting the requirements of visual comfort, the benefit to be derived from systems for natural light transportation are found in energy savings, both direct and indirect. These systems produce a direct reduction in the amounts of electricity consumed for lighting, with a reduction of the thermal gains in summer that are caused by the presence of light sources: the result is a reduction of the demand for energy used for cooling in summer. Indirect advantages include the possibility of using partially or completely underground spaces, which have a better thermal performance, as they offer higher resistance to heat transmittance. It is well known that significantly less energy is consumed for summer cooling and winter heating in these spaces than in common buildings.
Moreover, natural light transportation systems concur in solving the problem of daylighting compact building typologies with a low surface/volume ratio and are thus efficient from an energy point of view.
Up today many systems for daylight collecting and transportation are found all around the world [3]. State of the art shows a wide panorama of experiences and prototypes, sometimes very different one from the other, with different technology complexity and of course different efficiency.
Some new industrial products, mainly passive, are now also available on the market. Among them, systems provided with devices in the cupola which permit to redirect sun rays, increasing the efficiency, result of a great interests considering the favourable cost/benefit ratio [4].
The need for a systematisation of the knowledge on the subject and the aim to define design criteria, evaluation and simulation methods and measurement standardisation, convinced a group of experts to set up the Project ARTHELIO partially founded by the European Commission, to study, in a comprehensive way, the topic of daylight collecting, transport and mixing with artificial light.

2. "ARTHELIO INTELLIGENT AND ENERGY-OPTIMISED LIGHTING SYSTEMS BASED ON THE COMBINATION OF DAYLIGHT AND THE ARTIFICIAL LIGHT OF SULPHUR LAMPS"

ARTHELIO ([2]) is a three-year Project carried out in the framework of the Joule III – RES Non-Nuclear Energy Programme (Contract n. JOR3-CT97-0177). The project started on January 1998 and was successfully concluded on December 2000 [5].
Arthelio scored an important step about daylight transport knowledge, by defining design criteria, testing procedures, evaluation methods and by building up two prototypes suitable for two different building situations. The different working tasks are indicated in figure 1**.**

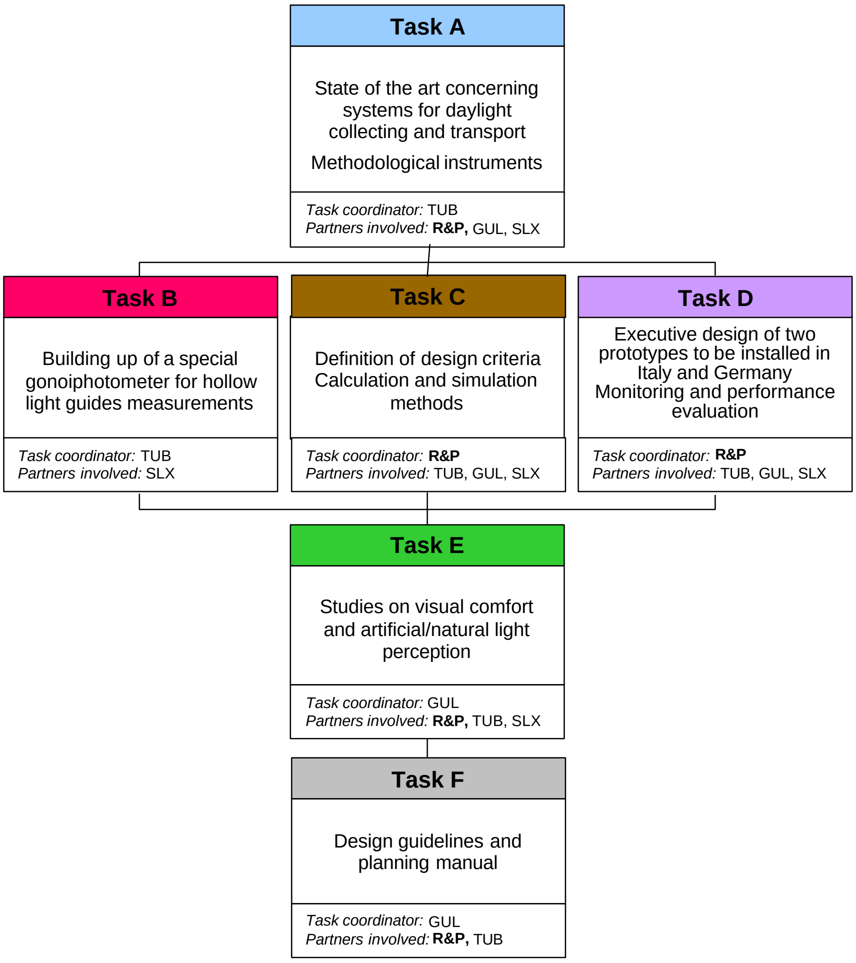

fig. 1: Arthelio project task layout.

The activities started with the definition of the state of the art. An accurate analysis of existing systems for daylight collecting and transport was performed, as well as the check of innovative products and materials and their classification according to different building typologies and inside activity. Aiming to provide measuring instruments an innovative Goniophotometer was built at the Technical University of Berlin. The goniophotometer is the first today available for measuring the spatial light distribution of hollow light guides (fig. 2).

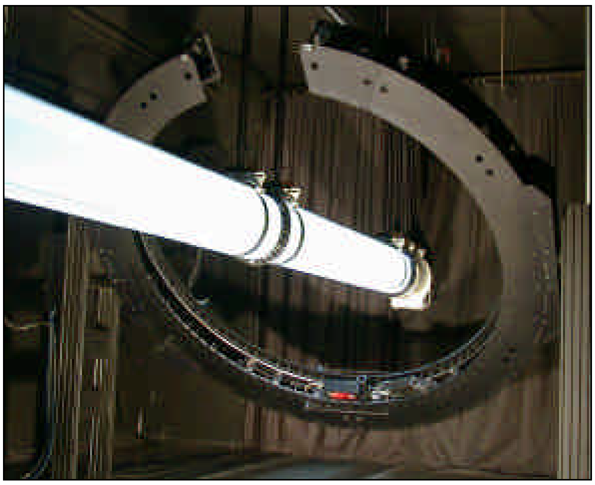

fig. 2: First goniophotometer for measuring the spatial light distribution of various hollow light guides (TUB, Berlin).

Studies on visual comfort and artificial/natural light perception were also performed using a 1:1 scale testing room by means of measurements and interviews

A system for daylight collecting and transport may be divided into three main functional units: "collecting head unit", "duct unit" and "diffuser unit". In order to evaluate the efficiency and the performance of the different components according to their dimensions, shape, lining materials, etc. different scale models (1:5 scale) were built up and performances were measured for a whole year, under real sky conditions and also using an artificial sky. In parallel, performances were evaluated through mathematical calculation methods and software simulations. The whole results made possible to define criteria and simplified tools for system design. On the basis of the achieved results two different prototypes, optimised for two different building typologies, were designed and installed in Italy and Germany [6] (figure 3, 4). The performances were monitored and users were interviewed to execute acceptance studies and to check comfort results.

At last a planning manual and design guidelines for architects were conceived for a correct use and application of the designed systems.

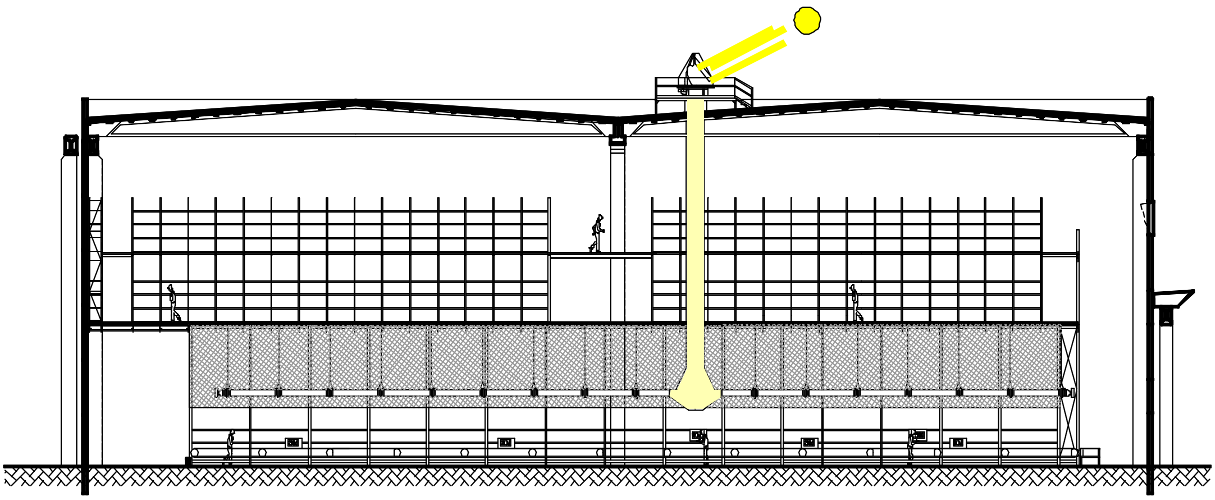

fig. 3: System with mobile collecting head unit (one axis rotation): daylight transport for about 13 meters and extraction in a defined position; combination with artificial light coming through lightpipes. System is installed in 3M EDC Carpiano, Milano (design: Ricerca e Progetto, Bologna; ALCS, Asti).

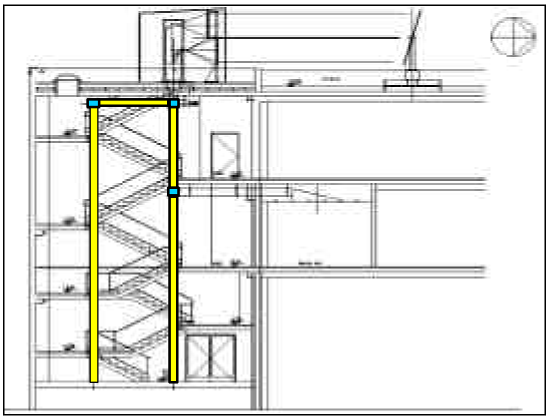

fig. 4: System with movable collecting head unit (two axis rotation); natural and artificial light integration and extraction in the same lightpipe. System is installed in Semperlux AG headquarter, Berlin (design: Technishe Universistat Berlin; Semperlux, AG; Ricerca e Progetto, Bologna; ALCS, Asti).

3. AN INNOVATIVE SYSTEM FOR DAYLIGHT COLLECTING AND TRANSPORT FOR LONG DISTANCES AND MIXING WITH ARTIFICIAL LIGHT COMING FROM HOLLOW LIGHT GUIDES

An innovative lighting system, which combines daylight and artificial light, has been designed by Ricerca & Progetto - Bologna (engineers Angelo Mingozzi Ph.D., Sergio Bottiglioni, Giovanni Fini Ph.D.) and A.L.C.S. – Asti (architect Roberto Casalone), in the framework of the ARTHELIO project.

The aim of this system (Fig. 5), which is now installed in 3M European Distribution Centre in Carpiano, near Milan, is to transport high quantities of daylight over long distances, at a good rate of efficiency, maintaining all its inherent positive properties.

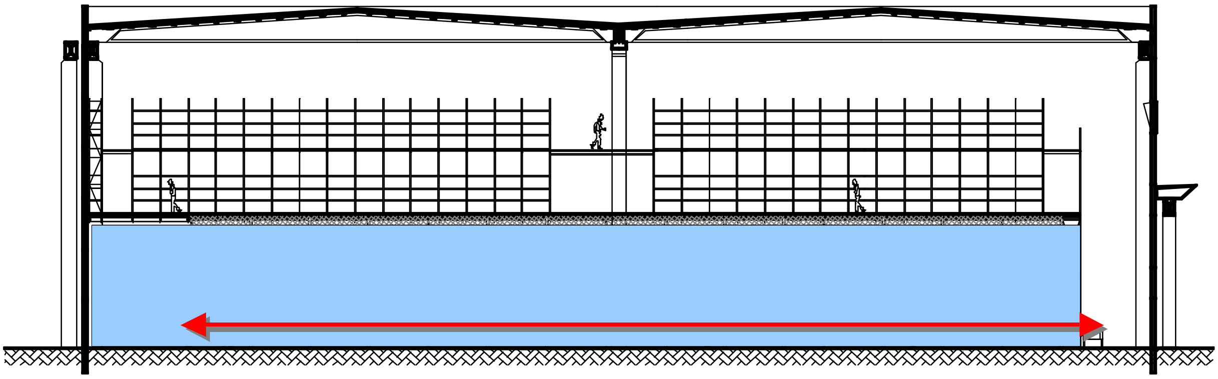

fig. 5: Design targets: provide daylight in a storage area only artificially lit and provide uniform lighting.

Referring to the existing classification of such systems, the one in Carpiano is of the movable collecting head unit system type with a single rotation around vertical axis.

In order to target high performances, an innovative solution was added, introducing simple mechanics for rotating the collecting head unit (fig. 6).

fig. 6: Collecting head unit.

In accordance with the programme of activities in the Arthelio project, the design process was undertaken as a series of steps:

- analysing the state of the art, including various surveys, on-site inspections, interviews, examination of literature and a study of other research projects on the topic;
- constructing scale models of the collecting head unit (1:5);
- performing mathematical simulations in parallel with measurements, carried out both in real conditions and using artificial sky facilities;
- constructing a 1:1 scale model of the final collecting head unit; undertaking design, measurements and mathematical simulations (sensitivity analysis) aimed at optimising the chosen solution.

The system focuses on visual comfort and, in the specific case of this application, aims at restoring visual comfort for the people who work in one of the distribution centre's storage areas, where the only lighting is artificial. In this working area, people pick up boxes from the shelves and place them on a conveyer belt, which conducts the boxes to the loading area. Visual tasks are thus performed in a large sector, a condition that requires uniformity of illuminance in the working area, in addition to an increase in visual comfort brought about by means of daylight.

The system combines daylight transport, whose general aim is to guarantee visual comfort, with an artificial lighting system, whose specific aim is to provide uniform illumination in the working area. As mentioned, the aim of the daylight transport system is to keep illumination at the quality of daylight, so that it can be felt to be natural, providing an important link to outdoors and especially providing awareness of the passing of time and of changes in the weather, both of which are basic elements for visual comfort.

4. SYSTEM FUNCTIONAL UNITS

An innovative solution was introduced, which combines simple mechanics for collecting head unit rotation and aims to obtain high performances. In this way, while keeping mechanical technologies simples the needs for maintenance are reduced. This is possible using special materials and innovative technologies

The system to be installed in Carpiano is made of the following functional units (Fig. 7). The daylighting part is composed of single axis rotation **collecting head unit,** a circular cross section **duct** and a **diffuser**. The artificial lighting part is composed by two **sulphur lamps** and two **hollow light guides**; both parts are connected. Luminous flux emitted by the sulphur lamps and the management of the artificial and natural light mixed quantities is regulated by an **artificial control system**. This includes illuminance and sensors which allow the regulation of moving valves and mirrors and people detection sensors which regulate the sulphur lamp flux dimming.

1. **Collecting head unit (single axis rotation)**
2. **Duct unit (L @ 13 m)**
3. **Diffuser unit**
4. **Sulphur lamps**
5. **Hollow light guides**
6. **Coupling and diffuser unit**
7. **Electronic control system to manage integration between daylight and artificial light**

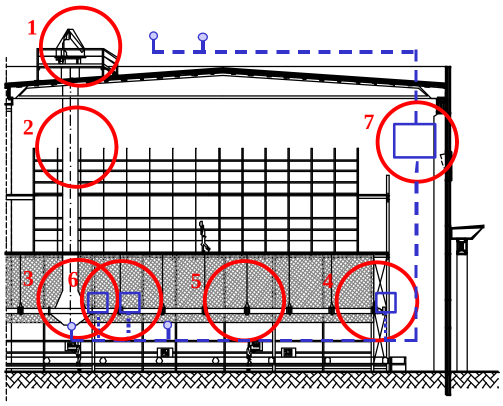

fig. 7: System functional units.

5. DESIGN AND TECHNICAL CHOICES (SPECIAL MATERIALS, COMPONENTS, TECHNOLOGY)

Although it is very innovative, the system is based on the application of simple mechanical technology in order to reduce construction and maintenance costs: this is possible by the use of special materials. An innovative concept is used for the daylight **collecting head unit**, which is the functional unit with the greatest responsibility for the quantity of daylight collected [7]. Using a Fresnel lens (3M-21X), a collecting head unit can be built so tracks the sun efficiently with only a single rotation around a vertical axis (fig. 8). This is feasible because of the 21X lens acceptance angle, which enables the sun's rays to be focused for almost every sun elevation angle resultant from the typical sun path at the latitude of installation. Focused rays are reflected by an anidolic mirror surface into the vertical duct, as close as possible to its axis (fig. 9). The anidolic surface has a special shape in order to allow daylight diffuse component captation, as much as possible.

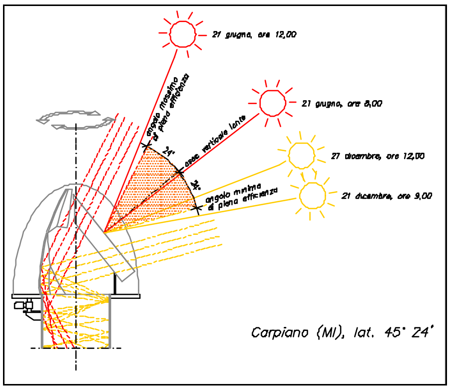

fig. 8: Collecting head unit: sun's rays are focused for almost every sun elevation angle.

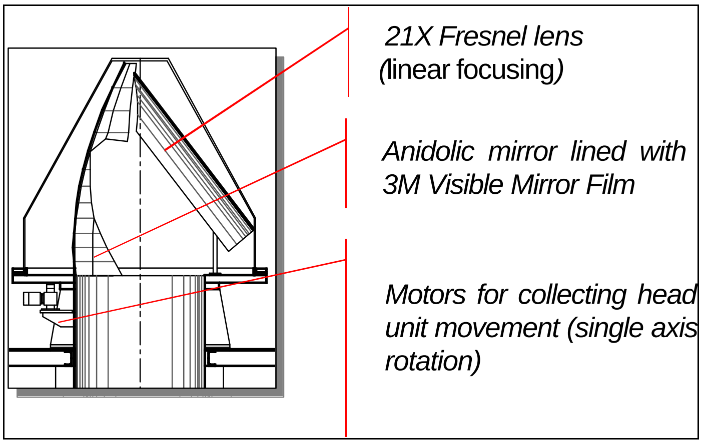

fig. 9: Collecting head unit functional units.

The **duct** for daylight transportation, has a circular cross-section with a 90 cm diameter and an overall length greater than 13 m (Fig. 10). The duct is lined with 3M Visible Mirror Film, a highly reflective Multi-Layer Polymeric Film. Luminous Reflectivity can be higher than 99% (Fig. 11).

fig. 10: Duct unit (D = 90 cm, L ≈ 13 m).

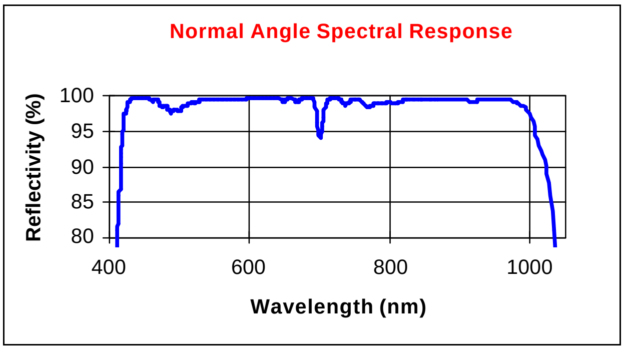

fig. 11: 3M Visible Mirror film: luminous reflectivity spectral response.

The **diffuser** unit located at the end of the duct extracts daylight with the aim of maintaining its quality. Because of the very large working area it wasn‘t possible to distribute the daylight collected in all the area. For this reason the idea was to concentrate the daylight extraction by creating a diffuser unit that could give the impression of a window even if it is far 15 m from the roof. This diffuser lights up naturally an area of about 14 square meters. The diffuser unit has a special shape which allows the natural light to be seen even from a great distance, obtaining important psychological stimulation and feeling of relation with the outside (fig. 12).
The unit is also connected to the artificial lighting system, which comprises horizontal **hollow light guides** (3M lightpipe) with **sulphur lamps** (Sulphur lamp Light Drive 1000 dimmable with an electronic ballast) as the light source (fig. 13). This artificial system provides uniform illuminance throughout the working area, integrating the daylight as a function of its reduction as the day progresses and outdoor meteorological conditions change.
A sophisticated **electronic control system** comprising sensors and motors enables the quantity of the artificial light extracted by the HLG and the quantity and direction of the light that integrates the daylight when this is not sufficient. Dimmers fitted to the sulphur lamps contribute to save energy dimming the light flux according to working presence. Dimming is automatically regulated by presence sensors.
The artificial system controls daylight integration according to daylight as a function of its reduction as the day progresses and outdoor meteorological conditions change.

fig. 12: Diffuser unit.

fig. 13: Coupling unit with hollow light guides.

When daylight amount is sufficient the natural light is extracted separately from the artificial light in order to save daylight quality (luminous spectrum, incoming direction, etc.) and ensure the positive physiological and psychological effects it has on people; during the night artificial light backs up lack of natural light (Fig. 14). Coupling system unit controls the amount and incoming direction of artificial light which integrates the natural one. Particularly, according to external meteoclimatic conditions, controlled by means of illuminance and luminance sensors, valves and shutter of the coupling system can manage intermediate situations and allow only a little amount of artificial light to enter in the coupling system module and not in the diffuser (Fig. 15).

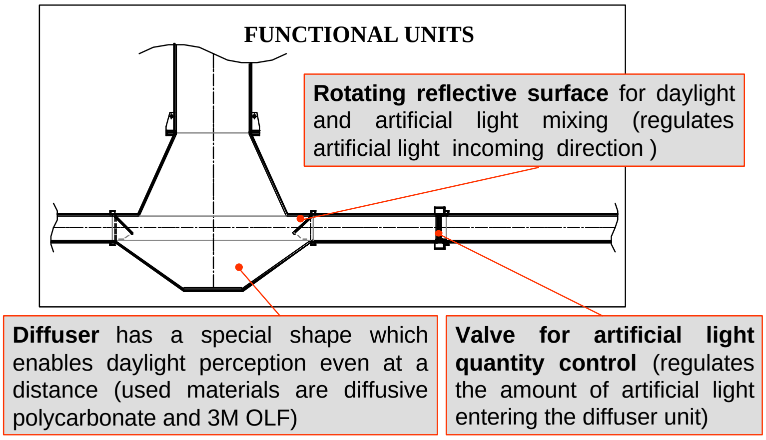

fig. 14: Diffuser functional units.

fig. 15: Diffuser and coupling operation at night and during the day.

6. TESTING AND MONITORING

Once installed, the overall system's performance has been monitored by measuring the lighting and by interviewing the people concerned.

The aim of the monitoring is to have an overview of the overall system performance and to collect data which can be used to evaluate energy savings and comfort issues.

In the storage area lighting has to guarantee:

- security to prevent accidents;
- good visibility according to the visual task;
- overall visual comfort conditions.

According to Italian UNI 10380 that area requires an illuminance level of 150/200 lux, measured on the conventional working plane (height 0,75 m from the floor). This because the space it's not continuously used. In any case the visual task implies that workers have to read numbers on the stored packages etiquette and so it was decided to increase the average illuminance value. This also because the dimming capability of the lamp allows to change luminous flux according to people presence. The uniformity factor should be greater than 0,8 and it is measured as the ratio between minimum illuminance value and mean illuminance value. The quality of daylight has to be maintained.

The testing of the prototype installation has been performed with remote controlled measurements and data storing of both the outdoor (daylight input) and indoor (daylight and artificial light output) light situations. The measurement system has been built up according to the following demands: measuring precision (the measurement components have to keep the criteria of the standard DIN 5032 class C): easy transportable and fast build up, simple operation, flexibility (increasing/decreasing of sensors) and software for data storing with time and date in ASCI-format. According to the above mentioned requirements the consortium decided to built up measurement components. Different types of sensors (illuminance, luminance, voltage) transfer the digital converted data to an evaluation box. The digital data conversion allows to transport the data over long distances without transfer flaws. The evaluation box stores the data with date and time. The reconverted data (ASCI-Format) are transferred directly to the COM-Port of a computer.

In order to have a complete overview of the system performance 18 light measuring sensors were installed.

The horizontal illuminance level in the height (0.75 m) of the working plane (conveyor belt) is measured by 12 illuminance sensors. The modelling of faces and objects is influenced very much by the vertical illuminance which is measured by 3 vertical illuminance sensors in the height of 1.6 m. The glare of the daylight output areas of the diffuser module is controlled by 2 luminance sensors. The dim level of the sulphur lamps is measured by voltage sensors and allows to evaluate the information concerning energy saving and presence of workers. The outdoor illuminance level is very important for the calculation of the daylight luminous flux collected by the heliostat and gives additional information about the weather conditions. A special outdoor illuminance sensor is placed horizontally on the roof near the heliostat. So the system efficiency could be estimated.

Special questionnaires were prepared to interview the workers and specialists persons in order to evaluate the system acceptance level and to check the increasing of comfort. The questionnaire is concentrated on the rate of agreement to a number of statements. The statements cover three principal areas; daylight, description and comfort. The first area is maybe of the greatest importance establishing people attitudes towards daylight and its influence in this room. The second area is mostly descriptive even if there are normative values in the questions about glare and "normal colour". This part is mostly a reference for how the respondent perceives the light. The third part tries to determine the comfort aspects and it is completely normative.

7. EVALUATION OF THE TEST RESULTS AND DETERMINATION OF THE FINAL SYSTEM PERFORMANCE

At the date of the paper the monitoring has been performed only for the winter season. Preliminary results which can be also give information for the other seasons are described below.

Sulphur lamp control

According to the sulphur lamp dimming control we have two artificial lighting illumination scenarios (obtained by the sulphur lamp dimming capability):

- when no people are in the area: reference illuminance is 180-190 lux. The illumination is necessary because of security purposes. In this case the amount of light is comparable to lighting levels in the other range of shelves;
- when people is working in the area: reference illuminance is 270-290 lux.

Figure 16 shows the illuminance level under the lightpipe in a typical working days with overcast sky. Sensor n. 12 is positioned by the conveyor belt and is not affected by natural lighting conditions.

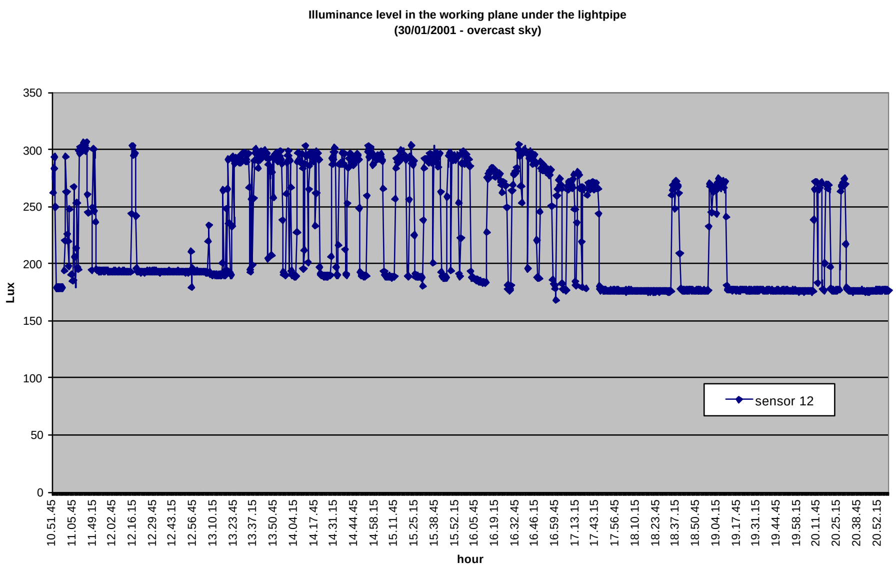

Fig. 16: Illuminance level under the lightpipe in a winter overcast sky day (Upper levels means sensors have detected persons in the area and sulphur lamps are dimmed up; low levels means nobody is there).

Daylight artificial light mixing control

Shutters and valves aim to control the daylight and artificial light mixing. Some tests were performed during a clear sky day (20/02/2001 from 14.45 to 15.00), aiming to check the effect on horizontal illuminance value due to different combination of mixing unit valves positions. The results are shown on figures 17 and 18.

Horizontal illuminance

During daytime, when the contribution of daylight extracted from the diffuser is sufficient, shutters and valves are automatically closed, to keep separated natural and artificial light

extraction in order not to affect daylight perception. In this case the illuminance under the diffuser is only due to natural light contribution. The illuminance in sensors n. 1/2 and n. 6/7 (located under the mixing unit) shows that there is a separation between natural and artificial light. This seems to be an optimal situation for daytime. In the same graph we can see that there is a quite good uniformity of artificial light distribution under the lightpipe (from 200 to 260 lux within a distance of about 10 m).
When the shutters are opened and valves are closed the mixing unit is artificially lit and no artificial light is allowed in the diffuser. In any case the illuminance level measured in sensors n. 4/5 (located under the diffuser) increases because of the artificial light contribution. The uniformity under the whole lightpipe included the mixing unit is acceptable and the illuminance under the light pipe is quasi not affected.
When all the valves are opened the illuminance under the diffuser is higher because of the integration of artificial light. Sensors n. 6/7 measures a higher value too, because the artificial light coming into the diffuser is reflected by the mirrored valves in that direction.
At night a theoretical illuminance level can be estimated by reducing to the artificial light, the contribution of daylight.

According to design objectives, in order to provide information and psychological stimulation to the workers, the diffuser luminance and related illuminance level measured under it (sensors n. 4/5) have to be related to outdoor daylight availability and for this reason they are supposed to change during the whole day (Figures 19 and 20). At night, the artificial light extracted from the diffuser provides more light in the areas which are besides the diffuser while under it, the illuminance level is reduced but still enough for security purposes (140 lux). If we consider the uniformity factor on the horizontal plane for the measured values, without calculating the contribution of daylight, which on the purpose of design is changing according to outdoor conditions, we obtain the results of the following table.

Scenario	Minimum (lux)	Mean (lux)	Uniformity factor
shutters and valves opened	203	253	0,80
shutters opened and valves closed	210	230	0,91
shutters and valves closed	151	200	0,76
theoretical by night (without daylight contribution)	198	220	0,90

Uniformity factor is lower than 0,8 only in the case of shutters and valves closed. In this case the overall illuminance measured on sensors n. 1/2 and n. 6/7 is kept lower because, as already said, we want to maintain separated artificial and natural light, when this last one is enough. In any case the value of 0,76 shows an acceptable uniformity lighting level.

Vertical illuminance

Vertical illuminance is measured in the same conditions of the different artificial/natural light combination described before. The results are shown on figure 18.
If we consider the uniformity factor on the vertical plane, for the measured values, we obtain the results of the following table.

Scenario	Minimum (lux)	Mean (lux)	Unifo rmity factor
shutters and valves opened	170	192	0,88
shutters opened and valves closed	153	167	0,91
shutters and valves closed	113	173	0,65
theoretical by night (without daylight contribution)	142	155	0,92

Uniformity factor is lower than 0,8 only in the case of shutters and valves closed. In this case, as explained before, the illuminance reduction under the connection between natural and artificial light is an objective of the design in order to maintain separated the two fluxes.

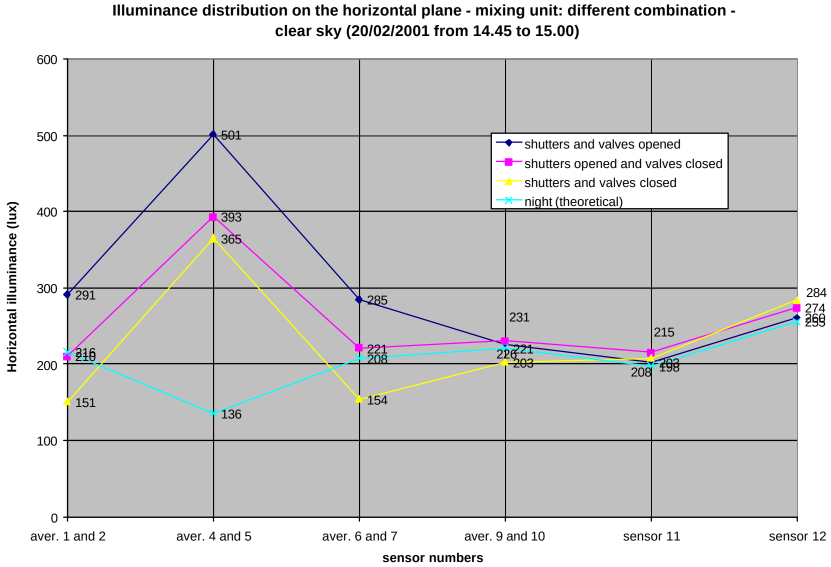

Fig. 17: Illuminance values in the working plane (for location refer to figure 21):

- sensors 1 and 2 are located under the diffuser rotating valve (left)
- sensors 4 and 5 are located under the diffuser
- sensors 6 and 7 are located under the diffuser rotating valve (right)
- sensors 9 and 10 are located under the mixing unit
- sensor 11 is located under the lightpipe close to the shutter
- sensor 12 is located under the lightpipe in a middle position

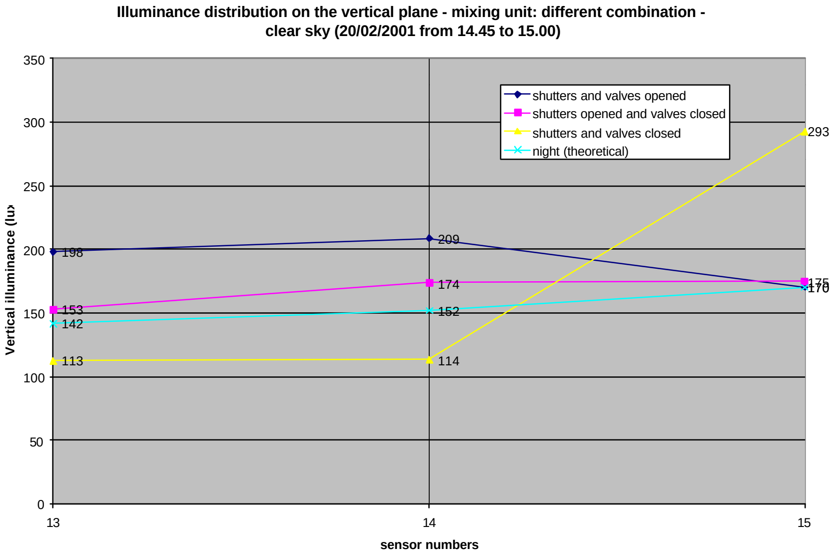

Fig. 18: Illuminance values on the vertical plane (for sensor location refer to figure 21):

- sensor 13 is located under the diffuser rotating valve (left)
- sensor 14 is located under the diffuser rotating valve (right)
- sensor 15 is located under the lightpipe in a middle position

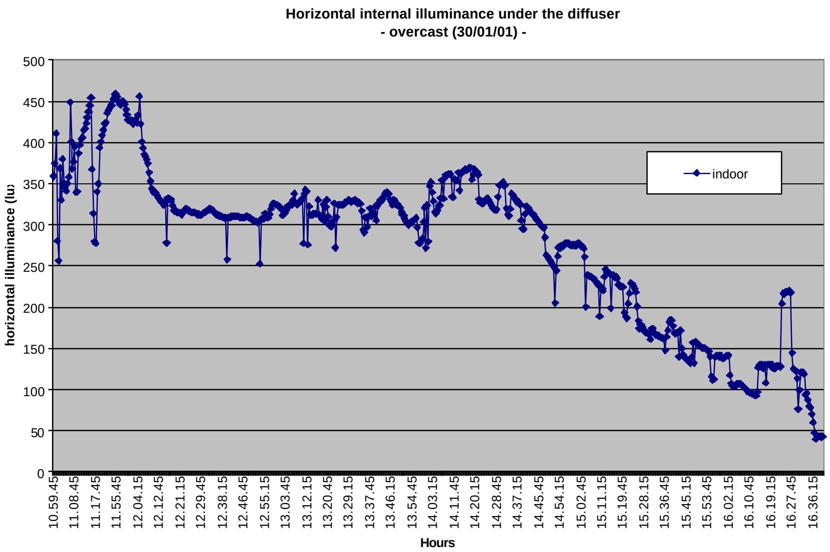

Fig. 19: illuminance levels due to natural light measured under the diffuser in a typical overcast sky day.

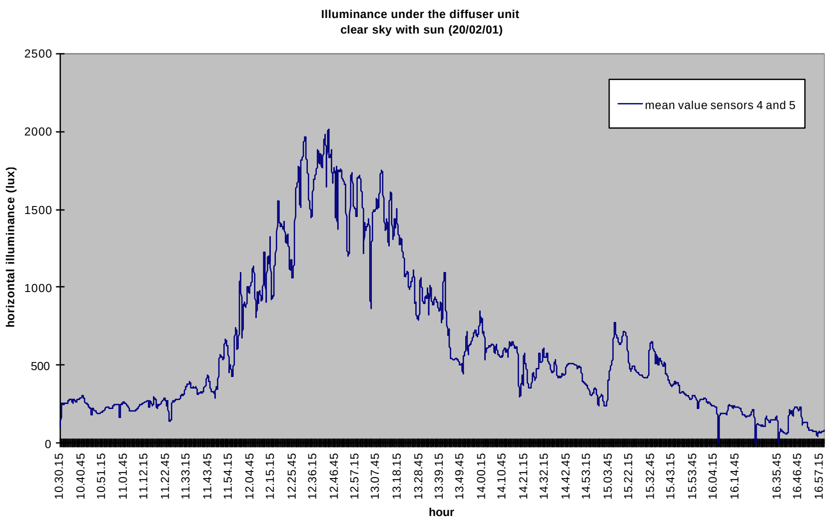

Fig. 20: Illuminance levels due to natural light measured under the diffuser in a typical clear sky day.

Daylight factor and efficiency

Daylight factor evaluated under the diffuser in the working plane gives an overview of the efficiency of the system.
The Italian regulation requires an average DLF > 2% in living places (bedrooms, offices, etc..). In this case a DLF between 1 and 1,5% could be sufficient.

Mean DLF evaluated in 2 points in the natural lit area during a clear sky day and an overcast sky day shows values higher than 2% (Figures 20 and 21). This makes suppose that there is a quite large area in which mean DLF is in the defined range and in which we have the impression and benefit of daylight. This consideration is supported also by spot measurement which have helped to understand daylight distribution.
System efficiency was evaluated through monitoring and spot measurements during defined sky conditions.
During overcast sky condition, average illuminances measured in the diffuser output was 890 lux and in an unobstructed horizontal position outside it was 11000 lux. This gives the

efficiency of the system which is 8% supposing an overcast sky (with uniform luminance distribution). In the working plane daylight factor was higher than 2%.
During clear sky condition, the efficiency is dependent from the hour and the date of the year, because even if the focus acceptance angle is fitting with every sun elevation in Carpiano (excluded elevations under 15°), the focusing line is changing position.
At 12.30 of the 20/92/2001 it was evaluated an efficiency of 55%, which means that 55% of the collected light flux (sunrays passing through the lens in a defined time) is extracted from the diffuser 20 m down the building.
This value is representative of the winter efficiency, even if the incoming sun rays in that hour were very close to the lens axis and as consequence the efficiency for sun with lower elevation should be a little reduced. During other seasons the efficiency should be a little bit higher because when sun elevation increases, a good rate of the incoming sun rays are in most of the cases entering straight into the duct and number of reflection before the extraction are reduced.

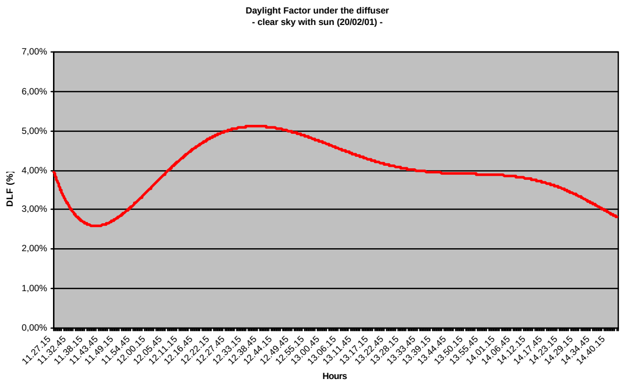

Fig. 21: Mean Daylight Factor evaluated in 2 points under the diffuser in the working plane in a clear sky condition.

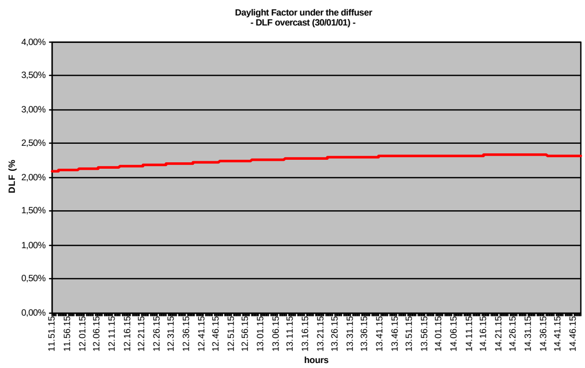

Fig. 22: Mean Daylight Factor evaluated in 2 points under the diffuser in the working plane in an overcast sky condition.

8. ENERGETIC EVALUATION

Energy savings can be calculated for different situations:
- savings due to the use of natural light;
- artificial lighting installation with 2 HLG's and 2 sulphur lamps more efficient than previous fluorescent tube installation comparing to the same illuminance level on the working plan;
- savings due to sulphur lamp dimming according to people presence sensors.

- Energy savings due to the use of natural light

  The system lights up naturally an area of about 14 square meters of floor for an average time of 6 hours per day for a whole year. This corresponds to 0,5 kWh of energy savings per day compared to the Carpiano fluorescent tube installation. Considering that the Distribution centre is operating all the year this means 182,5 Kwh per year of electrical energy savings.

- Energy savings due to the artificial lighting installation with 2 HLG and 2 sulphur lamps more efficient than previous fluorescent tube installation

  The installation is more efficient than previous fluorescent tube installation, comparing to the same illuminance level on the working plan.

If we compare the real consumption for a typical working day (including sulphur lamp dimming) and the consumption we would get with fluorescent lamps we get an energy saving of 42%.

- Energy savings due to the possibility of dimming artificial light

  The possibility to dim artificial light according to the presence of workers in the lit area allows saving energy when nobody is present in the area lit by Arthelio system.

  The average presence of workers is of four hours a day and considering that when nobody is present artificial light is dimmed to 25% of its power, energy savings can be calculated as follows.

  Terms of comparison:

  - Non dimmable system: two HLG work on 24 hours per day with Sulphur lamps dimmed at 80% of their power (not considering natural light),
  - Arthelio system with dimmable lamps: lights are dimmed at 8% of their power for about 20 hours a day.

  This means that for spaces with non-continuous use achievable energy saving is about 67%.

  This value obviously decreases according to longer permanence periods of workers in the lit space.

9. CONCLUSIONS AND POTENTIAL FOR FUTURE APPLICATIONS

Daylighting systems require a specific design, which is very profoundly related to the geographical context where the installation is to be made. This depends on artificial and natural obstructions outdoors, target levels of visual comfort, climate, etc..

Nowadays, the use of special materials with a high light transmittance and reflectance performance has produced efficient final results, increasing the potential for future applications.

The system defined in the framework of the ARTHELIO project, to be installed in Carpiano, near Milan, has simple mechanics for rotating the collecting head unit, due to the use of the Fresnel lens. This enables a performance comparable to sun-tracking systems to be achieved, while reducing construction and maintenance costs.

This solution is very suitable for applications in industrial buildings and has plenty of potential for use in all those types of buildings that have one dimension longer than the other and need daylight improvement and uniform artificial lighting to enable visual tasks to be performed throughout their interiors. Such building types, which include industrial and commercial buildings, car-parks and underground stations, are very common throughout Europe, which augurs very well for the possibility of replicating the system as designed for future applications.

Any cost-benefit analysis related to the system as defined must include comprehensive consideration of both energy savings and the possibility of space utilisation in which visual comfort targets are not satisfied.

For instance, the advantages of this solution must be related to the increase in visual comfort in underground buildings which are very energy-efficient in terms of very low thermal losses and visual impact, but are not efficient in terms of human comfort. Today's health regulations restrict the possibility of using underground spaces for working purposes for this reason. The possibility of introducing visual comfort could bring new possibilities of space utilisation.

Results carried out within the ARTHELIO project have enabled the different design variables to be classified systematically and defined as an important knowledge base for future applications.

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NOTES:

(1) Authors of the chapters are:
Chapter 1 (A. Mingozzi, S. Bottiglioni, R. Casalone)
Chapters 2, 3, 4 and 5 (A. Mingozzi)
Chapters 6, 7, 8 and 9 (S. Bottiglioni)

(2) The partners who took part of ARTHELIO Project are:

- **Technische Universitat Berlin** (TUB): the team is composed by Prof. Heinrich Kaase and eng. Thomas Mueller.
  TUB is responsible for tasks A and B.

- **Ricerca & Progetto** Galassi, Mingozzi e associati, Bologna (R&P): the team is composed by Ph.D. eng. Angelo Mingozzi, eng. Sergio Bottiglioni, Ph.D. eng. Giovanni Fini and Roberto Casalone.
  R&P is responsible for tasks C and D.

- **Semperlux AG** – Berlin (SLX): the team is composed by Dr. Dieter Albert and Dr. Paul Schmits.

- **Goeteborg University** (GUL): the team is composed by Prof. Jan Ejhed and arch. Gerhard Rehm.
  GUL is responsible for tasks E and F.