Integrated performance simulation of an innovative net zero energy modular building

Francesco Fantauzzi – M.Sc. Student, University of Perugia – ffantauzzi@hotmail.it
Paolo Belardi – DICA, University of Perugia – paolo.belardi@unipg.it
Francesco Asdrubali – CIRIAF, University of Perugia – francesco.asdrubali@unipg.it
Samuele Schiavoni – CIRIAF, University of Perugia – schiavoni.unipg@ciriaf.it
Sara Sambuco– CIRIAF, University of Perugia – sambuco.unipg@ciriaf.it

Abstract

Currently the value and the appeal of a house are deeply influenced by its own energy performance and its comfort. As a consequence, several examples of net zero energy buildings have been realized worldwide in the last decade, using renewable energy sources for their moderate energy consumption. An architectural experiment of this kind of buildings is represented by shipping container houses that could be used not only in emergency situations but also as alternative guestrooms or also low-cost houses. The paper presents the results of software simulations carried out to evaluate the energy and lighting performance of three kinds of shipping container houses characterized by different floor areas and usage. The bigger one is a typical shipping container having a surface of about 14 m² and a height of 2.4 m; the others have the same height but smaller surfaces, respectively of about 7 and 5.6 m². The furniture was designed to be moved thanks to upper runners in order to use the same area for different domestic activities during the day. Each one of them was planned to be a net zero energy building obtaining energy from solar panels and clean water from rainfall. The lighting design was carried out using DIALux while energy performance was studied through Energy Plus. The first one allowed us to optimize the selection and the position of LED lighting systems in order to assure the recommended values of the Illuminance E. Moreover, some graphical renderings were realized in order to have a clear and simple evaluation of the visual performance of the internal spaces, also taking into account the contribution of daylighting. The characteristics of the lighting systems were used for the evaluation of the whole energy performance of the building. Energy Plus is the dynamic simulation software used to determine the energy demand of each container, taking into account the heating and cooling facilities, the insulation properties of the building envelope, windows and doors included. The results of this theoretical study show that this solution is technically feasible, cheap and also comfortable not only for emergency housing.

Introduction

The global economic crisis has also affected the maritime freight in the EU-28. Eurostat shows that European ports in 2012 handled only 3,739 million tonnes of seaborne goods, respectively 0.8% and 6% below 2011 and 2008 data (Eurostat, 2014). Consequently, a large quantity of containers lies idle in port areas occupying spaces and causing disposal issues. The large availability, lightness and portability of these elements make their usage suitable for housing.

Several projects are currently focused on recycling these facilities as buildings; some examples are presented in (Container City, 2014) and in (Designboom, 2014). The challenges in using containers for residential purposes are to define the best thermo-insulation materials and to design the systems able to guarantee a comfortable indoor quality and wellbeing conditions. An example of a zero emission house made using containers was designed and monitored by Dumas (Dumas, 2014): in this case the indoor air conditioning is obtained using geothermal water. The scope of the present paper is to describe the thermal and lighting simulations performed to improve the indoor quality performance of temporary residential solutions realized using shipping containers. These were designed to be net zero energy building (Sartori et al., 2012) considering the best available technologies and the advanced predictive control schemes (Kolokotsa et al., 2011).

2. Case study description

2.1 Shape and function

Standard ISO shipping containers are 2.44 x 2.59 x 6.10 m. Three case studies were analysed: XXS (equal to one third of the container, 5.6 m²), XS (half, 7.0 m²) and S (Fig. 1 and Fig. 2, a complete one, 14.0 m²). Since a small amount of surface is available, furniture configuration can be changed by users according to their needs. This particular type of furniture required a blind wall. Obviously, the connections with the water supply network and electricity grid are unmovable. Special rails are installed on the container’s ceiling to permit the sliding of the furniture. Their small sizes allows their placement in urbanized areas so the cover materials are designed differently with the aim of integration between the containers and the context also considering sustainable materials (Asdrubali et al., 2012). The XXS and S solutions could be used respectively as short-term single guestrooms and emergency housing; for these reasons the research reported in the paper is focused on these two case studies.

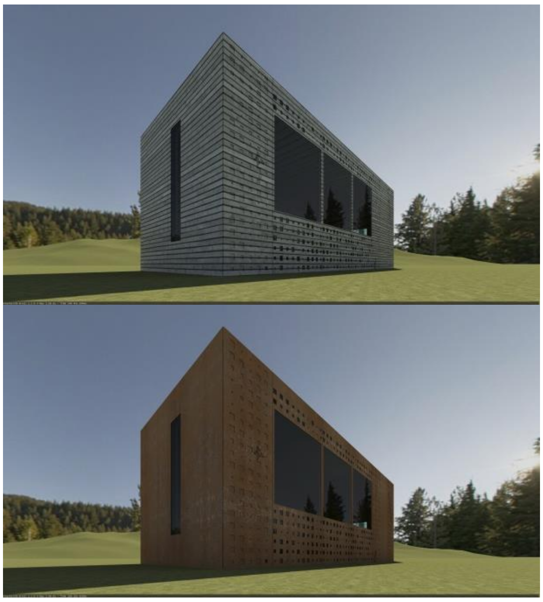

Fig. 1 – Render of an S case study. External view (wood and corten coverings)

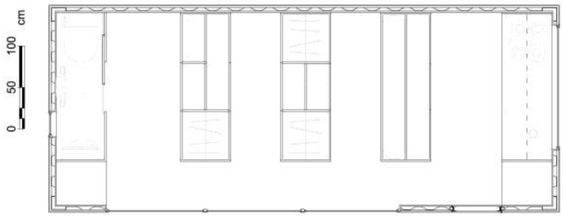

Fig. 2 – Planimetry of S case study

2.2 Energetic aspects

To provide low energy consumption values, the definition of the stratigraphy of the walls was conducted through the use of dynamic energy simulations. The walls, as well as the ceiling, are composed of an inner layer of Oriented Strand Board (OSB), two layers of polyurethane foam insulation separated by 1.8 cm of steel, a vacuum insulation panel and an outer covering panel. The floor is made of epoxy resin, steel, plywood, panel and vacuum insulation. The thickness of the layers was chosen after dynamic simulation to obtain the best configuration in terms of energy savings. The windows are double-glazed with argon, while the heating and cooling system is characterized by an air heat pump with split system. The installation of photovoltaic panels on the roofs was studied.

2.3 Lighting design

The lighting design for each case study was performed considering the change of the furniture arrangement during the 24h. Two configurations were analysed, *day* and *night*. In both cases, the position of the LED lamps should allow adequate Illuminance values on tables, floors and hobs also for poor daylighting contributions. LED lamps were chosen because even if their price is quite high, they are energy savers and do not emit heat. The LED lamps considered for the simulations are characterized by luminous flux of 1100 lumen, low energy consumptions (10 W, luminous efficacy 80.0 lm/W) and a colour temperature of 4200 K. Their optic allows a control of the luminance (UGR<19). The lamps are installed in recessed fixed luminaire, to avoid interferences with the sliding of the furniture. The optical characterization (in particular reflection and transmission coefficient) of floors, walls, ceilings, furniture, doors and windows was performed considering data from scientific literature, certifications and spectrophotometric measurements (Asdrubali et al., 2009) (Baldinelli et al., 2014). Preliminary simulations were carried out to define the quantity of luminaires: five lamps are required for S and three for XXS case study; in each case study one lamp works only for bathroom lighting. These data were then used to perform energy simulations. Each case study has a blind wall; energy simulations were carried out to define the direction of exposure of this element.

3. Simulations

Energy and Lighting simulation were performed to characterize energy consumption and indoor comfort.

3.1 Energy simulations

3.1.1 Methods

In order to arrive as close as possible to developing "nearly zero energy buildings" defined in the European Directive 2010/31/UE, the energy simulations were performed using EnergyPlus [Energy plus website, 2014] and DesignBuilder [DesignBuilder website, 2014] not only to verify the energy consumption but also as design tools. EnergyPlus is a dynamic simulation software able to model the system of heating, cooling, ventilation and other energy flows. DesignBuilder is a graphical interface of EnergyPlus, which allows the user to implement the model of the building and assign the physical and thermal properties (size, materials, plants, thermal loads). Using the weather data of Perugia, the heating and cooling loads necessary to maintain thermal control setpoints (from 15th October to 15th April 20 °C and from 15th April to 15th October 26 °C), conditions throughout HVAC and the energy consumption of primary plant equipment were calculated.
Two steps of simulations were developed: the first to define the characteristic of the layers, of the glazed surfaces and the best orientation of the container and the second to verify the efficiency of the design phase. Calculations were carried out considering the occupancy of 1 person per case study.

3.1.2 Results

The first step of simulations was carried out to define the stratigraphies and the building orientation.
Divided into six different layers characterized by a transmittance of 0.085 W/(m^2 K) for both the perimeter walls and the ceiling, the walls are composed of OSB (15 mm thick), polyurethane foam insulation (20 mm thick), steel (1.8 mm thick), foam polyurethane insulation (30 mm thick), vacuum insulation panel (50 mm thick), panel outer coating (if corian or corten: 12 mm thick, if wood: 30 mm thick). The thermal properties of vacuum insulation panels are: conductivity (0.007 W/(m^2 K)), specific heat (1000.0000 J/(kg K)) and density (180.00 kg / m^3).
The stratigraphy of the floor is composed of epoxy resin (3 mm thick), steel (2 mm thick), plywood (30 mm thick), and vacuum insulation panel (50 mm thick), panel outer coating (if corian or corten: thickness 12 mm, if in wood: 30 mm thick). The floor has a transmittance of 0.099 W/(m^2 K) (Fig. 3).

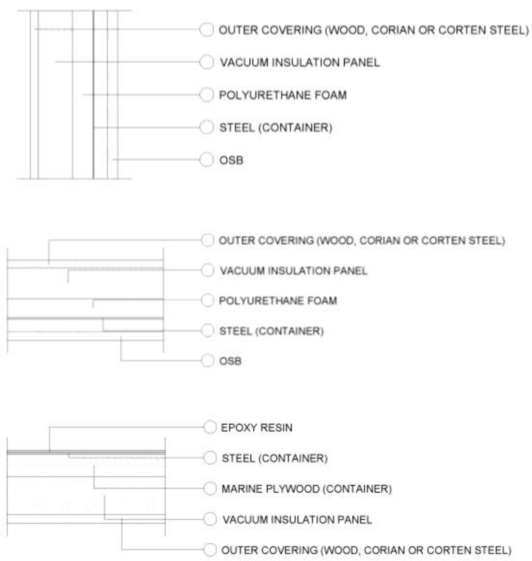

Fig. 3 – Coverage, wall and floor stratigraphies.

The chosen windows are double-glazed characterized by 6 mm thick inner and outer glass panes divided by a cavity of 13 mm filled with argon. The definition of glazed surfaces is associated to user needs, in particular to the

management of the internal space (Asdrubali et al., 2013).
The energy simulations performed probed that the blind wall should face south; this result was obtained analysing the difference between energy consumptions. Table 1 reports the energy production and consumption for the case study, considering respectively 7.2 m² and 4.3 m² of photovoltaic panels (Thin Film CdTe Module) on the S and XXS roofs. Total Energy Consumption is the sum of electricity consumption due to heat pump (air-conditioning and water heating) and to interior lighting. The buildings are supposed to be grid-connected, so that production in excess can be reversed into the grid which can be therefore used as storage.

Table 4 – Energy consumption and production for S and XXS case study.

Case Study	Total Consumption [kWh]	Specific Consumption [kWh/m²]	Energy Prod. [kWh]
S	759	59.4	1188
XXS	391	70.8	713

After the definition of the geometry including windows, doors, stratigraphy, the definition of the plants and the definition of the thermal control setpoints, it was possible to include also the contribute of thermal loads of lighting carried out by the lighting simulations. Having designed the use of LED lights, the value of thermal loads is low and it was set to 1 W/m². Observing Fig. 4**Error! Reference source not found.** and Fig. 5, it is possible to underline that the most important difference is the heating consumption while the difference of energy spent for cooling is less. Table 2 and Table 3 report respectively the total and specific electricity consumption for both case studies; the best configuration in terms of energy efficiency is the S container despite the XXS solution. The reason is related to the external surface area because the S/V ratio of XXS is higher than S/V ratio of S that limits deeply cooling energy consumptions. Table 4 shows a comparison in terms of water consumptions. Energy consumption due to home appliances was not considered in this stage of the study. The connection to the natural gas network could be avoided since air-conditioning and water heating are performed using electricity.

Table 5 – Electricity consumption results obtained by EnergyPlus software of XXS and S case study. Total values.

	XXS Electricity [kWh]	S Electricity [kWh]
Heating	167.05	369.22
Cooling	111.70	115.81
Interior Lighting	20.09	45.44
Hot Water	92.10	228.83
Total	391	759

Table 6 - Electricity consumption results obtained by EnergyPlus software of XXS and S case study. Specific values.

	XXS Electricity [kWh/m²]	S Electricity [kWh/m²]
Heating	30.25	28.87
Cooling	20.24	9.06
Interior Lighting	3.64	3.55
Hot Water	16.68	17.90
Total	70.8	59.4

Table 7 – Water consumption results obtained by EnergyPlus software of XXS and S case study. Total and specific values.

XXS Total Water [m³]	S Total Water [m³]	XXS Specific Water [m³/m²]	XXS Specific Water [m³/m²]
1.44	3.58	0.26	0.26

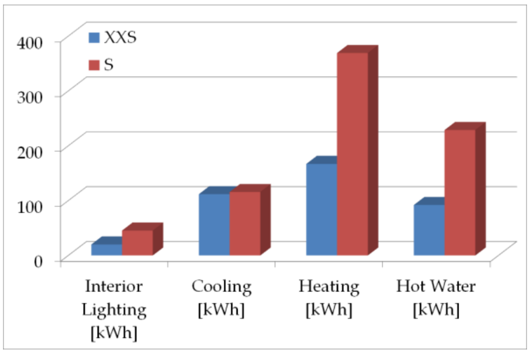

Fig. 4 - Comparison of electricity consumption results obtained by EnergyPlus software

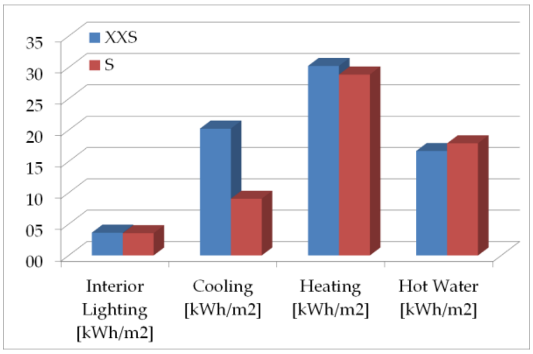

Fig. 5 - Comparison of specific electricity consumption results obtained by EnergyPlus software

3.2 Lighting simulations

3.2.1 Method

The simulations were performed using DIALux (DIALux website, 2014), a commercial software assessing artificial and natural lighting. 3D models of the S and XXS case study were realized including windows, doors and furniture. Grids of Illuminance calculations points were placed over tables (two for S and one for XXS case study), hobs and floors. Discomfort glares were evaluated. In each case study, the *day* and the *night* configurations were evaluated. In the latter case, daylighting was excluded. Glare was evaluated in compliance with the UGR method (UNI EN, 2011). The effects of daylighting were analysed assigning to the innovative modular buildings the geographical coordinates of Perugia (Italy), at the equinoxes and solstices and at the following periods: 2 hours after sunrise, noon, 2 hours before sunrise. The estimations of the daylighting contributions in the grids were calculated averaging the results of the 12 simulations (3 simulations for each one of the 4 days considered). Lighting simulations were performed to determine the optimal luminaires position that allows to obtain adequate Illuminance values and also to limit glare effects.

3.2.2 Results

The outcomes of the thermal simulations established that the solar panels, and consequently the blind walls, should face south.

After defining the exposition, the daylighting simulations were carried out for both case studies.

The calculation grids were placed over two tables (respectively named S – table 1 and S – table 2) and the hub (S – hub) of the S case study and over the table (XXS – table) and hub (XXS – hub) of the XXS case study. In the present paper, only the results on tables are reported in detail (Table 5).

The results show that, in conditions of clear skies, Illuminance values are quite high for S – table 1 and XXS – table so windows should be provided with curtains. The Illuminance is low for S – table2 and consequently artificial light is needed. The values of the coefficient of uniformity U_0, defined as the ratio between the minimum and the average value of the Illuminance in the calculation grid, can be considered compliant to the UNI EN 12464 requirements for areas characterized by writing and reading activities (0.6).

Table 5 – Illuminance values due to daylight in *day* configurations in the calculation grids placed on tables.

Calculation grids	**Illuminance [lux]**		**Uniformity Coefficient U_0**	
	Clear sky	**Overcast sky**	**Clear sky**	**Overcast sky**
S – table 1	1287	151	0.5	0.6
S – table 2	269	195	0.6	0.6
XXS - table	1093	373	0.6	0.4

Considering overcast sky conditions, Illuminance decreases dramatically under 500 lux on tables. Artificial lighting design assumes a decisive role to assure an adequate visual wellbeing in each configuration of the case studies.

Firstly, the LED luminaires described in section 2.3 were placed regularly: the line linking a luminaire with its closest luminaire is normal or parallel to the building walls. Artificial light simulations were then performed (without considering daylight) for both *day* and *night* configurations (Fig. 6). Table 86 reports the Illuminance and the coefficient of uniformity evaluated in the calculation grids considering the effect of artificial light due to the preliminary placement of luminaires in the *day* configuration of the two case studies. configuration of the two case studies.

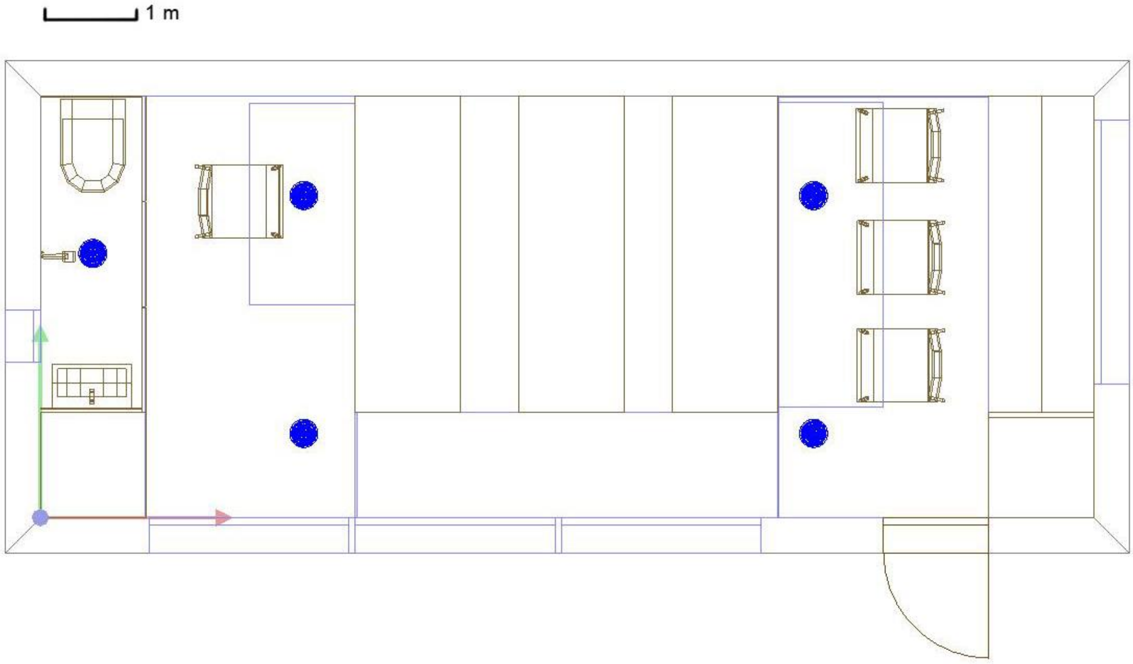

Fig. 6: Luminaires (in blue) for S case study. The pink bar is 1 m long.

Table 8 - Illuminance values due to artificial light in day configurations

Calculation grids	Illuminance [lux]	Uniformity Coefficient U_0
S – table 1	430	0.8
S – table 2	430	0.8
XXS – table	246	0.5

Concerning S – case study, the Illuminance values on tables are close to the 500 lux required by the UNI EN 12464 for areas characterized by writing and reading activities. These values can be considered adequate considering that the data in Table 8 do not consider daylight. For these reasons, the preliminary placement in the S – case study was considered the definitive one.

The low values observed on the table of XXS case study suggested changing the position of the luminaries. The average values of Illuminance, estimated on table and hob considering the optimised luminaires localisation (Fig. 7), can be seen in Table 7.

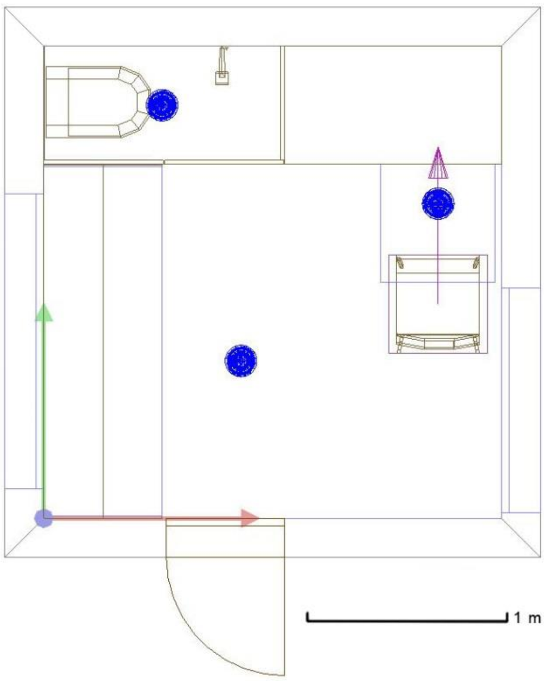

Fig. 7 - Luminaires (in blue) for XXS case study.

Concerning hobs, since they are placed in front of windows, the Illuminance values are always over the 500 lux, but also under the minimum value of U_0 recommended by UNI EN 12464 for kitchens (0.6).

Table 9 - Illuminance values due to artificial light in day configuration of XXS case study considering the optimised luminaire position.

Calculation grids	Illuminance [lux]	Uniformity Coefficient U_0
XXS – table	471	0.9
XXS - hub	160	0.3

This is due to the proximity of the hob to the window. The installation of curtains limits this effect, allowing a more diffusive distribution of daylight. The Illuminance values and the uniformity coefficient evaluated on floors due to daylight (day configuration) and to artificial light (night configuration) were respectively higher than the 100 lux and the 0.4 requested by the UNI EN 12464 for circulating areas and corridors. The positioning of the luminaires and the materials chosen for the furniture, walls, floors and ceilings allows us to maintain glare under the 20 UGR (Unified Glare Rating) in each case study for both *day* and *night* configurations. In 8 a lighting render is reported.

Fig. 8 - Render of XXS case study. Artificial light in day configuration

4. Conclusions and Discussion

The research analysed the energy and lighting performances of two examples of net zero energy modular buildings realized using recycled shipping containers. The first one, named XXS, was designed as a short-term single guestroom; the second one, named S, as temporary accommodation for emergencies. The furniture is designed to be easily moved through special guides in accordance to users' needs. Firstly, preliminary lighting simulations were performed to define the kind and the number of lamps required in each case study. LED lamps were chosen because they are characterized by low energy consumption (the ones used in the study only require 10 W), an adequate luminous flux (1100 lumen) and a high colour temperature (4200 K). The preliminary evaluations established that 5 and 3 luminaires are needed respectively for S and XXS case study. Then these data were used for energy evaluations to set the values of thermal loads. The first step of energy simulations allowed us to define the building envelope (stratigraphy and windows) and the orientation: polyurethane foam, vacuum insulation panels and double glazed windows (6-13-6, filled with Argon) were chosen to optimise the energy performance. The energy simulations also demonstrate that the blind walls should face south.

The energy consumption estimated by EnergyPlus is 59.4 kWh/m^2 for S solution and 70.8 kWh/m^2 for XXS configuration. These results demonstrate that the containers are easy and cheap accommodation that provide optimized performances in terms of energy efficiency.

These data allowed us to perform lighting performance due to natural and artificial light on calculation grids placed over tables, hobs and floor. Two configurations of furniture were tested. The visual parameters tested are Illuminance, uniformity coefficient and glare. Several lighting simulations were carried out to define the most performing lamp positions. The lighting systems, the position of the windows and the optical characteristics of furniture, walls, ceilings and floor, ensure an adequate visual comfort.

The production of electricity thanks to PV panels is adequate to consider the building a net zero energy one (at central Italy latitudes).

Therefore, the theoretical, innovative building studied in the paper is not only an energy-saver but also a cheap and comfortable solution to be used not only for emergency housing but it is possible to use them as temporary accommodation that can be placed in different areas and can be moved easily to different places.

References

Asdrubali F., Baldinelli G. and Bianchi F. 2013. "Influence of cavities geometric and emissivity properties on the overall thermal performance of Aluminium frames for windows." *Energy and Buildings* 60: 298-309. doi: 10.1016/j.enbuild.2013.01.028.

Asdrubali F. and Baldinelli G.. 2009. "Theoretical modelling and experimental evaluation of the optical properties of glazing systems with selective films." *Building Simulation* 2 (2): 75-84. doi: 10.1007/S12273-009-9112-5.

Asdrubali F., Schiavoni S. and Horoshenkov K.. 2012. "A review of sustainable materials for acoustic applications." *Building Acoustics* 19 (4): 283-312. doi: 10.1260/1351-010X.19.4.283.

Baldinelli G., Asdrubali F., Baldassarri C., Bianchi F., D'Alessandro F., Schiavoni S. and Basilicata C.. 2012. "Energy and environmental performance optimization of a wooden window: A holistic approach." *Energy and Buildings* 79: 114–131. doi: 10.1016/j.enbuild.2014.05.010.

Container City website. 2014. Accessed November 28, http://www.containercity.com/

Designboom. 2014. Accessed November 28 http://www.designboom.com/architecture/top-10-shipping-container-structures-of-2013-12-2-2013/.

DesignBuilder website. 2014. Accessed November 28, http://www.designbuilderusa.com/.

DIALux website. 2014. Accessed November 27 http://www.dial.de/DIAL/en/dialux/archive/2012/april.html.

Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings.

Dumas A., Trancossi M., Madonia M. and Coppola M.. 2014. "Zero Emission Temporary Habitation: A Passive Container House Acclimatized by Geothermal Water". *Journal of Solar Energy Engineering* 136 (4). doi: 10.1115/1.4027884

EnergyPlus website. 2014. Accessed November 27 http://apps1.eere.energy.gov/buildings/energyplus/.

Eurostat website. 2014. Accessed November 28 http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Freight_transport_statistics#Maritime_freight.

Kolokotsa D., Rovas D., Kosmatopulos E. and Kalaitzakis K.. 2011. "A roadmap towards intelligent net zero- and positive-energy buildings." *Solar Energy* 85: 3067-3084. doi:10.1016/j.solener.2010.09.001

Sartori I., Napolitano A. and Voss K.. 2012. "Net zero energy buildings: A consistent definition framework", *Energy and Buildings* 48: 220-232. doi: 10.1016/j.enbuild.2012.01.032.

UNI EN 12464-1:2011, Light and lighting - Lighting of work places - Part 1: Indoor work places.