Achieving Energy Savings in Urban Planning by Using Direct Solar and Diffuse Daylight in Early Stage Design

HENDRIK VOLL
Department of Environmental Engineering
Tallinn University of Technology
Ehitajate Tee 5,Tallinn, 19086
ESTONIA
hendrik.voll@ttu.ee

Abstract: Starting from December 10th in 2008 became into force the standard number 894 („Daylight in Apartment Buildings“) of The Republic of Estonia. The standard states, that every new apartment building has to correspond to the daylight requirement regarding direct solar radiation and diffuse daylight. In case the building does not fulfill the requirements stated in the standard, the building has to be redesigned in order to obtain the construction permission. To educate Estonian architects and engineers and explain the key-factors – the design of the single building façade and complete urban district –direct solar radiation table named heliodon and diffuse daylight test chamber the mirror-box overcast sky were established to Tallinn University of Technology. The present paper focuses onto the concept of heliodon table and mirror-box. Besides the paper presents a method how to design a building that fulfills the daylight standard requirements as well as the requirements for energy efficiency stated in regulation nr 258. In the end planned urban district is analyzed and tested for direct solar access.

Keywords: Heliodon table, Diffuse daylight test chamber, Solar radiation, Urban planning, cooling load.

1. Introduction

Starting from December 10th in 2008 Estonia has a new standard, “Daylight in Apartment Buildings”. In this new standard one of the new elements for architects and urban planners to consider is the three hours direct solar radiation. The standard states that in each apartment, school, kindergarten, hospital etc. (except office space) up to three rooms at least one room has to achieve at least three hour lasting constant direct solar access from 22.April until 22.August. Apartments larger than three rooms at least two rooms have to achieve at least three hours of direct solar radiation. In case of a very complicated city district, downtown area for example the time of a solar access could be diminished down to 2,5 hours in case of permission by city planning authorities. Also in case of a city district where buildings are taller than 45 meters the direct solar radiation could be divided onto two parts. However the longer period has to guarantee at least 2 hour lasting constant direct solar access from 22.April until 22.August [1]. In case the three hours direct solar access requirement is not possible to fulfil one could design the space for office space for example.

Besides direct solar radiation another parameter, the minimum daylight factor requirement has been introduced. The daylight factor describes the ratio of inside illuminance over outside illuminance at a specific point, expressed in percent [1].

$$DF = 100 \times (E_{in} / E_{ext}) \quad (1)$$

Where,

DF; The daylight factor, [%],
E_{in}; Inside illuminance at a fixed point, [lx],
E_{out}; Outside horizontal illuminance under an overcast sky, [lx].

The new standard states, that all the rooms including offices should have the lowest daylight factor of 2 or above as spaces with a lowest daylight factor below 2 would probably feel dark even during summer overcast days and would require electrical light(s) to be on.

To carry through the practical tests and to educate architects and engineers regarding the new standard, a new "passive architectural cooling and heating laboratory" was established to Tallinn University of Technology. The laboratory consists of energy and daylight simulation software's including IES, eQuest, EnergyPlus, IDA, Riuska, Bsim, Ecotect, Vip+, BV2, PHPP7 and scientific teaching tools like overcast simulator and direct sun heliodon table to test the building scale models and visualize the main important principles of simulation software.

2. Overcast Sky Simulator

The shadowless artificial overcast sky condition created in mirror-box is a test condition defined by the international commission of illumination. The shadowless sky is generally three times brighter at zenith (directly overhead) than it is at the horizon. Figure 1 illustrates the inside view of the mirror-box used for daylight tests at Tallinn University of Technology.
The mirror-box is used to measure the daylight factors. Besides the daylight factor, the mirror-box also allows examining the perceptual quality of a space, the feeling of brightness, and if a balanced luminous environment is created.

Figure 1. Overcast sky simulator interior view.

Five photocells are used to measure the percentage of available daylight in overcast condition. The used photocells are LI-Cor 210 with 60 degree cone of vision. One "control cell" is placed on top of the scale model oriented towards zenith to measure the amount of available daylight. Inside the model, four photocells are placed on work zone height to measure the amount of light reaching the interior. The photocells inside the room are moved in parallel with the window facade. The interior readings are then divided by the exterior reading, directly giving the daylight factor (percentage of outdoor illumination indoors). These numbers are used as a rough measure of the daylight design performance. The light flux metering equipment measuring the daylight factor is shown in Figure 2.

Figure 2. Flux metering equipment measuring the daylight factor

Figure 3 shows example of the perceptual quality of diffuse daylight. Uper picture showing a room with window share of 15% per facade has the lowest daylight factor in the room below 2 and would probably feel dark even during the summer month overcast days. Lower picture on figure 3, room with window share of 80% per facade has the lowest daylight factor in the room of about 12 and would probably not require electrical lighting during summer month overcast days [2].

Figure 3 Pictures of perceptual daylight quality inside room.

3. Heliodon Sun Simulator

The heliodon table is used to examine the direct solar access for apartment buildings and besides shading devices for commercial buildings that eliminate direct sun from areas where visual tasks are critical. The heliodon table is comprised of a tilting/rotating table (the earth), a stationary 1000 watt theatrical light source (the sun) and the mirror that reflects the light beam from the light source back on heliodon table. The table can be adjusted to represent the latitude, tilted to simulate any month of the year, and rotated to analyze any time of a day. By filming the room interior, the heliodon table tests are used to examine how the direct rays of the sun interact with different facade design.

The primary method to examine how the direct rays of the sun interact with specific building design is through photography and short film clips. The heliodon table used for direct solar analysis is shown in Figure 4.

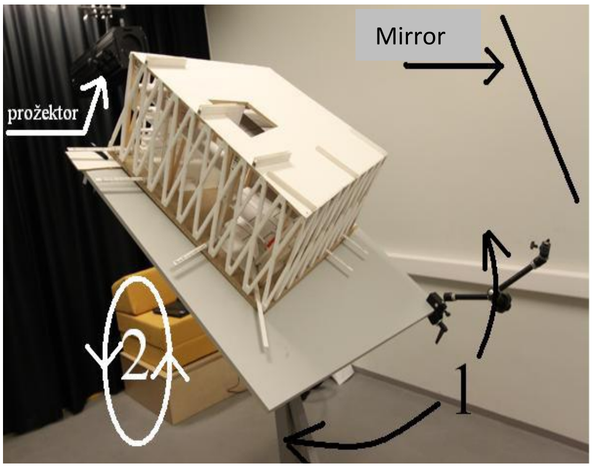


Figure 4 Heliodon table.

Figure five presents the heliodon table test main idea for apartment buildings. The pictures show the light path(direct solar radiation) movenent inside the apartment room. In that example the three hours lasting constant solar access requirement is fulfilled [3].

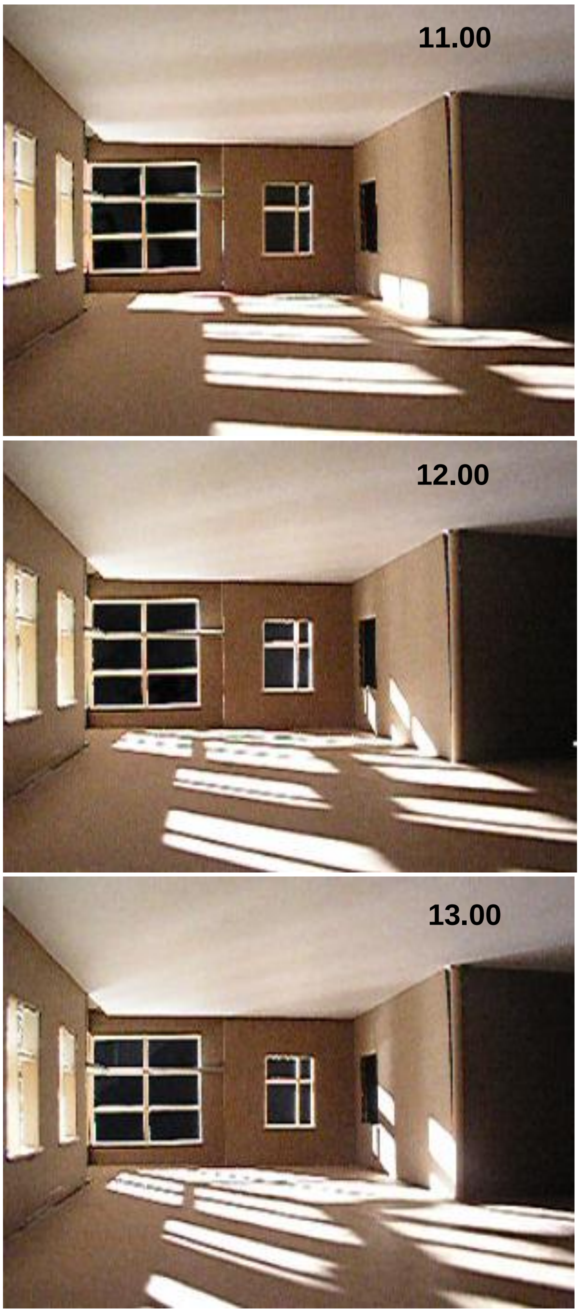


Figure 5 Example of three hours lasting direct solar acess requirement.

4. Regulation 258

Starting from July 1st in 2009 became into force the regulation number 258 („The Minimum Requirements for Energy Efficiency") of Government of The Republic of Estonia. The regulation states, that every new and significantly renovated building has to correspond to the minimum requirements of energy efficiency. In case the building does not meet the requirements stated in the regulation, the building has to be redesigned. The energy consumption of a dwelling derives mostly from heating the building, and which is affected by insulation and ventilation-system. As in offices considerable amount of energy consumption is derived from cooling, the situation is more complex [7].

5. Way to Combine the Regulations

In some cases there might arise a problem that if a building corresponds to daylight requirement it does not fulfill the demands stated at the minimum energy requirement or vice verse. The following is a method to analyze the building in a way that the requirements in both regulations can be fulfilled.

Figure 6 presents the two office room layouts in scale model used in the illustrative cooling power demand simulations and the daylight availability tests.

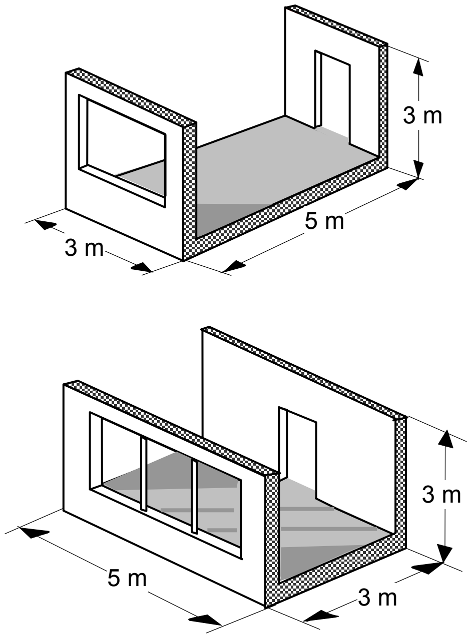
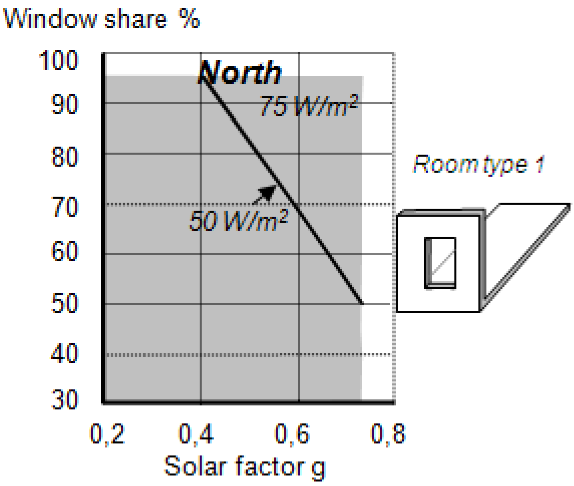
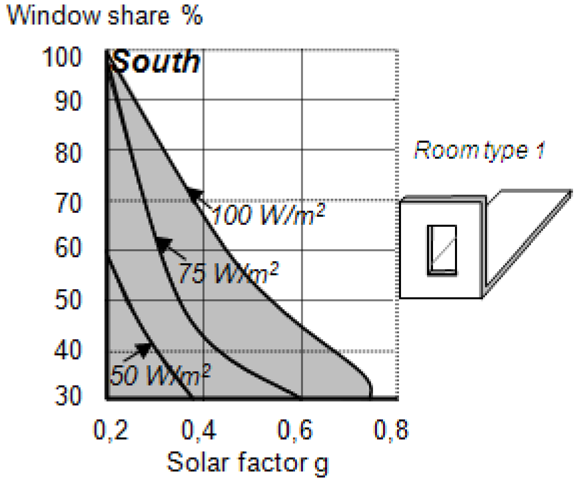


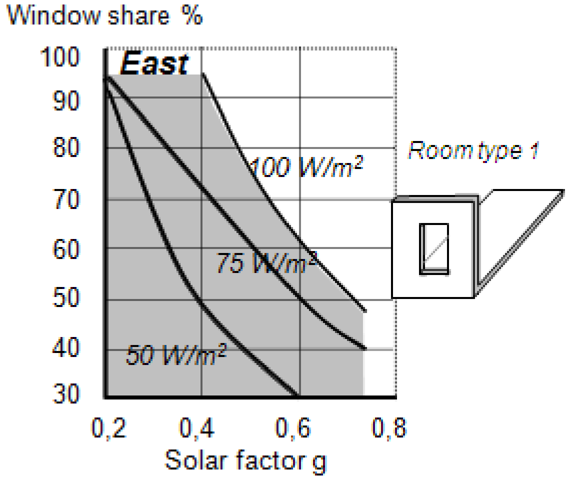
Figure 6 Upper picture: office room type 1, Lower picture: office room type 2

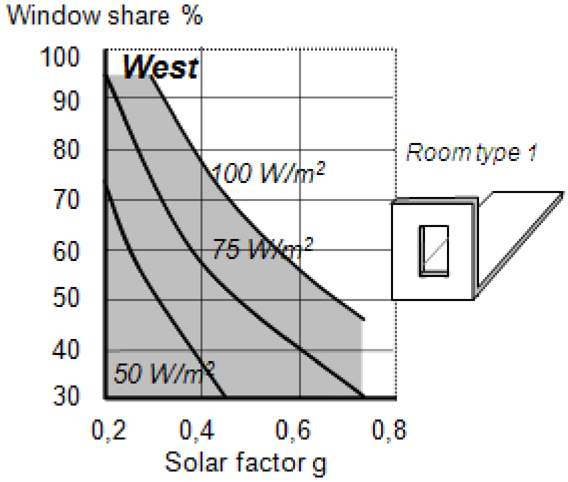
The solar factor g (sometimes also called the shading coefficient) is the ratio of solar heat gain through a glazing to the solar heat gain through a single clear glass. The smaller the number, the better the glazing is to preventing solar heat gains but poorer to let natural daylight inside the room [5]. In office room simulations the following values were used. U-values: Facade wall 0.27 W/(m^2·K); Window 1.6 W/(m^2·K); Ceiling 0.15 W/(m^2·K). Installed lighting power 10 W/m^2, office equipment 10 W/m^2, and people 6 W/m^2. Figure 7 shows the possible window shares for different maximum cooling power demands (50, 75 and 100 W/m^2) as function of solar factor for room type 1 and 2 north and south orientations. It is also possible to install cooling loads above 100 W/m^2, however in order to fulfil the demands in regulation 258 it is strongly recommended not to design the building facades in a way that the cooling demand is that high [8], [9].

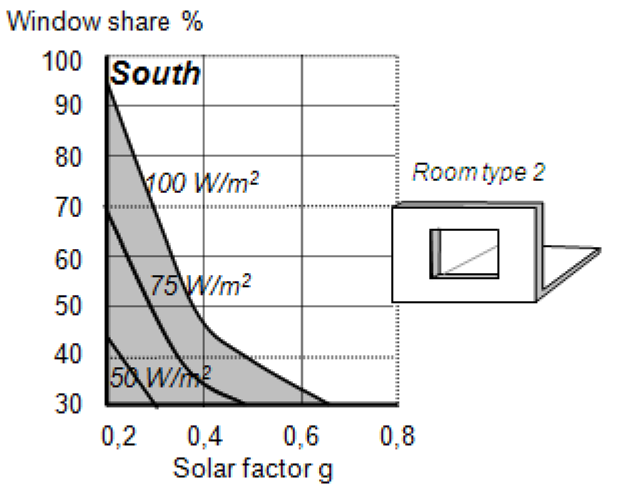
The lines in Figure 7 show the relation between the window share and the solar factor resulting in the same maximum cooling power demand. This relation, in form of the product, is in most cases close to a constant value. This means e.g. that a combination with 60% window share and a solar factor of 0.4 will give quite similar cooling power demand as 40% window share and a solar factor of 0.6, as the product of the two are the same in both cases.

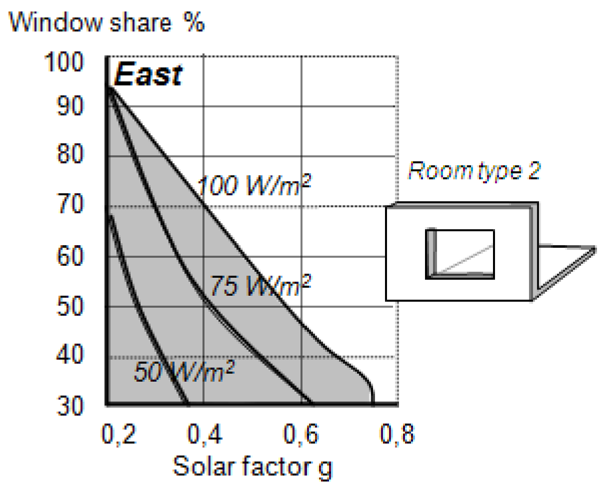


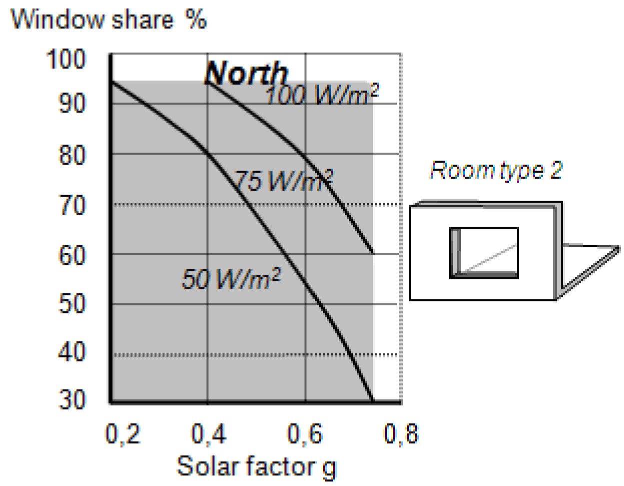












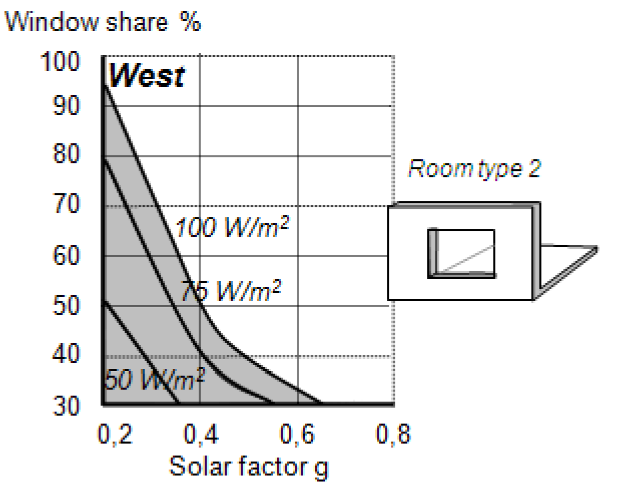


Figure 7 Possible window glass share and solar factor combination for room type 1 and 2 for maximum cooling power demand 50, 75 or 100 W/m^2.

For north orientations the product of window share and solar factor for a certain maximum cooling power demand could be much larger compared to all other orientations. The south orientation has the highest maximum solar irradiation in both W/m^2 and Wh/m^2 and therefore results in the highest cooling demands. To keep the cooling power demand below 50 W/m^2 for south orientation the product of window share and solar factor must be about 0.1 or below.
The combination of window glass share and solar factor feasible for east and/or west facade is in between the values for north and south [2].

Figure 8 shows the results for both room types for fulfilling the requirement: the daylight factor should be 2 or above and the difference between the highest and lowest daylight factor should be below 20. If these requirements are to be fulfilled, the window glass share and solar factor combination must lay within the marked light grey area. The hatched area below that area indicated as “dark” means the lowest daylight factor in the room would be below 2. The area indicated as “gloomy” means the contrast between the lowest and highest daylight factor exceeds 20. Thus the line separating the "daylit" area and "dark" area shows the minimum possible combinations of window glass share and solar factor for fulfilling the daylight requirements.

To fulfil the daylight requirements in room type 1 this product should be ≥ 0.24 and for room type 2, ≥ 0.16.

The line separating the "daylit" and "gloomy" area shows the limits for possible combinations of window glass share and solar factor for fulfilling the daylight requirements without risk of a gloomy space. The product of window glass share and solar factor should therefore be 0.33 or below for both room types.

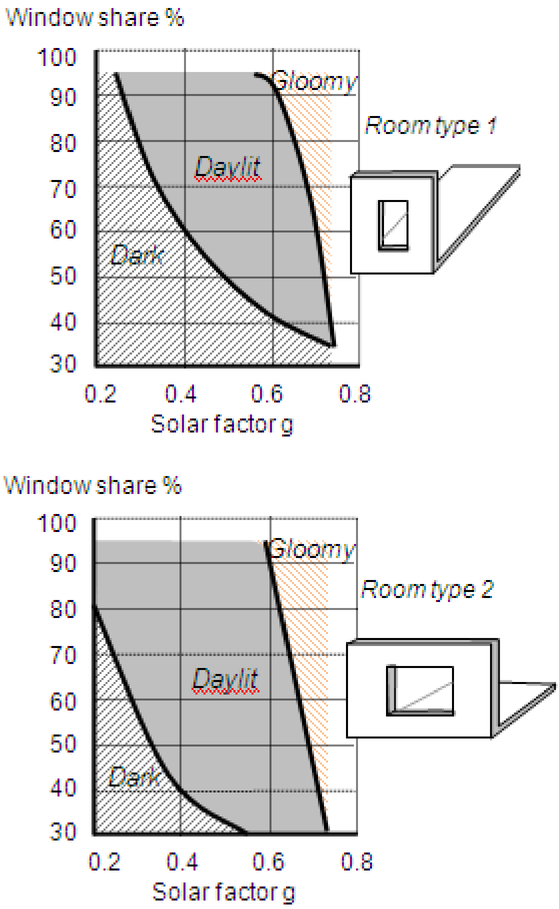


Figure 8 Possible window glass share and solar factor combinations for fulfilling the requirements: The daylight factor should be 2 or above and the difference between the lowest and highest daylight factor must not exceed 20. The result is valid for all orientations.

Figure 9 shows possible window shares for office room type 1 and 2 that fulfills the cooling and daylight requirements: the maximum cooling power demand should not exceed 100 W/m^2, the lowest daylight factor should be 2 or above and the difference between the highest and lowest daylight factor should be below 20.

Windows oriented north gives a wide range of possibilities to choose window shares and solar factors, as there is a little risk of exceeding high cooling power demands. However, using too small window shares or too low solar factors, or combinations of both, might result in a "dark" room. Using a too large window share would on the other hand might lead to gloomy rooms and result in a high heating power demand.

South orientation has the highest cooling power demand and by that large window areas together with poor solar factors are not recommended to use because they might result in very high cooling power demands. For south orientations when the cooling power demand is below 100 W/m^2 there should not be any risk of a gloomy room caused of too large illuminance contrast during overcast days.

The amount of window glass share possible for east and/or west facade is in between the results for north and south orientation when same cooling load and daylight requirements are considered.

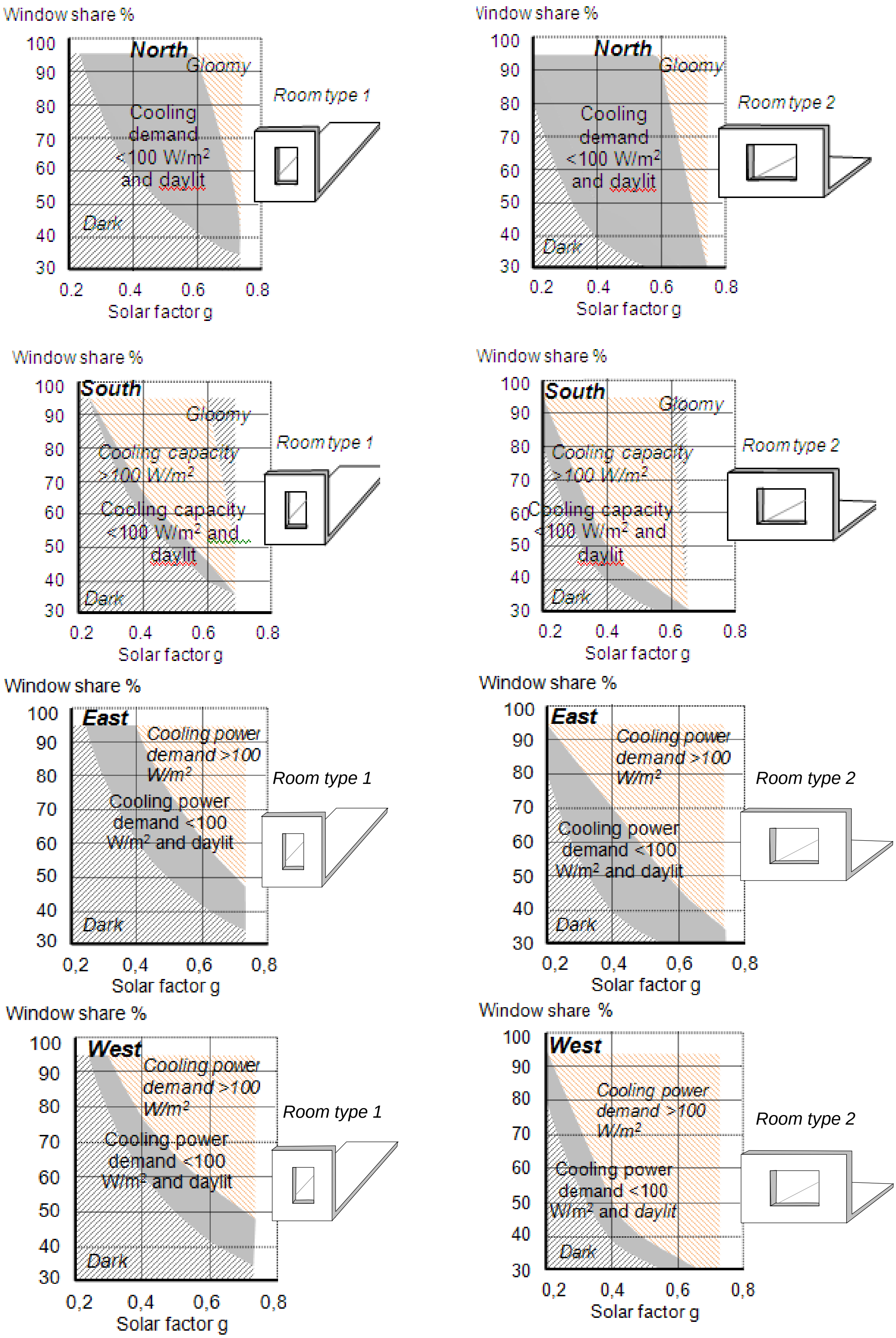

Window share %
North
Gloomy
Cooling demand <100 W/m² and daylit
Dark
Room type 1
Solar factor g
Window share %
North
Gloomy
Cooling demand <100 W/m² and daylit
Dark
Room type 2
Solar factor g
Window share %
South
Gloomy
Cooling capacity >100 W/m²
Cooling capacity <100 W/m² and daylit
Dark
Room type 1
Solar factor g
Window share %
South
Gloomy
Cooling capacity >100 W/m²
Cooling capacity <100 W/m² and daylit
Dark
Room type 2
Solar factor g
Window share %
East
Cooling power demand >100 W/m²
Cooling power demand <100 W/m² and daylit
Dark
Room type 1
Solar factor g
Window share %
East
Cooling power demand >100 W/m²
Cooling power demand <100 W/m² and daylit
Dark
Room type 2
Solar factor g
Window share %
West
Cooling power demand >100 W/m²
Cooling power demand <100 W/m² and daylit
Dark
Room type 1
Solar factor g
Window share %
West
Cooling power demand >100 W/m²
Cooling power demand <100 W/m² and daylit
Dark
Room type 2
Solar factor g

Figure 9 Possible window glass share and solar factor combination in rooms facing south for fulfilling the requirements: a cooling power demand below 100 W/m^2, a daylight factor above 2 and a difference between the highest and lowest daylight factor less than 20.

6. Planned Urban District

In 2009 a new city district was planned to Tallinn, Estonia. The district named the Luther district consists of 14 new buildings from 8 to 14 floors and totally potentially of 1621 new apartments. The Tallinn University of Technology was made an offer to analyze the direct sun radiation in this new planned city district. As the Luther district was one of the first larger city districts in Estonia that has to fulfil the requirements stated in a new daylight standard a scale model was ordered. The scale model is to remain to the University as one of the teaching tools for architects, engineers and students to study city planning regarding the daylight standard. Laser cutting technology was used to establish the scale model in scale 1:100 [4], [6]. The scale model is presented in figure 10.

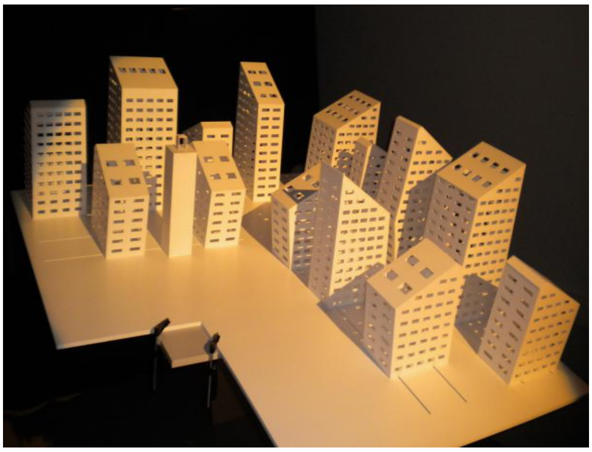


Figure 10 The scale model of the Luther district

The model was constructed so that all the buildings could be moved(slided) from the direction from north to south or east to west. There is also an option to remove all the buildings and to reconstruct different city district. This option is very useful in the future for teaching purposes for architects and engineers in coming years.
For direct solar analyses each facade orientation, east, south and west were tested separatelly. Figure 11 shows and example of three buildings, nr 2, 4 and 6 picked to give an idea of a method used in testing. The test results for these three buildings are given in table nr 1. As the tests showed in building nr 2 for south and west facade the three hour direct solar requirement is fulfilled, but for east facade the requirement is fulfilled just for 2 uper floors. This means that building number 2, apartment plans situating in floors 7-8 can be designed in a way desired by an architects. However for apartments designed in floors 1-6 to fulfill the direct solar access requirement at least one window of each apartment should face south or west.

The east facade was the most problematic facade regarding the 3 hours direct solar access also for building number 4. Apartments in building nr 4 in order to fulfill the direct solar access requirements have to be designed in a way that at least one window of each apartment faces south or west.

Table 1 Direct solar access analysis for buildings nr 2, 4 and 6.

	East	**South**	**West**
Building 2	2 uper floors OK	OK	OK
Building 4	Not fulfilled	OK	OK
Building 6	Not fulfilled	Fulfilled for 2 uper floors	OK

When it comes to building nr 6, three hour direct solar access requirement is not possible to fulfill for east facade neither for south facade's 6 lower floors (as indicated in red in figure 10). Apartments in building nr 6 in order to fulfill the direct solar access requirements have to be designed in a way that at least one window of each apartment in every floor faces west. In case the architect is not willing or considers it too complicated the building nr 6 could be designed for office space.

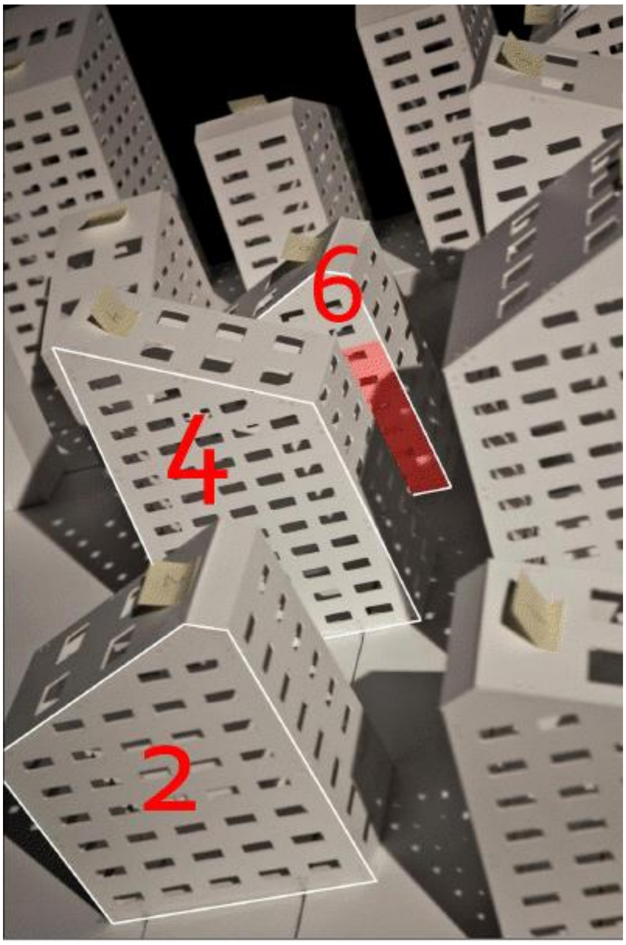


Figure 11 Buildings nr 2, 4 and 6 tested for daylight regulation.

7. Conclusion

Starting from December 10th in 2008 Estonia has a new demanding standard, "Daylight in Apartment Buildings". That new standard states completely new requirements and demands for urban planning. In order to educate architects and engineers a "Passive architectural cooling and heating laboratory" was established to Tallinn University of Technology. The laboratory consists of energy and daylight simulation software's and scientific teaching tools like overcast simulator and direct sun heliodon table. The present paper focused onto the concept of heliodon table and mirror-box. Besides the paper presented a method how to design a building that fulfills the daylight standard requirements as well as the requirements for energy efficiency stated in regulation nr 258. In the end of the article planned urban district was analyzed for direct solar access.

References

[1] Eesti Standardikeskus. Loomulik valgustus Elu –ja bürooruumides, EVS 894: 2008. Tallinn Estonia

[2] Voll, H. (2008). *Cooling Demand and Daylight in Commercial Buildings. The Influence of Window Design*, Chalmers University of Technology department of Energy and Environment. Pg 121. Göteborg..

[3] Voll,H.(2005). Cooling *Demand in Commercial Buildings. The Influence of Building Design*, Chalmers University of Technology department of Energy and Environment. Pg 157. Göteborg.

[4] I.A. Choudhury, S. Shirley, *Laser cutting of polymeric materials: An experimental investigation*, Optics & Laser Technology Vol. 42, No. 3, 2010, pp 503-508.

[5] Bergsten, B. (2004). *Free cooling in Commercial Buildings*, , Chalmers University of Technology department of Building Technology. Pg 198. Göteborg.

[6] Pääsuke, K. (2010). Development and Manufacturing a Selfshielding Model. *In: Latest Trends on Engineering Education: 7th WSEAS International Conference on Education and Educational Technologies, Corfu Island Greece, July 22-24, 2010.. (Toim.) P. Dondon, O. Martin..* Greece: WSEAS, 2010, 122 - 127.

[7] Kõiv, T-A.;, H.; Kuusk, K.; Mikola, A. (2009). Indoor Climate and Energy Consumption in Residential Buildings. *In: Selected Topics on Energy and Development-Environment-Biomedicine 2009: Proceedings of the 3rd International Conference on Energy and Development-Environment-Biomedicine (EDEB 09). (Toim.) Panos Pardalas; Nikos Mastorakis; Valeri Mladenov; Zoran Bojkovic.* WSEAS Press, 2009, (Energy and Environmental Engineering Series A Series of Reference Books and Textbooks), 82 - 86.

[8] Voll, H.; Kõiv, T-A. (2009). Energy Efficient Daylight Assessment -The Influence of Facade Design. *In: Selected Topics on Energy and Development-Environment-Biomedicine 2009: Proceedings of the 3rd International Conference on Energy and Development-Environment-Biomedicine (EDEB 09). (Toim.) Panos Pardalos, Nikos Mastorakis, Valeri Mladenov, Zoran Bojkovic.* WSEAS Press, 2009, (Energy and Environmental Engineering Series. A Series of Reference Books and Textbooks), 47 - 52.

[9] Kõiv, T.-A.; Voll, H.; Mikola, A.; Kuusk, K.; Maivel, M. (2010). Indoor Climate and Energy Consumption in Residential Buildings in Estonian Climatic Condition. WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT, 6(4), 247 - 256.