Development of a Study Scale Model for Energy and Daylight Analysis

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Abstract: 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. To educate Estonian architects and engineers and explain one of the key-factors – the design of the facade –direct solar radiation table named Heliodon and diffuse daylight artificial skybox were established and a model of a building was manufactured. The model has different types of facade layouts in different sides to visualize their influence of heating/cooling loads and energy demand. The present paper focuses on the introduction of Tallinn University of Technologies daylighting lab, developing process of the exemplary model from conceptual idea to real physical model and in the end gives an example how the designed scale model will be used for educational purposes.

Keywords: Cooling demand, Energy efficiency, Daylight, Rapid Prototyping, Selective Laser Sintering

1. Introduction

Since July 1st 2009 Estonia has a new minimum energy regulation. The regulation stipulates architects and engineers to intense cooperation. The fact that the local architects study in Estonian Academy of Art and the engineers in Tallinn University of Technology (TUT) causes often confusion on the local construction field. In spring 2010 TUT started a program which attempts to join the architects and engineers. To conduct the practical tests and lessons, a new Energy and Indoor climate laboratory was established to TUT. The laboratory consists of energy simulation software and scientific teaching tools like overcast simulator and direct sun heliodon table to test the building scale models and visualize the principles of simulation software.

2. Overcast Sky Simulator

The 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 TUT. The mirror-box is used to measure the daylight factors (DF). DF describes the ratio of inside illuminance over outside illuminance at a specific point, expressed in percent [8].

DF of 2 or above give us a feeling of daylit space [10]. Spaces with a lowest DF below 2 would probably feel dark even during summer overcast days. If the difference between the highest and lowest DF in a space exceeds about 20 the space might feel gloomy.

Figure 1. Overcast sky simulator interior view.

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. 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 [8].

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) and a stationary 1000 watt theatrical light source (the sun). 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 [9].

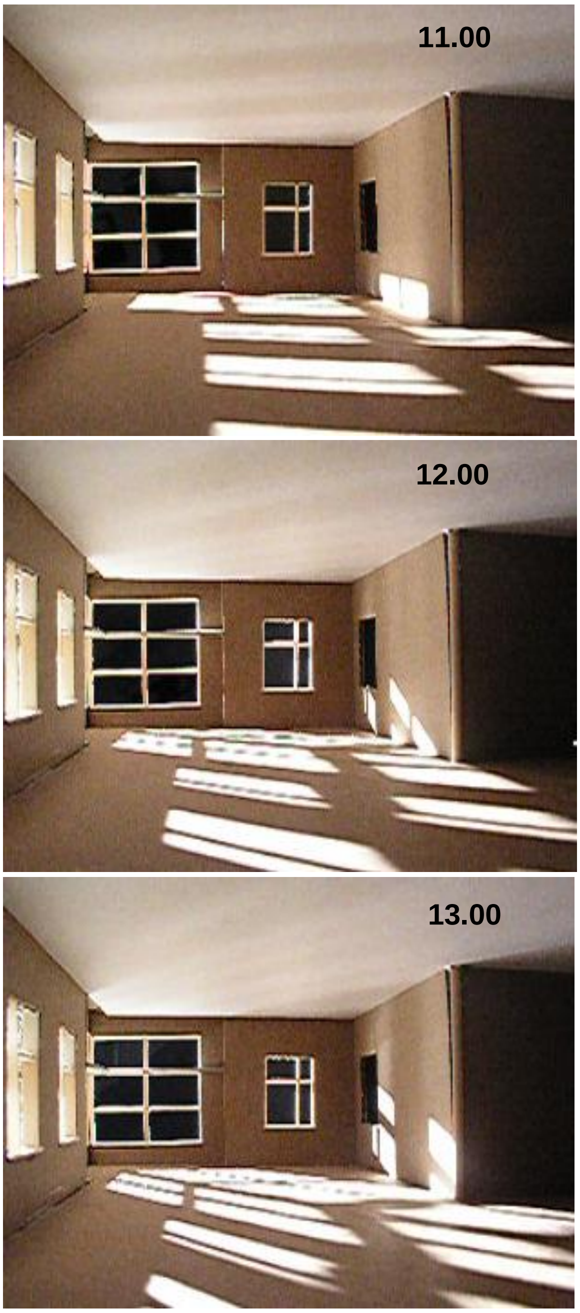


Figure 5 Example of three hours lasting direct solar acess requirement.

4. Concept of the selfshielding model

In present chapter the concept of the selfshielding model is described. The concept is illustrated by a sketch (fig. 6) and the requirements of the model are as follows. The model has to have four floors. The height of one floor should be 100 mm hence the total height approximately 400 mm. The first floor has to be square and have four rooms in series on each side. The required overall dimensions of the first floor are 600 x 600 mm, hence the rooms are also square (side of the room 150 mm). Each following floor has to be longer by one row of rooms so that one of the facade will be stepped.

Consequently the dimensions of all four floors starting from the first floor: 600 x 600 mm, 600 x 750 mm, 600 x 900 mm and 600 x 1050 mm. As the use of diffuse light sensors is prescribed, the model has to be demountable for placing the sensors.

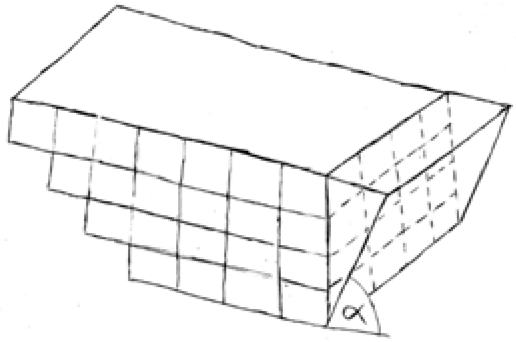


Figure 6. Concept of the model.

The solution of the facade has to enable to use windows with different sizes. The sizes of the windows are defined by their share of the total facade area: 0%, 20%, 40% and 70%. The concept of the windows has to enable the use of sunshades.

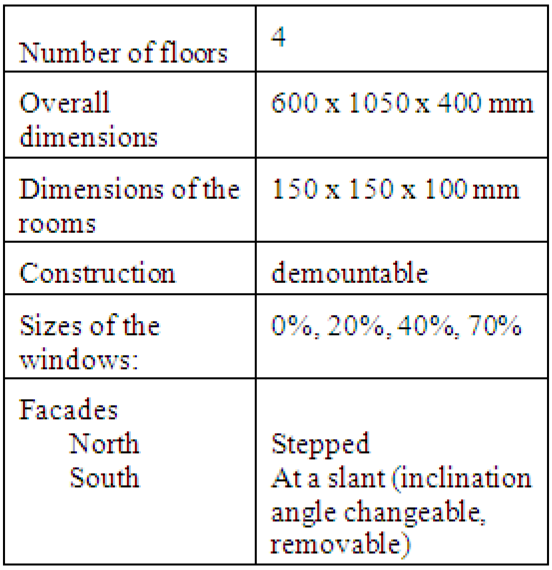
As mentioned before, one of the facades has to be stepped to illustrate the selfshieldment of this type of facade. It is also usual to have facades at a slant, but the effect of the self-shieldment depends then, in addition to the angle of the facade, on the latitude and the season present. The exemplary model has to have also a facade at a slant and as the direct sun heliodon table enables to test the models in different latitudes and seasons, the angle of the facade at a slant of the exemplary model has to be changeable. Although the present requirement increases the complexity of the task, the advantage of visualizing such solutions cannot be underestimated.

The specifications and the constraints are summarized in table 1.

5. Potential technologies

The concept can be realized by using different technologies, from which each will have bigger or smaller effect to the final solution (design for manufacturing). In present section several potential technologies are described and analyzed.

Table 1. Specifications of the concept of the model.



Number of floors	4
Overall dimensions	600 x 1050 x 400 mm
Dimensions of the rooms	150 x 150 x 100 mm
Construction	demountable
Sizes of the windows:	0%, 20%, 40%, 70%
Facades North South	Stepped At a slant (inclination angle changeable, removable)

5.1 Selective Laser Sintering

Rapid Prototyping (RP) is a technique for the direct conversion of 3D computer aided design (CAD) data into a physical prototype using a number of techniques, mostly based on slicing a computer model of a 3D object into multiple 2D layers and building them up, one layer at a time [1]. One of the main differences between conventional manufacturing technologies and RP technologies is that parts are produced by adding material not removing it, hence the RP is also often named additive manufacturing (AM). With traditional methods the manufacturing of a part requires several timeconsuming preparative steps like selection of the technology (/-ies), selection of the tools, generation of the toolpaths, selection of clamping the part during operations etc.

Selective Laser Sintering (SLS) is a powder based RP technology that allows generating complex 3D parts layer by layer [2]. In the building-process (fig. 7) first a layer of powder is spread onto the building platform, next the present cross-section is hatched with a laser beam. As a result the temperature of the material rises over its melting point and as the material cools down solidified layer is formed. The unsintered material, which surrounds the part, has the supportive function. As the parts cannot be sintered directly to the building platform, a powderbed is needed. In addition several layers of material are spread onto the produced parts. Both, the powderbed and top-layers, carry the function to smoothen the cooling process after manufacturing.

SLS is considered suitable to produce complex functional plastic parts. The technology enables even to produce moving joints as one part, hence assembling operation is usually unnecessary. To manufacture the described model with SLS, first a three dimensional model is needed. As the model itself is an assembly, which has to be demountable afterwards, the fits of the model have to be defined very precisely to assure the tight fitting and simultaneously the disassembly of the parts. An assembly as complex as present requires an thoroughgoing analysis. In addition, the overall dimensions of the model are 600 x 1050 x 400 mm, but the dimension of building chamber of the SLS system on disposal are 200 x 250 x 330 mm, hence the manufacturing with present system necessitates the splitting of the model into at least 12 sections. As lots of parts of the described model are simple floor and wall panels, it is unreasonable to manufacture the present parts with such relatively expensive technology.

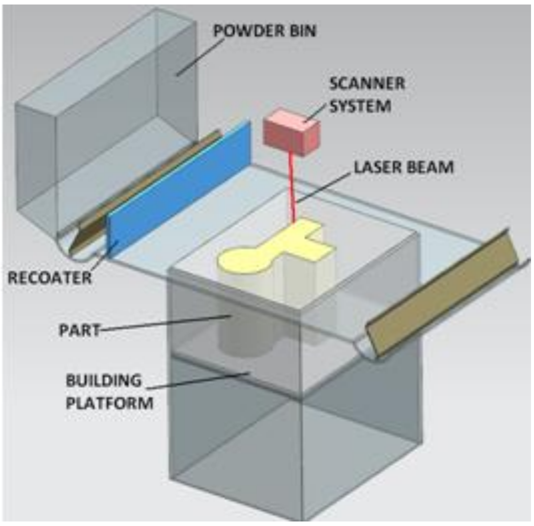


Figure 7. Process of Selective Laser Sintering [3].

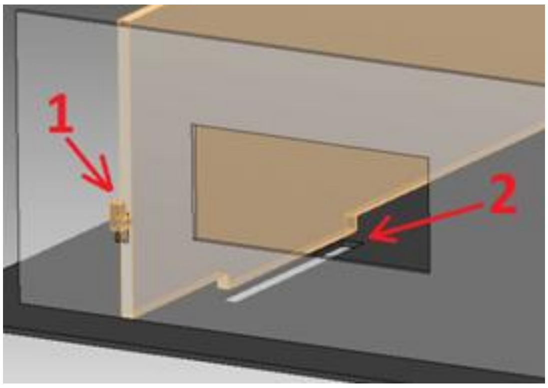


Figure 8. Tenons (1 and 2) which can be used by panels manufactured by laser cutting.

5.2. Laser cutting

One potential technology by which to manufacture the present model is also laser cutting. Laser-aided cutting has brought about a revolution in manufacturing industries, being used to cut a variety of materials such as metal, wood, glass and plastic. The laser is directed at the required surface and moved around to cut the material in the desired shape [4]. As the model consists basically from walls and floors, these all can be considered as 2-dimensional panels, which can be cut out from sheetplastic. The panels can be joined by using different types of tenons (fig. 8). Laser cutting is comparatively precise (0,05 ... 0,2 mm) [5], which is enough to produce the fits for such tenons.

Although the solution is promising it has several uncertainties. First, as the panels are joined by tenons and no bonding agent can be used to assure the demountability, the rigidity of the model is questionable. Second, the design of the tenons has to enable compatibility, which is difficult to check and assure.

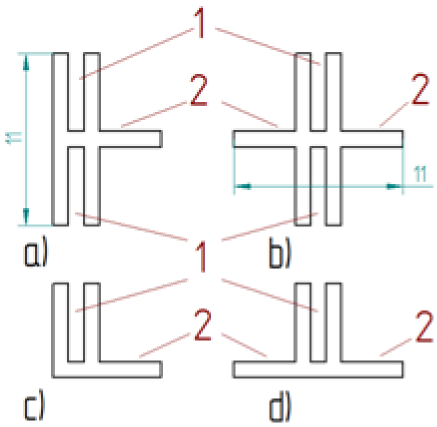


Figure 9. The cross-sections of the profiles of the construction.

6. Selective Laser Sintering combined with laser cutting

The previously described solutions have several strengths and weaknesses, hence the model was built by combining these two technologies. The walls and floors are simple panels which were reasonable to manufacture by laser cutting. SLS can be used to manufacture the complex parts like joining and construction elements etc. The design of the joining elements has to enable the easy and stable fastening of the panels, however, the amount of material has to be minimized to reduce the own weight and material cost.

7. Design and manufacturing of the model

The chosen joining elements are in principle profiles with slots (fig. 9. nr 6) for walls and supporting edge for floors (fig. 9 nr 7). Profiles c and d on figure 9 are for the first floor; a and b for the second, third and fourth floor. The model is held together by five frames of the profiles: four floors and the roof. To manufacture the frames, the frames were divided into sections of the size of building platform of the SLS system (200 x 250 mm).

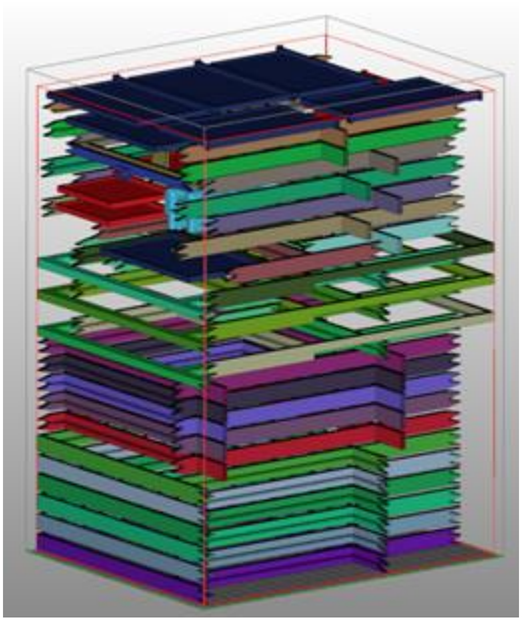


Figure 10. The positioned parts in jobfile of SLS machine.

The four floors and the roof together consisted of 58 parts of the frame. The material, used for manufacturing the parts by SLS, was PA 2200 ($\sigma = 48$ Mpa [6]).

To prepare the job-file all the parts of the frame were oriented and positioned in special software (VisCam). By preparing the job-file the parts have to be positioned tightly to maximize the effectiveness of the run, still sufficient distances must be guaranteed to avoid the merging of the parts. The positioned parts in the model of job-file are shown on the figure 10. In the next step the positioned parts were divided into layers and the paths of laser for scanning were created. After manufacturing the parts were cleaned by sandblasting.

The parts of the frames were connected and fixed by tenons and bonding agent (fig. 11). As the wall-thickness of the profiles was only 1 mm, the effective design of the.

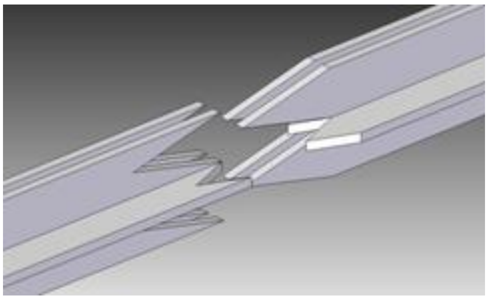


Figure 11. The tenons of the frames of constructions.

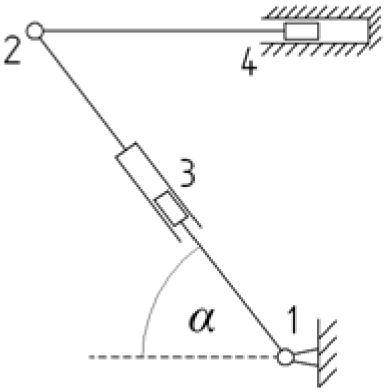


Figure 12. Kinematic chain of the facade with changeable inclination angle.

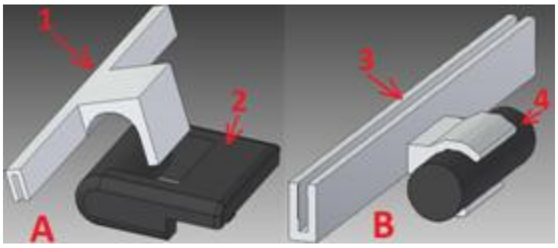


Figure 13. Joints of the movable façade.

tenons had a crucial role. The design of the tenons was driven by the objective to reduce the degrees of freedom of the joining profiles. In addition, the chosen v-shape of the tenons centered the parts to one another in gluing-operation and increased the contact-surface.

As different sized windows were required, five sets of facade panels were manufactured (0%, 20%, 40% and 70% of the facade area). All the rooms are separated by partition walls, which are also inserted into the slots like the facade panels. The partition walls are tied with each other also by the tenons to increase the rigidity of the model.

7.1. Facade with changeable inclination angle

In addition to the stepped facade the model had to have a facade at a slant the inclination angle of which is changeable. The angle α (fig. 12) of the moving facade has to be varied from 40° to 90°.

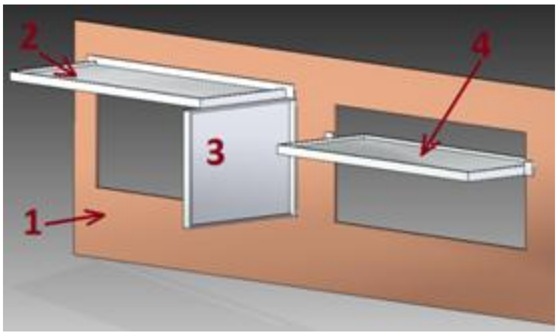


Figure 14. Sunshades which were used by the models.

The concept requires rotating joints in lower and upper side of the facade (fig 12. 6 and 7) and as the change of the inclination angle changes simultaneously the length of the facade itself and the roof, two translational joints are needed (fig. 12. 8 and 9). In addition, the moving facade has to be removable. Considering all the mentioned aspects, joints presented on figure 13 were used in the solution. The joints were designed as a part of the construction and therefore manufactured also by SLS. The pivot of the lower joint (fig. 13 B. nr 9) is a part of the frame of first floor and the rotating cylinder (fig. 13 B. nr 8) is a part of the moving facade. The rotating cylinder is fastened to the pivot by a snap. The upper joint (fig. 13 A) consists also from a pivot which is attached to the moving facade and rotating hook which is attached to the sliding roof.

The change of length of the facade and the roof is solved with panels sliding in one anothers slots.

7.2. Finished model

The final CAD model is shown on the figure 15 and the finished physical model on figure 18. The CAD assembly-model was used to verify the dimensions and eliminate errors. The physical model shown on figure 18 has the sunshades on south and east side of building. There are three types of sunshades used in the present model: sunshades which are attached above the windows (fig. 14. nr 7), onto the side of windows (fig. 14. nr 8) and between the window itself are used light-shelves (fig. 14. nr 9). All the sun-shades are attached to the facade by tenons and therefore the shades are removable. All of the sun-shades were manufactured by SLS.

The light-shelves improve uniformity of illuminance by reducing light levels near the window [7]. As the light-shelves are rather rarely used in Baltic states, it is even more essential to visualize their practical aspects to local architects and engineers.

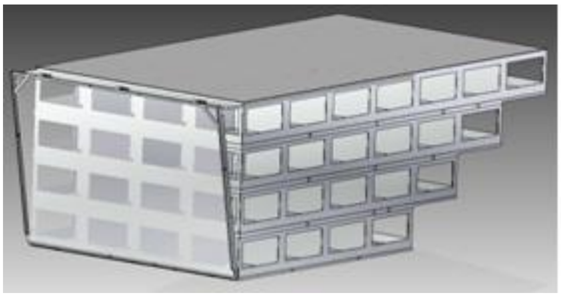


Figure 15. The final CAD model.

8. Use of a scale model

By using the developed scale model in heliodon table, mirror-box in parallel with energy and/or load simulations, students or active architects/engineers get the understanding how do different choices of façade design have different consequences in daylight distribution and cooling/heating load requirement.

Figure 16 presents the two office room layouts in scale model used in the illustrative cooling power demand simulations and the daylight availability tests.

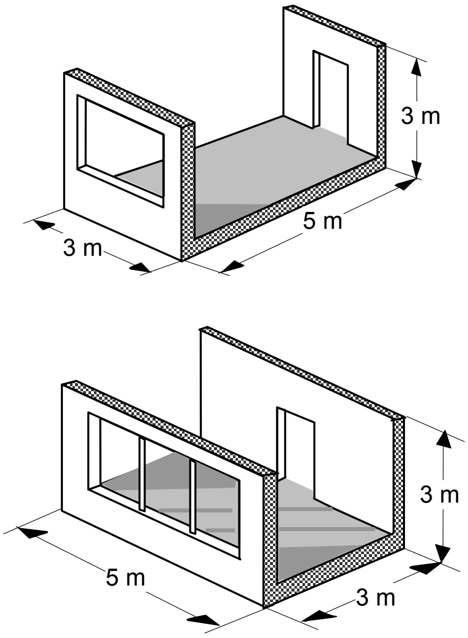


Figure 16 Upper picture: office room type 1, Lower picture: office room type 2

Figure 17 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.

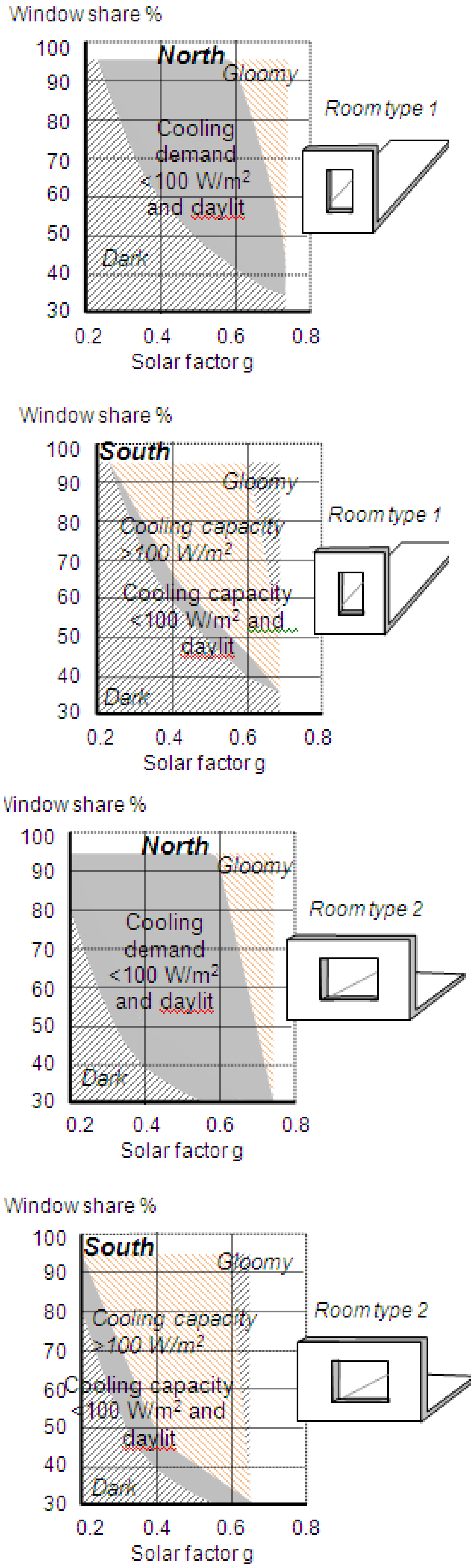


Figure 17 Possible window glass share and solar factor combination in rooms facing south for fulfilling the requirements: a cooling power demand below 100 W/m^2, a daylight factor above 2 and a difference between the highest and lowest daylight factor less than 20.

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.

As can be seen from figure 17 even small differences in choices have remarkable consequences. When making similar tests for different location the results would be completely different [11]. By using the developed scale model we are able to go through multiple different cases that give the user the needed understanding how to design climate based buildings.

9. Conclusion

In conclusion, a model of selfshielding building was developed, designed and finally manufactured using Selective Laser Sintering (SLS) and laser cutting. The model has 4 floors and facades with different design to visualize their influence of heating/cooling loads and energy demand.

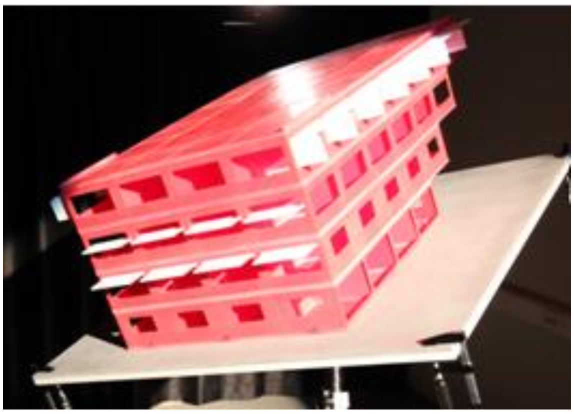


Figure 18. The final model

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References

[1] B. Liu, L.C. Zhang, J.H. Mo, B. Qian, *New method of improving parts accuracy by adding heat balance support in selective laser sintering*, Journal of Zhejiang University SCIENCE, Vol.10, No 3, 2009, pp 361-369.

[2] R.J. Wang, L. Wang, L. Zhao, Z. Liu, *Influence of process parameters on part shrinkage in SLS*, International Journal of Advanced Manufacturing Technology, Vol. 33, 2007, 498–504.

[3] Pääsuke, K.; Voll, H. (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.

[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] P.K. Wright, *21st CENTURY MANUFACTURING*, Prentice Hall, 2001

[6] EOS GmbH - Electro Optical Systems, *Material Data Sheet: PA 2200*, 01.2009

[7] S.T. Claros, A. Soler, *Indoor daylight climate–influence of light shelf and model reflectance on light shelf performance in Madrid for hours with unit sunshine fraction*, Building and Environment Vol. 37, No. 6, 2002, pp 587-598.

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

[10] Voll, H. (2009). Cooling Demand and Daylight in Commercial Buildings - The Influence of Window Design. Proceedings of the 3rd WSEAS Int.

Conf. on Energy Planning, Energy Saving, Environmental Education, Tenerife, Canary Islands, Spain, July 1-3, 2009 (65 - 70).WSEAS

[11] Kõiv, T-A.; Voll, 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.