Facade-Floor-Cluster

Methodology for Determining Optimal Building Clusters for Solar Access and Floor Plan Layout in Urban Environments

Francesco De Luca¹, Andrei Nejur², Timur Dogan³
¹Tallinn University of Technology ²University of Pennsylvania ³Cornell University
¹francesco.deluca@ttu.ee ²nejur@upenn.edu ³tkdogan@cornell.edu

Daylight standards are one of the main factors for the shape and image of cities. With urbanization and ongoing densification of cities, new planning regulations are emerging in order to manage access to sun light. In Estonia a daylight standard defines the rights of light for existing buildings and the direct solar access requirement for new premises. The solar envelope method and environmental simulations to compute direct sun light hours on building façades can be used to design buildings that respect both daylight requirements. However, no existing tool integrates both methods in an easy to use manner. Further, the assessment of façade performance needs to be related to the design of interior layouts and of building clusters to be meaningful to architects. Hence, the present work presents a computational design workflow for the evaluation and optimisation of high density building clusters in urban environments in relation to direct solar access requirements and selected types of floor plans.

Keywords: Performance-driven Design, Urban Design, Direct Solar Access, Environmental Simulations and Evaluations, Parametric Modelling

INTRODUCTION

The importance of daylight and solar access for the construction of pleasant and healthy living environments is as old as building practice itself. Exposure to solar radiation was already considered an important characteristic to be taken into account during urban planning in Ancient Greece for the determination of the orientation, height and distance of buildings (Butti and Perlin 1980) (Figure 1). In his The Ten Books on Architecture, Vitruvius underlines the importance of designing buildings specific for latitude and climate (Morgan 1914).

In more recent times planning regulations for sunlight access contributed significantly to the shape and image of cities. The New York Zoning Resolution of 1916 in order to get the desired floor area forced developers to realise the gradual stepping-back of high-rise buildings characteristic of Manhattan at the time (Willis 1995). Adequate quantity of natural light and ventilation were among the main requirements that shaped the plan of Barcelona of 1859 by Ildefons Cerdà in which the square blocks were only occupied on two opposite sides of alternating orientation NE-SW or NW-SE (Coch and Curreli 2010).
Direct solar radiation is the most appreciated source of natural illumination for its superior quantity and quality due to the full colour range more than other components, such radiation diffused by the sky or reflected by the surrounding environment (Reinhart 2014). The use of natural light as the main source for interior illumination was predominant until the second half of the last century when energy became cheap, justifying the excessive use of electric lighting and influencing the design of buildings such as the use of increased floor plan depth. The use of daylight regained importance after the oil crisis of the 1970s and consequent energy efficiency concerns (Reinhart and Selkowits 2006). The actual momentum of daylight is also due to the increasing evidence of its relation with occupants’ physiological and psychological well-being due to the variability of natural light related to the alternation of day and night that reinforce the circadian rhythm (Samuels 1990).

Nowadays regulations for daylight and access to natural light for existing and new buildings are different from country to country, and in some cases also between different cities of the same country. In Estonia direct solar access in residential premises is regulated by the standard “Daylight in dwellings and offices” (Estonian Centre for Standardisation 2010). The standard states that when a new building is realised, its mass and height should be designed in order not to deprive existing surrounding dwellings of more than 50% of their actual direct solar access hours on a daily basis during the period between 22 April to 22 August. For new buildings it is required that at least one room for apartments up to three rooms receives minimum 2.5 hours of direct solar access every day during the above mentioned period of the year.

**BACKGROUND**

The solar envelope method permits one to calculate the maximum bulk and heights of one or more buildings in relation to their location on a given lot in order to allow the surrounding existing facades to receive the required amount of direct solar access (Knowles 1981, 2003). The method uses sun azimuth and altitude angles for the specific latitude at the required hours and days of the year and shadow fences on the surrounding facades above which sunlight must be guaranteed.

Computer software to calculate solar envelope surfaces has been developed for decades. After pioneering tools usually not released to be used by designers characterised by few functionalities that permitted their use to a limited number of urban configurations, nowadays advanced tools permit one to generate solar envelopes easily with adequate flexibility to be used in different urban scenarios (Solemma 2015, Sadeghipour and Smith 2013).

The available tools integrated in popular design and parametric software nevertheless present limitations. The main ones are the difficulty to include the surrounding buildings in the calculations and the fixed start-and-end hours selection. This prohibits analyses that require more nuanced definitions of time of interest i.e. quantity of hours during the day without an exact time limits indication. To overcome these limitations, the authors have developed more...
efficient solar envelope generation workflows and methods to be used in dense urban environments and in cases of ordinances that require a different time selection as for the Estonian daylight standard (De Luca 2017a, De Luca and Voll 2017a).

The solar collection surface method has been developed to determine the minimum height at which windows of new buildings should be located in relation to the location and orientation on a given lot of the building and to the height and distance of surrounding buildings in order for glazed areas not to be overshadowed during specific hours of the day and period of the year, so as to fulfil the minimum required direct solar access (Capeluto and Shaviv 1999, 2001). The above mentioned computer tools also permit one to calculate solar collection surfaces for specific latitudes and urban configurations.

Also in this case the available tools have significant limitations i.e. calculate direct solar access hours on the horizontal surface of the lot whereas windows are located on the vertical surfaces of the building walls that receive less sun light than horizontal surfaces and, similarly to the solar envelope, use a fixed start-and-end time setting that is not efficient in the case of quantities of required direct solar access hours that is to say when it is not possible to specify which hours.

To tackle these limitations a workflow has been developed to generate more efficiently solar collection surfaces in relation to the Estonian daylight standard with the scope to determine portions of building facades fulfilling the requirement of a minimum 2.5 hours of direct solar access in the required period (De Luca and Voll 2017b).

Nevertheless the solar collection surface method, at the basis of actual computer tools or of the mentioned advanced workflow, is only efficient for a single building characterised by a simple rectangular footprint. The reason is that it cannot take into account self-shading of articulated buildings or shading of a cluster of buildings on each other because solar collection surfaces are built on empty lots to be used in a variety of scenarios.

In order to efficiently evaluate the direct solar access performance of building clusters in urban environments, analysis of sun light hours needs to be performed for each configuration. In this regard a method has been developed that takes into account maximum building volumes through a solar envelope on the given lot, performs analysis of sun light hours and computes the portions of the building façade that fulfil or don’t fulfil the direct solar access requirement of new residential premises of the Estonian daylight standard and calculates floor areas (De Luca 2017b).

The algorithm developed permits one to compare a multitude of building cluster pattern variations to evaluate trade-offs of façade ratios fulfilling the direct solar access requirement against building density (total buildable floor area). While it is useful for initial investigations the method presents two limitations: some floor contour polylines generated from the intersection of the building masses and the solar envelope are too irregular to be used for actual design; and more importantly the performance evaluation is limited to the envelope of the cluster buildings without taking into account its influence on the possible design of building floors.

The present research constitutes a significant advancement of the previous work in relation to the mentioned limitations. It uses three-dimensional cells to model the building masses for more sound envelopes and floor subdivision and it performs an initial floor plan division in relation to the façades direct solar access performance. Different floor plan layouts are tested against the floor plan divisions for the evaluation and optimisation of building cluster layouts.

Since the 1960’s several methods for automated floor plan layout design have been developed such as Shape Grammars, Generative Systems, Constraint-based, Cellular Automata and Space Syntax (Lobos and Donath 2010, Schneider et al. 2010). While a vast amount of research on automated plan layouts exists, a lot of it is dedicated to building plausible form for virtual game environments (Lopes et al. 2010).
Currently there is a lack of studies that include environmental factors as a constraint for the interiors design. This study uses graph traversal as the basis for the development of a search algorithm (Skiena 2008). Graph theory is used in different studies for floor plan optimisation, mostly to analyse relationships of interior spaces through graph nodes and edges in the form of bubble diagrams and to provide a number of possible design solutions and single apartment layout patterns (Nassar 2010, Nourian et al. 2013).

Due to the large quantity of dwellings, up to several hundreds, present in each building cluster variation and the initial stage of this research phase, graph theory is used in this study for a more limited task. The search algorithm realised automatically divides floor plans constituted by squared cells on the basis of façades direct solar access performance in order to evaluate the fitness of different floor plan layouts determined by the designer and the performance of building cluster variations.

**METHOD**

The present research develops a performance-driven design method to find optimal configurations of building clusters for direct solar access in urban environments, buildable floor area and floor plan layout. The direct solar access performance is related to the Estonian daylight standard for existing and new buildings. The aim is to realise high density building clusters with the largest possible quantity of total floor area and the largest ratio of new dwellings fulfilling the solar access requirement using three different apartment size options. The work has been developed integrating parametric and environmental design tools available in Grasshopper for Rhinoceros and custom tools realised in Python. The parametric model developed for the performance evaluation of building clusters in urban environments is composed of four parts.

**Building pattern generation**

For the development of the method, the lot containing the building clusters is located in a dense urban environment. On the lot the solar envelope is generated in advance to determine the maximum height of the cluster buildings, on the basis of their size, location and orientation, using the mentioned advanced workflow (Figure 2). The maximum height of the solar envelope is set to 45 metres, the same as the highest surrounding buildings.

In the current phase of the work, to limit the complexity of the model all the cluster configurations present four buildings, each one located in one equal sector obtained from the subdivision of a squared lot of 150 m in size. The first part of the parametric model permits one to change the width, location and orientation of every cluster building inside its own area independently. The building depth is fixed (24 m) and the orientations allowed are perpendicular to each other (90° difference). The building's footprint sizes are always a multiple of 3 m. The parametric model
allows a minimum distance between buildings of 8 m as required by local fire prevention regulations.

Consequently the planar squared cells 3-metres in size are extruded by 3 metres to form the polyhedra of the building ground floor. A vertical array of polyhedra with 15 steps generates the maximum building mass composed by cubic cells divided by floor. The parametric model determines the allowed height of the four buildings, deleting the floors located outside the solar envelope mesh.

The final part of the first block of the parametric model sorts the buildings’ cells in three groups: Outer, the most external building cells; Inner, for a depth of two cells that together with the outer cells set 9 m as the available floor depth for the dwellings; Core, the cells not accounted as a usable floor plan where stairs, elevators, circulation and building systems are located (Figure 3 top).

**Direct solar access**

In the second block of the parametric model, direct solar access simulation, is performed. The environmental design tool generates the sun path for the required period, the sun’s position is calculated every 15 minutes and the relative sun vectors are used to calculate the quantity of sun light hours received by each outer building cell.

For the scope the vertical external faces of the outer cells of each floor/building are isolated and the total quantity of sunlight hours during the required period is calculated. A portion of the parametric model computes if each outer cell has at least one external surface, of maximum two, that receives the required minimum 2.5 sunlight hours per day. If the condition is met then the cell fulfils the requirement.

The outer cells are divided into two groups and are colour coded: those that fulfil the requirement, are coloured light blue and marked with the value 1; those that don’t fulfil the requirement, are coloured dark blue and marked with the value 0. In this way it is possible to assess the portions of the building façades that fulfil or don’t fulfil the requirement for each cluster building and for each variation (Figure 3 center). The information relative to the façade direct solar access performance is used for division of the floor plans.

**Floor plan division**

The third section of the parametric model generates a division of each floor plan of every cluster building on the basis of the floor façade performance relative to the direct solar access requirement. The inner cells of the floor plan are sorted and associated to the outer cells that fulfil the requirement, are colour coded light blue and assigned to the group marked with value 1, or are associated to the outer cells that don’t fulfil the requirement, colour coded dark blue and assigned to the group marked with value 0.
The allotment of the inner cells is executed through a tool developed for the present research based on the Breadth-First Search (BFS) algorithm. BFS explores a graph constituted by vertices \( V \) and edges \( E \) connecting the vertices to select all the vertices reachable from a source vertex \( S \) through the adjacency list of the graph and computes the smallest number of \( E \) between \( S \) and \( V \) i.e. the shortest distance (Cormen et al. 2009).

On the basis of the adjacencies of the floor plan cells a network (graph) of nodes and edges is built. Each cell is a data node connected to its face sharing neighbours via the graph edges. Starting from the inner cells adjacent to the outer ones, iteratively the algorithm assigns each inner cell to group 1 or 0 on the basis of the number of neighbours of group 1 or 0. A rule set by the designer defines the order of precedence in cases of cells adjacent to the same quantity of cells of both sets. The process stops when all cells are assigned. In this way each floor plan is divided into areas influenced by the facade portions that fulfil or don’t fulfil the requirement. The core cells are excluded by the search process (Figure 3 bottom).

**Floor plan layout evaluation**
The floor plan cells assigned to group 1 (light blue) and group 0 (dark blue) are used to evaluate the ratio of dwellings that fulfil or don’t fulfil the requirement of specific layouts chosen by the designer. For the development of the method three floor plan layouts are chosen (Figure 4).

Floor plan layout type A is composed of small apartments, all of 6 cells (2 rooms - 54 m²). The layout of type B is composed of small and medium size dwellings of 6 and 9 cells (2 rooms 54 m² - 2-3 rooms 81 m²). The floor plan layout of type C is realised by medium and large size apartments of 9 and 12 cells (3 rooms 81 m² - 108 m²). Every dwelling of every size, 6, 9 or 12 cells, fulfils the requirement if it contains at least 3 cells of group 1. In this way division of the floor plan is used to evaluate if each apartment has an area ratio suitable to a minimum of one room which receive the required direct solar access.

Optimal configurations of building clusters are those that permit to build the maximum total floor area with the maximum ratio of dwellings fulfilling the requirement.

**CASE STUDIES**
The method can be applied in different ways during the schematic design phase to find the optimal building cluster configurations for direct solar access, floor plan layout and total floor area. Possible applications are through manual selection of buildings location, size and orientation parameters and activation of the simulation and computation process, automation for the determination of all possible parameter combinations or through optimisation processes.

![Figure 4](image)

Scheme of floor plan layout type A with units of 6 cells (top), type B with units of 6 and 9 cells (center) and type C with units of 9 and 12 cells (bottom) for one of the four possible buildings width.
As the first and the second methods are very time consuming, and additionally the first does not guarantee that optimal results are found, multi-objective optimisation through the Grasshopper plugin Octopus (Vierlinger and Bollinger 2014) has been used for the study cases. The objectives used are:

- Objective 1 - Maximisation of the number of apartments that fulfil the requirement (MAF)
- Objective 2 - Maximisation of the total buildable floor area (MFA)
- Objective 3 - Maximisation of the total number of apartments (MNA)

The first and second objectives are conflicting because massive buildings overshadow each other, thus decreasing the ratio of apartments fulfilling the requirement. The scope is to find optimal building cluster configurations for Objective 1 and 2 and trade-offs of the two. The third is a reinforcement of Objective 1 for the generation of high density clusters and permits to evaluate combinations of floor plan layout types for each building cluster configuration.

The method is tested on two case studies with the same lot but with different urban environments. In the first case study, buildings of different heights surround the plot at a close uniform distance suitable for a street, whereas in the second case study some buildings are more distant, forming two open areas between the lot and their location (Figure 2).

For each case study four multi-objective optimisation processes are performed using the floor plan layouts of type A, B and C and additionally a “mixed” type M for all of the cluster buildings. In order to maximise the number of apartments fulfilling the requirement and the total number of apartments for every cluster variation, a portion of the parametric model selects the layout with the highest ratio of dwellings fulfilling the requirement (up to 100%) among the floor plan layout types A, B and C for each floor of every building. Using floor plan type M each cluster building is constituted of different floor plan layouts.

Case study 1
Due to the shape of the solar envelope characterised by two slopes approximately symmetrical toward the east and west, a uniform slope towards the north and a steep slope towards the south, the vast majority of the optimised cluster configurations for the four floor plan layout types present buildings with a high aspect ratio footprint with the long sides aligned north-south (Figure 5).

This is the building orientation with a larger floor area and smaller number of apartments not fulfilling the requirement located on the short northward side that hardly receive the required direct solar access in dense urban environments. The cluster configurations optimised for MAF present buildings with a larger distance between them. This forces the buildings to be located in areas of the plot where the height of the solar envelope is shorter, thus reduc-
ing their total floor area and total number of apartments. The configurations optimised for MFA and MNA present tight layouts toward the centre of the lot, since this is the area in which the height of the solar envelope is maximum, at the expense of the ratio of dwellings fulfilling the requirement.

Using the floor plan layout type A or B it is not possible find a building cluster configuration with all of the apartments fulfilling the requirement, whereas type C permits this at the expense of total buildable floor area and number of apartments (Table 1). The reason is due to the larger size of the apartments with a larger façade used for floor plan layout type C, which increases the possibilities to have at least one room or window (façade module) receiving the required sun light. Using floor plan layout type M, it is also possible to find building clusters optimised for MAF (100% of apartments fulfilling the requirement) and with a significant increase in the number of dwellings compared with type C.

**Case study 2**

In the second case study the urban form generates a solar envelope characterised by a more articulated shape. Comparing the one of case study 2, it presents the addition of two bulges located toward the open areas beside the lot. As the solar envelope is larger than in case study 1 the majority of the building cluster configurations present larger maximum floor areas.

For the same reason as for case study 1, the building cluster configurations optimised for MAF present buildings with a high aspect ratio footprint, aligned north-south and located quite far apart from each other in order to reduce mutual overshadowing at the expense of total floor area and number of apartments. Conversely the different shape of the solar envelope of case study 2 influences the building cluster configurations optimised for MFA and MNA to a greater extent. Searching for larger mass buildings, in many cases the optimisation solver selected the orientation east-west for one or both of the buildings located under the solar envelope bulges, since this allows to take advantage of large footprints and the maximum possible height (Figure 6).

Similarly to case study 1 the floor plan layout type C and M are those that permit one to design building clusters with all of the apartments fulfilling the direct solar access requirement (100% of the dwellings). Also for case study 2, the use of buildings with floor plan type M permits the significant increase of total number of apartments compared with floor plan layout type C, even though the maximum floor area remains similar. The taller buildings comparing case study 1 of the cluster configurations optimised for MFA and MNA, despite being orientated east-west thus exposing the long side to the north, permits to obtain higher ratios of apartments fulfilling the requirement due to reduced overshadowing of the buildings surrounding the lot (Table 1).

![Figure 6](image_url)

*Figure 6*  
Building cluster configurations of case study 2 optimized for MFA and MNA using floor plan layout type A (left) and for MFA using floor plan layout type M (right).
Table 1
Results of the multi-objective optimization processes for case study 1 and 2. MFA maximum floor area (m²), MAF maximum ratio of apartments fulfilling the requirement (%) and MNA maximum number of apartments. Bold text indicates the maximum values for each case study/floor plan type.

<table>
<thead>
<tr>
<th>Case study 1</th>
<th>MAF</th>
<th>MFA</th>
<th>MNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>82.2</td>
<td>44064</td>
<td>816</td>
</tr>
<tr>
<td>B</td>
<td>73.6</td>
<td>42768</td>
<td>610</td>
</tr>
<tr>
<td>C</td>
<td>85.2</td>
<td>42552</td>
<td>420</td>
</tr>
<tr>
<td>M</td>
<td>80.6</td>
<td>41796</td>
<td>364</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case study 2</th>
<th>MAF</th>
<th>MFA</th>
<th>MNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>89.7</td>
<td>49140</td>
<td>910</td>
</tr>
<tr>
<td>B</td>
<td>91.1</td>
<td>45252</td>
<td>642</td>
</tr>
<tr>
<td>C</td>
<td>95.1</td>
<td>43200</td>
<td>424</td>
</tr>
<tr>
<td>M</td>
<td>90</td>
<td>43632</td>
<td>620</td>
</tr>
</tbody>
</table>

CONCLUSIONS
The proposed study presents a method for the evaluation and optimisation of building clusters in urban environments during the schematic design phase in relation to direct solar access requirements in Estonia, buildable floor area and preferred type of floor plan layout.

The method has been applied to two case studies on two different urban areas through multi-objective optimisation. In this way it has been possible to determine building masses that respect the rights of light, allowing surrounding existing building facades to receive at least 50% of the existing daily insolation, optimised for the objective of the highest possible ratio of new apartments that fulfil the solar access requirement of a minimum 2.5 hours of direct sun light in at least one room every day for the period between 22 April and 22 August or optimised for the objective of the largest total buildable floor area or for trade-offs of the two objectives. The method also permitted to compare the performance of floor plan layouts composed by different apartment types and sizes in terms of ratio, total and per floor/building, of dwellings that fulfil the direct solar access requirement.

The developed method can easily be adapted to other countries and locations that use the quantity of sun light hours as a daylight requirement by changing the amount and type of selection of the daily hours and period of the year, but not to those countries whose daylight regulation is based on land use such as setbacks, floor to area ratio and fixed heights.

This study emphasises the potential of performance-driven methodologies in architecture and urban design through the integration of computational design and environmental simulations for building compliance and occupants’ comfort. Despite the well-defined field of investigation the present research makes it evident that computational design methods can efficiently integrate the quantitative performance of buildings and urban districts with the formal aspects of the architectural discipline.

The future work of this research has three directions. The first is to improve floor plan optimisation through the automatic selection of single dwelling types and not floor plan types like the present study, and through automated floor plan layout design. The second is to include the possibility of a varying number of cluster buildings. The third is the integration in the studies of other performance aspects such as interiors daylight, energy and urban microclimate, to improve the whole performance and quality of the living environments.

REFERENCES
Solemma, LCC 2015, DIVA version 4, www.solemma.com/, last accessed 19.05.2018