A NOVEL MULTI-CRITERIA WORKFLOW BASED ON REVERSE SOLAR ENVELOPES FOR THE DESIGN OF RESIDENTIAL CLUSTERS

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ABSTRACT

This paper proposes a novel multi-criterion workflow based on Reverse Solar Envelopes (RSEs) for the design of residential clusters. This eight-step semi-automatic workflow was implemented as a new open-source Grasshopper plug-in for Rhinoceros and used to design building envelopes in two existing urban areas located at different latitudes. In each iteration, a building massing optimization was conducted in terms of the Floor area ratio (FAR) and ratio of the facade with a certain level of solar access (SAr). It was possible to find, in one hour per plot of computation time, the trade-off design solution for different minimum solar access (SA) requirements. Maximum relative difference in terms of each new building's trade-off performance ranges between 65% and 200%. The consideration of stricter SA requirements could compromise FAR values in high latitudes. Moreover, the method could provide design solutions that largely fulfill the requirements without increasing the computation time.

Keywords: Solar access, building massing, optimization, generative design, grasshopper plug-in

1 INTRODUCTION

By 2030, the 80% of the world population will live in cities (Sanaieian et al. 2014). Sunlight has been proved a key influence factor on human health and performance (Samuels 1990; Lockley 2009). Moreover, the consideration of key aspects of daylight in buildings such as solar access (SA) are present in standards like the European standard EN 17037:2018 (European comission 2018). Architects and researchers know about the importance of considering the solar envelope (SE) during early design stages (Knowles 1980; Isaac Guedi Capeluto and Plotnikov 2017; I G Capeluto and Shaviv 2001). By considering the SE, the building massing process could depend on surrounding buildings (De Luca, Nejur, and Dogan 2018), design objectives, the method to generate the solar envelope (Sepúlveda and De luca 2020), solar ordinances (De Luca and Dogan 2019) among others. Subtractive methods (Stasinopoulos 2018) to generate solar envelope such as the Reverse Solar Envelope (RSE) based on sunlight our selection criteria have been proved more efficient than traditional SE for a wide variety of urban contexts and solar access ordinances (De Luca and Voll 2017; De Luca, Dogan, and Sepúlveda 2021; De Luca and Dogan 2019). In addition, RSE has been integrated with attribute information of point cloud data in a novel computational workflow based on the generation of voxel-based design approach (Alkadri et al. 2020).

In practice, several tools are available to help architects to consider SA requirements during the design process: for the generation of the traditional shadow fence-based (Sadeghipour Roudsari 2012; Solemma LLC 2022) and solar ordinance/context-dependent SEs (Sepúlveda and De Luca 2022). For the design of building clusters, there are a wide variety of computational approaches: from traditional obstruction mask method (Pereira, Silva, and Turkienikz 2001) to sophisticated methods based on multi-objective evolutionary optimization (Wu et al. 2021) or combining parametric and machine learning approaches (Feng, Lu, and Wang 2019). However, the learning curve for these novel approaches could be an important barrier for the user in practice (Nault et al. 2018). Moreover, solar radiation and energy have been typically considered as objective variables in previous studies (Natanian and Wortmann 2021; Wang, Song, and Tang 2020; Xia and Li 2021). The impact of neighborhood layouts on solar radiation and resilience have been also studied with generative design methodologies within the Chinese (Wang, Song, and Tang 2020) and Canadian contexts (Hachem-Vermette 2019; Hachem, Fazio, and Athienitis 2013). Despite previous investigations integrated the SE concept in developed massing techniques for multiple urban blocks, the applicability of these are limited by climatic and/or solar ordinance considerations (Vartholomaios 2015; Kim et al. 2017; De Luca 2017; De Luca, Nejur, and Dogan 2018). Nevertheless, there is a lack of open-source and intuitive design clustering methods that on one hand, can guarantee different solar access levels not only for the new but the existing buildings, and on the other hand, provide the practitioner enough freedom to choose building footprint orientation, shape, and position within in each buildable plot. Consequently, the aims of this paper are the following:

- To implement an iterative workflow for building cluster massing based on the novel Reverse Solar Envelope as Grasshopper tools available for practitioners;
- To test the use of the proposed workflow to optimize the solar access and floor area ratio of residential clusters in two existing medium-dense urban areas located at different latitudes;
- To analyze the simulation time required by the proposed workflow as well as the overall cluster performance when considering two different minimum solar access requirements.

2 METHODOLOGY

We used a simulation-based methodology. Specifically, the workflow proposed in this paper is based on an updated Grasshopper components called Solar Envelope Tools (SET) as part of the Grasshopper plug-in Solar Toolbox for Rhinoceros (Sepúlveda and De Luca 2022; Sepúlveda and De luca 2020). Figure 1 shows the proposed design process of a hypothetical residential cluster. We developed new tools and used them through the proposed workflow to design building envelopes in two real urban areas located in Estonia and Netherlands (section 2.10). The workflow consists of eight steps, which are explained in the following subsections (from section 2.1 to 2.9). For each step, all the required inputs are described.

2.1 Urban Area Definition

This step corresponds to Figure 1a. We defined the existing surrounding buildings of the urban area under development as mesh geometry (input 1). This step includes the definition of the collection of windows as surface geometry for which solar access must be guaranteed (input 2). In addition, the set of buildable plots should also be defined in this step (input 3) (e.g. A, B, C, and D).

2.2 Critical Plot Identification

When an urban planner or designer have different buildable plots, one challenging decision would be which sequence of plots should be followed to design a building cluster. A random design sequence of plots could limit new buildings volume/area and solar access levels not only of the existing but new buildings. In this step of the workflow (Figure 1b), a simple criterion based on the metric known as obstruction index (OI) is used to determine the most critical buildable plot (De Luca, Dogan, and Sepúlveda 2021). The algorithm consist of calculating the number of visible sun rays (input 4= related to a specific analysis period) blocked by each plot-related theoretical block (input 5= maximum height of 20 m). This OI can be calculated as the sum of the output called as VisSVOutCore from the updated SET component SunVectSel (inputs 6-9= e.g. MinAltitude=10°, DeadAngle=10°, CntrlGeo=0, and VectorsSel=0). For example, as can be seen in Figure

1b, the number of total blocked sun rays from the existing 24 windows is 708, 551, 815, and 1240 for the buildable plots A, B, C, and D, respectively when considering a maximum height of 20 m. Thus, the most critical plot is D whose OI is maximum. This implies lower RSE volume, hence, the most limited design flexibility among the four plots.

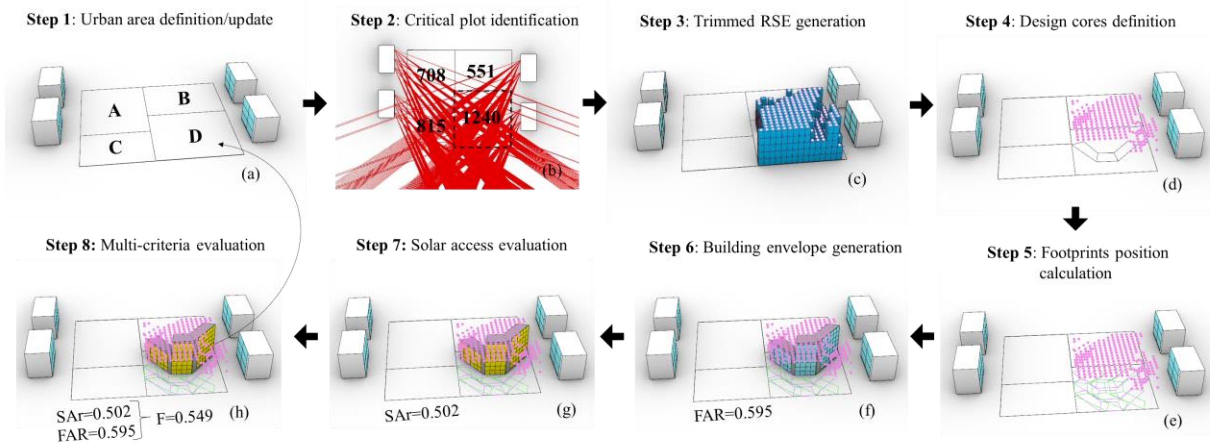

Figure 1: Workflow proposed in this investigation to design residential clusters based on Reverse Solar Envelopes (RSEs). Obstruction index is the number of blocked sun rays per each theoretical volume. F= Fitness value, FAR=Floor-area ratio and SAr= Solar Access ratio=ratio of the facade that fulfill the SA requirements (e.g. a minimum of 1.5 direct sun hours per day according to the EN 17037:2018).

2.3 Trimmed RSE generation

Once we have identified the most critical plot, we generated the RSE using the novel component called GenRSE (Figure 1c). This component generates the RSE and the “trimmed” RSE (tRSE) from inputs such as: sorted and selected sun vectors from each window (SunSelVect and Windows) from the component SunVectSel (inputs 6-8 and inputs 9-10: e.g. VectorsSel=1 and VectorsType=6), maximum height (MaxHeight), and 3D cell dimensions (inputs 11-13: e.g. GridSizeX=2.8 m, GridSizeY=2.8 m, and FloorHeight= 4 m). The typical RSE volume is formed by a group of voxels whose OI is null (Figure 1d). In addition, the tRSE represents the centroids of the cell caps located at the maximum height for each XY subdivision with uninterrupted continuity from the plot surface until these bottom cells (Figure 1d). Thus, the volume under tRSE is always equal or lower than the RSE volume, eliminating the classic hourglass shape of the RSE.

2.4 Design Cores Definition

The next step consists of defining the footprint of the new building (input 14) (Figure 1d). This decision can be influenced by the designer and/or developer’s practice. Therefore, this workflow provides freedom to select the footprint of the building as well as orientations of interest. For instance, we show in Figure 1e an open U-shape building footprint oriented towards South. We used in-built Grasshopper components to define the building footprint (shape and size) and its orientation.

2.5 Footprints Position Calculation

Once the building footprint is defined, the new component called FootPrintsGen generates all the geometrically viable positions of the building footprint within the buildable plot (output InFootPrints) (drawn footprints shown in Figure 1e). Specifically, the inputs are the Plot (input 3), DesignFootPrint (input 14), and step sizes for x and y direction of the plot named as OffSetX (e.g. 3 m) (input 15) and OffSetY (e.g. 3 m) (input 16), respectively.

2.6 Building Envelope Generation

The sixth step consists of generating the building envelope: volumes and windows (Figure 1f). Firstly, the designer can define using in-built Grasshopper components different partitions of the building footprint (e.g. 3 segments shown in Figure 1e) and then, extrude each footprint partition until the maximum tRSE volume (input 17) calculated in the third step (section 2.3). This operation is conducted by using the new SET components HeightsGen, WindowsClean, and basic Grasshopper in-built functions. Thus, HeightsGen can calculate the extrusion height for each footprint partition to fit the new building volume within the tRSE (considering inputs 5 and 13). Thus, the building volumes can be extruded and windows (e.g. 2.5x2.5 m) generated using in-built Grasshopper components. In addition, the FAR metric, which is well known by architects and designers, is calculated as the ratio between the new building total floor area and the buildable plot area. Finally, the component WindowsClean can be used to eliminate undesirable generated windows (input 18) on inner partitions formed between the new building volumes (input 19).

2.7 Solar Access Evaluation

Once having the volumes and windows of the new building, a solar access evaluation is needed to quantify the hours with visible sun of the new building's windows. This SA evaluation is conducted with the updated SET component SunVectGen and the novel components SunHoursStats and WindowSel. In order to conduct this sun hours analysis, we need to define an auxiliary plot (input 20, e.g. different from the buildable plots A, B, C, and D) to input to the SunVectGen component as well as information about the urban context including the new building volumes (inputs 6-9 and input 19). The output VisibleSun is used as input in SunHoursStats (input 21) component, which calculates the minimum number of daily sun hours (MinSH) within the analysis period associated to each window (MinID). The component WindowSel uses (inputs 22-25) the windows surfaces, MinID, MinSH, and SHt (threshold of minimum number of daily sun hours imposed by the designer) to generate the windows whose MinSH is equal or higher than the threshold SHt given by the architect/designer (e.g. 1.5 h as the minimum level of solar access defined by the EN 17037:2018). Finally, the second metric of interest in this workflow, named as SAr represents the ratio between the number of the windows that fulfill SHt and the total number of windows considered in this analysis. For instance, in the building combination shown in Figure 1g, the half (SAr=0.502) of the windows fulfill the minimum SA requirements defined by the EN 17037:2018 (minSH=1.5 h/day).

2.8 Multi-criteria Evaluation

The step 8 of the proposed workflow aims to conduct a comparison between all new building combinations (Figure 1h): extruded volumes from different orientations and footprint positions within the critical buildable plot. Specifically, we used the objective function F (1) to quantify how good is one design combination.

$$F(FAR, SAr) = \alpha FAR + \beta SAr\ (-),\ \ \alpha + \beta = 1 \tag{1}$$

Where weight coefficients values (inputs 26-27) α and β are between 0 and 1. Thus, the fitness value F can be equal or higher than 0, and represents how good is a building combination in terms of received solar access and FAR, the higher, the better. The architect/designer should define the value of these weight coefficients according to a specific criterion of interest. For example, 100% FAR-based criterion would be α=1 and β=0. Conversely, α=0 and β=1 if the designer considers a 100% SAr-based criterion. However, if the designer considers a balanced trade-off criterion (50%-50%), α=0.5 and β=0.5 (Figure 1h).

2.9 Urban Area Update

The last step of the workflow consist of updating the urban context shown in Figure 1a with the new building mass displayed in Figure 1h. The designer should add the new building volumes and windows that fulfill the SA requirements (SHt) from section 2.7 and 2.8 in the next iteration, which follows the same steps explained from section 2.1 until 2.7. Typically, the workflow should be applied NP-1 times, being NP the number of buildable plots. We should apply the workflow once per plot. For the last iteration, it is not any more necessary the identification of the most critical plot, hence; step 2 is not necessary (Figure 1b).

3 CASE STUDIES

In this work, two cases study were considered. Specifically, our aim was to design a new residential cluster in each plot with the best trade-off performance (the highest fitness value F) between FAR and SAr metrics defined in section 2.8. A plot of 34979 m^2 is located in Tallinn, Estonia (59.4370°N, 24.7536°E) (Figure 2) with a target total building floor area of 12000 m^2 and a plot of 15126 m^2 is located in Zoetermeer, Netherlands (52.0607°N, 4.4940°E) with a target total building floor area of 9000 m^2 (Figure 3). Both plots are located in medium-dense urban areas of these cities, and the maximum buildable height was set to 20 m. The Zoetermeer plot is surrounded by buildings of 9-36 m in height on the south-west and north-west sides. The Tallinn plot is surrounded by buildings of 7-16 m in height in all directions except from the south side. We divided Tallinn and Zoetermeer plots into 5 (Figure 2b) and 4 (Figure 3b) buildable plots, respectively. We used different geometric layouts to test the novel method in different design conditions. For the Tallinn case, we chose a radial distribution of the plots to have spaces for green areas between buildings of the cluster. In addition, for Zoetermeer case, a more classic subdivision was considered to exploit the smaller plot areas in comparison with Tallinn case.

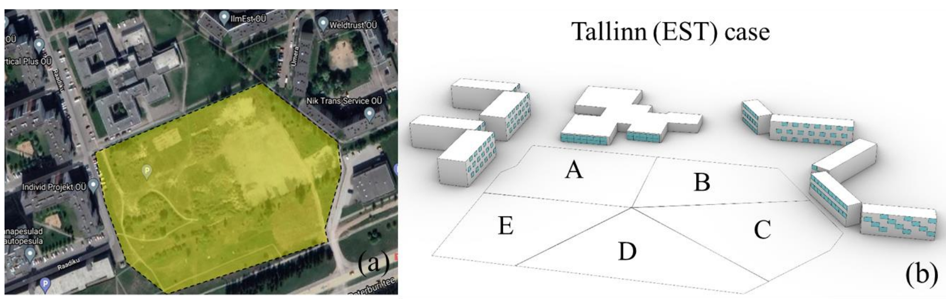

Figure 2: Top view of the actual development area located in Tallinn, Estonia (Google maps 2022) (a). Perspective view of the virtual model and buildable plots created in Rhinoceros for Tallinn case (b).

We considered two different thresholds for the minimum sun hours per day for each surrounding buildings' window (VectorsSel=1) (SHt defined in section 2.7): 1.5 h/d and 3 h/d (VectorsSum=SHt), which correspond to a minimum and a medium level of sunlight exposure/solar access according to the EN 17037:2018. The analysis period was set from February 1 until March 21 (all the possible days proposed in the EN 17037:2018) and the time step was set to 2 (1 sun position every 30 minutes) as already used in previous investigations (Sepúlveda and De luca 2020; De Luca and Dogan 2019). For the generation of the RSE (section 2.3) in both case studies, we set both grid sizes (GridSizeX and GridSizeY) as the shortest plot dimension divided by a factor of 25. The floor-to-floor height was set to 4 m for both cases. The method used to generate the sorted and selected vectors with the SunVectSel component (section 2.3) is based firstly on the maximum angular distance from the center of the plot (Cntrlgeo=1 and DesignPoint= centroid of the plot). Secondly, this sorting method prioritizes sun vectors with the highest sun altitude angles (VectorsType=6). The main reason to choose this method among the 11 methods available in the new SET component SunVectSel is that methods based on sun altitude and angular distances proved to maximize the RSE volume, providing design flexibility (Sepúlveda and De luca 2020; De Luca, Dogan, and Sepúlveda 2021).

We took into account two different building footprints: V-shape and Z-shape with areas of 745 m^2 and 799 m^2, respectively. In addition, eight different orientations were considered: from north (N) to north-west (NW) every 45°. The offset distances (OffSetX and OffSetY) to generate all the footprints positions (section 2.5) were set to a sixth of the shortest dimension of the plot. In total, the different plots for Tallinn and

Zoetermeer cases contain 489 and 173 oriented building footprint combinations per chosen SHt (as mentioned, SHt=1.5 h/d and 3h/d), respectively.

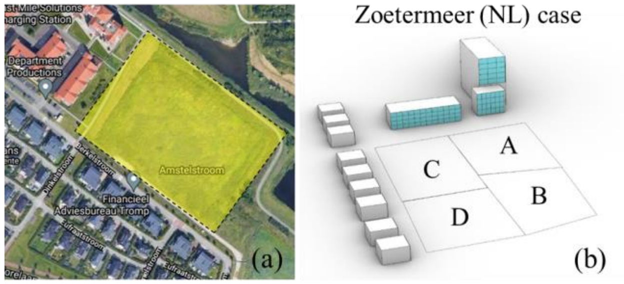

Figure 3: Top view of the actual development area located in Zoetermeer, Netherlands (Google maps 2022) (a). Perspective view of the virtual model and buildable plots created in Rhinoceros for Zoetermeer case (b).

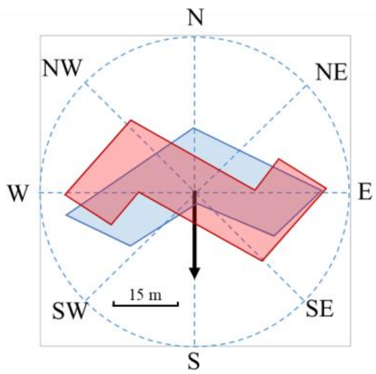

Figure 4: The two building footprints and eight orientations considered for each case study.

4 RESULTS AND DISCUSSION

4.1 Tallinn Case

The building performance metrics F, FAR, and SAr for each workflow iteration of the Tallinn case are shown in Figure 5. The optimal order to design the residential cluster is the following: A, E, C, D, and B. The FAR range associated to the optimal residential cluster is approximately 0.34-0.54 (floor building areas: 2365-3995 m^2) and 0.16-0.54 (floor building areas: 1113-3995 m^2) for a SHt of 1.5h/d and 3h/d, respectively (Figure 5a and 5b). The SAr range is approximately 0.45-0.50 and 0.37-0.51 for a SHt of 1.5h/d and 3h/d, respectively.

When considering a minimum level of solar access according to the EN 17037:2018 (SHt=1.5 h/d), the F fitness value could vary in the range 65-188% in relative terms with respect to the minimum F. Moreover, when considering SHt=3 h/d, the F variation could be between 89% and 200%. The magnitude of these performance variations strengths the use of the proposed workflow. Meaning that if the designer had chosen a random building footprint (e.g. only considering a target building floor area) and orientation for each plot, it would be unlikely to obtain the optimal residential cluster that fulfills both: the target building floor area and a preferred level of solar access.

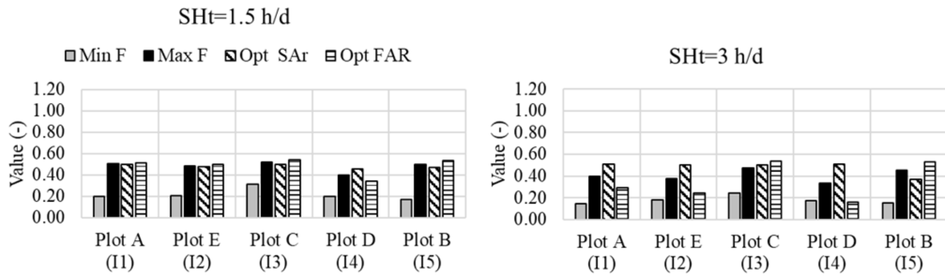

Figure 5: Building performance metrics for Tallinn case when imposing a certain minimum number of sun hours (SHt) of 1.5 h/d (a) and 3 h/d (b).. Min=Minimum, Max=Maximum, Opt=Optimal, and I=iteration.

The simulations were running in a 64-bit Windows10 machine with processor Intel(R) Core(TM) i7-8850H CPU 2.60GHz. For Sht=1.5 h/d, the simulation time required by each workflow iteration was 157, 43, 110, 33, and 95 min for A, E, C, D, and B plots, respectively. For Sht=3 h/d, the simulation time required by each workflow iteration was 120, 43, 31, 33, and 95 min for A, E, C, D, and B plots, respectively. The difference between simulation times was caused by different factors. The first aspect is the plot area and shape differences: the larger and more squared plot area, more number of footprints positions. The second factor is the trimmed RSE volume, which can vary depending on the windows, surrounding buildings, and SHt value considered in the analysis: the larger the tRSE volume, the larger the new building is and more number of windows have. For instance, for SHt=3h/d, the tRSE volume is lower than when considering SHt=1.5h/d. Despite the same number of building combinations, the extruded buildings heights are lower than when considering SHt=1.5 h/d, decreasing the number of windows.

If we define fSAr as the ratio between the number of windows that fulfill minSH and the number of windows that fulfill SHt, Figure 6 proves the validity of the proposed workflow to guarantee a certain level of solar access during early design stages of a building cluster. The high SA performance of the cluster related to SHt=3h/d compromises FAR values related to plots A, E, and D (Figure 6b) (Mukkavaara and Sandberg 2020).

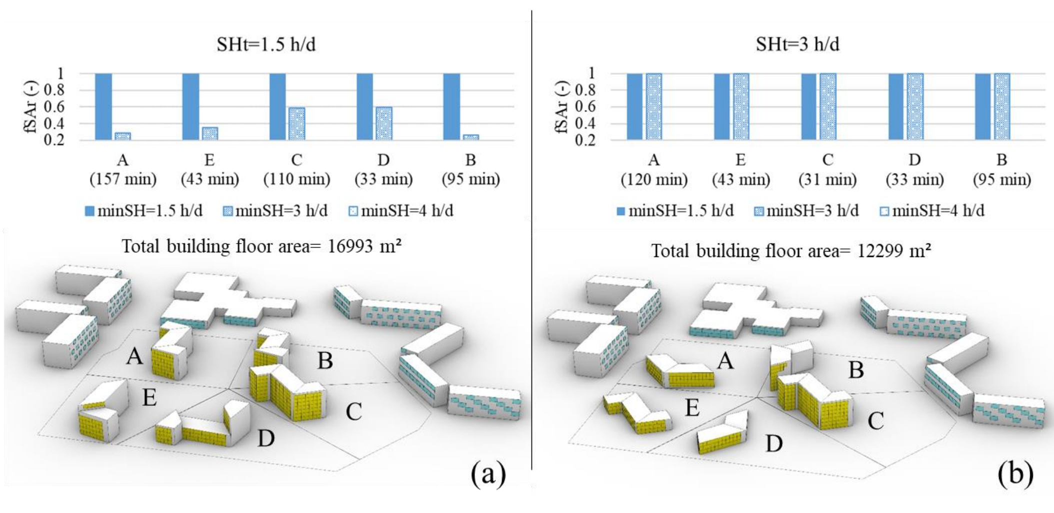

Figure 6: New urban environment for Tallinn case after using the workflow when imposing a certain minimum number of sun hours threshold (SHt) of 1.5 h/d (a) and 3 h/d (b). minSH= assessed minimum number of sun hours per day and fSAr=number of windows that fulfill minSH/number of windows that fulfill SHt.

4.2 Zoetermeer case

The building performance metrics F, FAR, and SAr for each workflow iteration of the Zoetermeer case are shown in Figure 7. The optimal order to design the residential cluster is the following: C, D, A, and B. The FAR range associated to the optimal residential cluster is approximately 0.4-1.07 (floor building areas: 1490-3995 m^2) and 0.43-1.08 (floor building areas: 1490-4207 m^2) for a SHt of 1.5h/d and 3h/d, respectively (Figure 7a and 7b). The SAr range is approximately 0.51-0.64 and 0.47-0.51 for a SHt of 1.5 h/d and 3 h/d, respectively.

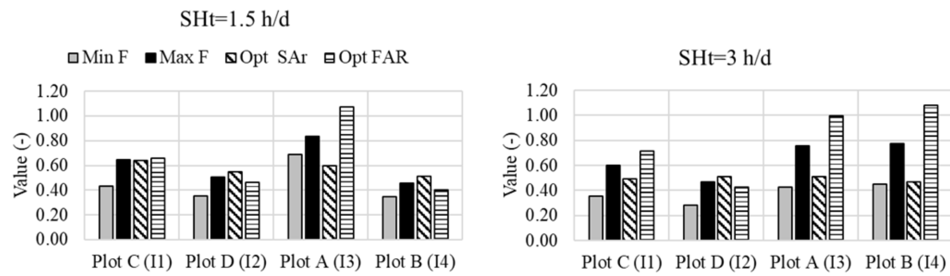

Figure 7: Building performance metrics for Tallinn case when imposing a certain minimum number of sun hours (SHt) of 1.5 h/d (a) and 3 h/d (b). Min=Minimum, Max=Maximum, Opt=Optimal, and I=iteration.

When considering a minimum level of solar access according to the EN 17037:2018 (SHt=1.5 h/d), the F metric could vary in the range 21-50% in relative terms with respect to the minimum F. Moreover, when considering SHt=3 h/d, the F variation could be between 65% and 78%. For the Zoetermeer case, the magnitude of these performance variations also strengths the use of the proposed workflow.

For Sht=1.5 h/d, the simulation time required by each workflow iteration was 70, 25, 45, and 47 min for C, D, A, and B plots, respectively. For SHt=3 h/d, the simulation time required by each workflow iteration was 64, 24, 46, and 45 min for C, D, A, and B plots, respectively. In this case, the consideration of different SHt does not have significant influence on the simulation time required in each workflow iteration because the plot areas are very similar. In fact, when considering stricter SA requirements during the design process (SHt=3 h/d), the high SA performance of the optimal cluster (Figure 8b) does not compromise the FAR values (Figure 7b) (total building floor areas between 9859 m^2 and 12223 m^2). This was possible thanks to the feature of the workflow to consider different building footprints, allowing flexibility during the optimization process within each workflow iteration. As can be seen in Figure 8a and 8b, the optimal building shape and footprint vary with SHt for each plot. Using conventional design approaches to find the optimal residential cluster is not intuitive at all. Thus, the proposed workflow could help architects and designers in this challenging task.

Figure 8 proves the validity of the proposed workflow to guarantee a certain level of solar access during early design stages of a building cluster (fSAr=1 for minSH=1.5h/d when SHt=1.5h/d and fSAr=1 for minSH=3 h/d when SHt=3 h/d). In fact, all plot C and D building windows receiving 3 h/d of sunlight, receive even at least 4 sun hours per day although a SHt of 3 h/d was chosen (Figure 8b). This proves that depending on the case study, by imposing stricter SA requirements (SHt), could lead into solutions that largely fulfill the requirement.

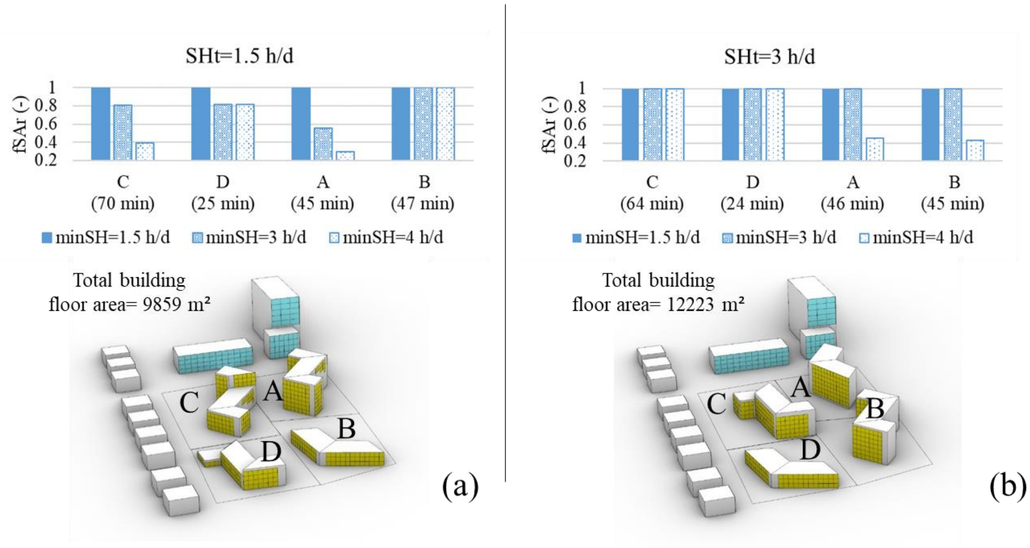

Figure 8: New urban environment for Zoetermeer case after using the workflow when imposing a certain minimum number of sun hours threshold (SHt) of 1.5 h/d (a) and 3 h/d (b). minSH= assessed minimum number of sun hours per day and fSAr=number of windows that fulfill minSH/number of windows that fulfill SHt.

5 DISCUSSION AND CONCLUSIONS

The main motivation of this investigation is the lack of open-source and intuitive design clustering methods that on one hand, can guarantee required solar access levels not only for the new but also for the existing buildings, and on the other hand, provide the practitioner enough freedom to choose building footprint orientation, shape, and position within in each buildable plot. Thus, this paper proposes a novel multi-criteria workflow based on the Reverse Solar Envelope (RSE) method for the design of residential clusters. The workflow is based on the updated Grasshopper plug-in Solar Envelope Tools (SET) for Rhinoceros. We use new tools through the proposed workflow to design building envelopes in two urban areas located in Tallinn, Estonia and Zoetermeer, Netherlands. The proposed workflow consisting of eight steps should be applied for each buildable plot. For each plot, the building performance metrics Floor area ratio (FAR) and ratio of the facade with a certain level of solar access are optimized. The main outcomes of this research are the following:

- The design of an optimal residential cluster is not an intuitive task. When having different plots at once, the optimal plot sequence to design depends on diverse aspects. One of the proposed workflow's outputs is an obstruction angle-based criterion to sort the buildable plots, maximizing the design flexibility in each plot through the maximization of the RSE volume;
- By using the proposed workflow, it was possible to find in 1 hour per plot the best solar access-FAR trade-off design solution for each case study and different minimum number of daily sun hours (1.5 h/d and 3 h/d). In fact, a poor massing design of each new building (building footprint, orientation, and number of floors) could decrease the solar access-FAR trade-off performance (metric F) between 65% and 200%. Therefore, the magnitude of these performance losses also strengths the use of the proposed workflow in early design stages;
- The consideration of stricter solar access requirements (e.g. 3 h/d instead of 1.5 h/d) could compromise FAR values in high latitudes (as Tallinn Case). However, it could also provide design solutions that largely fulfill the requirements in terms of FAR and solar access levels without an increase of the computation time (as Zoetermeer case).

This workflow is based on basic metrics such as the FAR-SAr and subjective criteria quantified by weight factors α-β. In practice, energy performance and daylight provision are also relevant design criteria. FAR-based residential clusters might have a poor SAr because the level of self-shading effect, leading to: (1) a decrease of cooling demand during summer, (2) an increase of the heating demand during winter, and (3) decrease of the daylight provision. However, in future research, energy and daylight (simplified) metrics could be included whether the actual workflow or an extension of it (e.g. including the possibility of fixed shading sizing to mitigate overheating and cooling demand).

Regarding the case studies, this research focuses on two existing medium-dense urban areas located at two different latitudes (50° and 60°). Further work is to evaluate the advantages of using our workflow to design residential clusters in high/low-dense urban areas located at other latitudes. We only considered two building footprint types within our optimization model, a wider consideration of building footprint could lead to residential clusters with better overall performance than those obtained as outputs of the proposed workflow in this research. Future work should study, for a certain case study, how different building footprint typology or "free-form" buildings based on solar radiation gain and space efficiency (Zhang, Zhang, and Wang 2016) could influence the overall performance of the optimal residential cluster. In addition, RSE hourglass shape could be used to increase new buildings FAR values. Finally, simulation time could be reduced by adding the multi-cores feature to the most time-consuming SET tools. Thus, this could make the presented method faster and more flexible.

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