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DEVELOPMENT OF THE URBAN SURFACE MANAGEMENT SOFTWARE FOR PVS AND STORMWATER WITH CONNECTIVITY TO URBAN MODELING INTERFACE

Jung Min Han[1], Christoph Reinhart[2]
[1]Harvard University Graduate School of Design, Cambridge, MA
[2]Massachusetts Institute of Technology, Cambridge, MA

ABSTRACT

As green technologies are becoming more frequently integrated into the architectural design, there is a growing need for tools to support architects conducting environmental analyses. Especially in urban-scale analyses, green technologies such as photovoltaics (PVs) and green roofs have led to significant electricity production and reduction in carbon emissions. PVs have developed from applications of different scales, and now are a major source of electricity. Another way of managing urban areas is Low Impact Development (LID). Especially important is the potential of horizontal surfaces in urban areas, which comprise the largest portion of surfaces useful to green technology. For example, roofs represent up to 32% of the horizontal surfaces in built-up areas (Frazer, 2005), and thus are related to potential energy fluctuations and water management. In practice, it is currently quite difficult to simulate or predict the benefits and overall effects of deploying PVs because most urban-scale modeling tools provide only limited functionality when applied to green technology. This research has developed urban analysis add-ons for Rhinoceros and Grasshopper that address green technology such as PVs and LID and investigated their potential benefits. By including a case study of proposed tools with connectivity to *umi* (Reinhart, 2013), this research offers an important urban-scale implementation of green technology.

INTRODUCTION

The use of photovoltaics (PVs) has increased at an exponential rate for more than two decades. During this period, PVs have evolved from small-scale applications into a major source of electricity generation. The technology required to harness the radiant power of the sun is already available, and solar power has the potential to provide a significant amount of the energy that Americans consume. According to Beta ́k et al. (2012), the electricity consumption of many countries could be completely offset by deployment of solar radiation from a relatively narrow region. Due to improvements in technology and the economics of scale, the cost of solar energy has declined significantly. Since then, deployments of PVs have garnered attention in the building and energy industries, due to their ability to supplement building energy use. Therefore, it can be assumed that the active application of PVs will involve built-up areas (Hofierka and Kanˇuk, 2009).

With the current trend of rapid urbanization, cities have suffered from the results of land development; such development has led to an increase in flooding, accentuation of channel erosion, and degradation in the quality of streams from runoff pollution (Whipple et al., 1983). The increased number of impervious surfaces that has replaced vegetated areas has led to a higher rate and volume of stormwater runoff (Kim et al., 2004). Such problems can partially be mitigated by altering both buildings and urban surfaces. Especially important is the potential capacity of roof areas. These spaces make up the largest portion of the total building surface, and thus became a key target for the application of sustainable technology. Roofs can represent up to 32% of the horizontal surfaces in built-up areas (Frazer, 2005), and are related to potential energy fluctuation and water management.

Roof vegetation is a well-known green technology that is used on roof surfaces; it has great potential to mitigate the urban heat island effect. Green roofs and bioretention can also lessen stormwater runoff from building surfaces by redirecting the flow into storage systems for use in urban irrigation (Oberndorfer et al., 2007). Both PV systems and surface vegetation replacing conventional roof surfaces can contribute to sustainable practices and the reduction of greenhouse gas emissions. Using PVs could help achieve positive environmental impacts on vast areas of fossil carbon, allowing building owners to avoid exploiting this energy source (Raugei, 2012). Moreover, harvesting the runoff from surface vegetation could result in alternative water supply and cost-effective conservation practice (Tong, 2016). Low Impact Development (LID) practices have been evaluated for their effectiveness in retaining large volumes of runoff. Among the various LID strategies, green roofs capture the most significant amounts of rainfall in a variety of different climates (Dietz, 2007).

The integration of PVs and green roofs can bring about synergies of function and effectiveness by providing a combination of cooling and shading effects (Hui and Chan, 2011). Integrated PVs and green roof systems are a new trend in the building sector, since they provide additional benefits. Integrated systems address many urban issues by increasing the efficiency of PVs without the loss of the benefits provided by green roofs. This can be attributed to the process of evapotranspiration that produces an evaporative cooling effect, reducing air temperatures and increasing PV efficiency (Lamnatou, 2015). According to Lamnatou (2015), the increase in PV output due to an integrated system of PVs and green roofs can vary from 0.08% to 8.3%, depending on several factors.

Though there are advantages to using PVs and green roofs (such as electricity generation, increasing PV systems' efficiency by reducing CO2 emissions, etc.), the high cost of installation often makes people reluctant to employ them. However, the relatively low maintenance fees and environmentally friendly benefits are not to be ignored, especially in conjunction with these systems' substantial potential to generate electricity and store it to avoid the use of fossil fuels. One advantage of green roofs is their ability to clean the environment by filtering pollutants such as CO2, NOx, and SOx. Their aesthetic beauty and qualitative advantages are also important. Thus, PVs and green roofs are vital new sources of energy and sustainable concepts of surface design; they are likely to become long-term strategies and serve as the foundation of new technology development and integration.

OBJECTIVES

As high-performance building designs have received considerable attention in the field of architecture, the need has grown for tools that support architects engaging in environmental analyses. Quality environmental analysis during the design process can have extremely beneficial effects on performative building designs. Especially important is a clear understanding of the design problem and efficient analysis of environmental conditions; together, these can increase the possibility of creating responsive designs during the early design stage (Radford and Gero, 1987). Coupling engineering tools with architectural modeling software such as Rhinoceros® assists in accurately assessing the environmental performance of buildings during the early design phase. The urban energy modeling tool called *umi* allows users to carry out energy, daylighting, and walkability assessments of the neighborhood in which the building will be located (Reinhart et al., 2013). Rhinoceros plug-ins and Grasshopper add-ons have been developed to integrate Archsim (Dogan, 2014) and expand *umi*'s urban performance metrics. However, performance evaluations of PVs and LID are still new.

Simulation-based analysis and design decision-making have been widely adopted in the retrofitting of conventional buildings. However, architects and building owners' basic knowledge of the physics of renewable energy sources and their comprehensive understanding of adaptation are still limited. Therefore, a coupled model of sustainable design features and architectural modeling tools is needed to lessen the gap between the scientific and economic benefits of green technologies. A parametric representation of a design is one in which selected values within the design model are interpreted as variables. Conventionally, the physical features of a building (such as its materials, scale, orientation, and shape) can be varied for parametric study. However, parametric design tools are not only able to achieve highly complex geometry, but also can optimize the retrofitting of existing buildings. If architects use parametric modeling tools in their environmental analysis and technical support, sustainable decision-making will soon be more prominent during the design stage.

All in all, due to increasing environmental concerns in the field of building design, many architects are now trying to implement into their work green features such as the use of PVs and green roofs. Following this trend, there have been several attempts to evaluate the benefits of these types of green technologies, but current tools require a fundamental knowledge of each feature regardless of whether users have an engineering background. Therefore, it is necessary that a designer-friendly platform is developed for use in design decision-making. An integrated system for the evaluation of PVs and green roofs has not yet been established. Integrated solutions and means of analysis for both will allow architects to use these features more often in their designs. This research developed plug-ins for *umi* that can be used to design PVs and stormwater management strategies in an urban context.

SOFTWARE DEVELOPMENT

Three major developments are described below that address important features in the urban energy model. First, there is a discussion of the urban geometry manager, which was configured to handle manifold sets of urban building blocks. Next, the PV panel generator and stormwater runoff calculator are introduced. All functional components offer major connectivity with *umi* (Reinhart, 2013) and Archsim (Dogan, 2014).

Urban geometry manager

The urban geometry manager has three functions: urban roof management, ground management, and data conversion. All three functions are implemented in C# script in Grasshopper and utilize Rhinoceros® geometry API. As can be seen in Figures 1 and 2, users can easily take building blocks from the modeling interface and extract the horizontal roof surfaces after passing the urban roof management component. The urban ground manager allows users to take all possible ground surfaces detached from the bottom areas of building blocks. By employing both horizontal surface managers, users can easily manage urban surfaces by employing different green technologies.

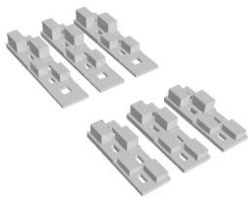

Figure 1. Original geometry of an urban complex.

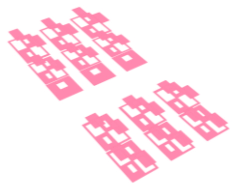

Figure 2. Selected horizontal surfaces.

The data converter is a key component in managing discretized roof geometries in urban building blocks. When integrating workflow with other performance-based simulation tools in Grasshopper (such as Archsim), the data converter combines discretized roof blocks from the same building into a data structure similar to that of the original building blocks. Figure 3 illustrates the functionality of the data converter component, which takes geometries and simulation results and maps them onto building geometries keeping building id of a given roof surface. In other words, components match the number of branches of the tree structure for geometric and numerical data, allowing for later evaluations of results. Figure 4 delineates the integrated workflow of the urban geometry manager with its connectivity to *umi* and Archsim.

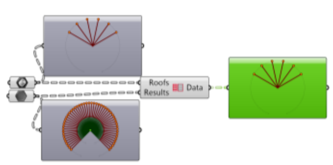

Figure 3. Data converter

Urban PVs manager

PVs are one of the most well-known green technologies and have a significant number of potential applications in urban areas. However, there are various concerns regarding their installation on roof areas. The major issues with installation and operation include mounting the PVs, as well as optimizing their angle and the size of the array. This research demonstrates fundamental aspects of PVs installation and relevant customized components for their use in an urban context. The PVs grid optimizer employed in this study takes all possible surfaces as the target surface and determines the maximum number of PVs arrays based on the panel size and rotation angle. With this component, users are able to optimize the PVs installation location and thus produce a greater amount of electricity.

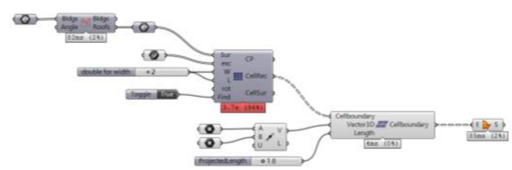

Figure 5. Two major functions of PVs optimization.

The PVs grid optimizer was designed by utilizing a brute force algorithm and conducting an exhaustive search for both the appropriate size of the array and placement of the angle of rotation. According to the latitude and shading of the context, users are able to specify the rotation angle of the array and obtain an optimized arrangement of PVs (see Figure 6). Another key factor is the exclusive target area. With this component, exclusive curves are able to take input and exclude target areas inside the curve when placing PVs on a given surface. By employing this function, design space could remain empty and thus be put to other uses (such as green roofs), while other surfaces accommodated the PVs array (see Figure 7). Areas excluded from the boundary curves could remain to implement other green practices.

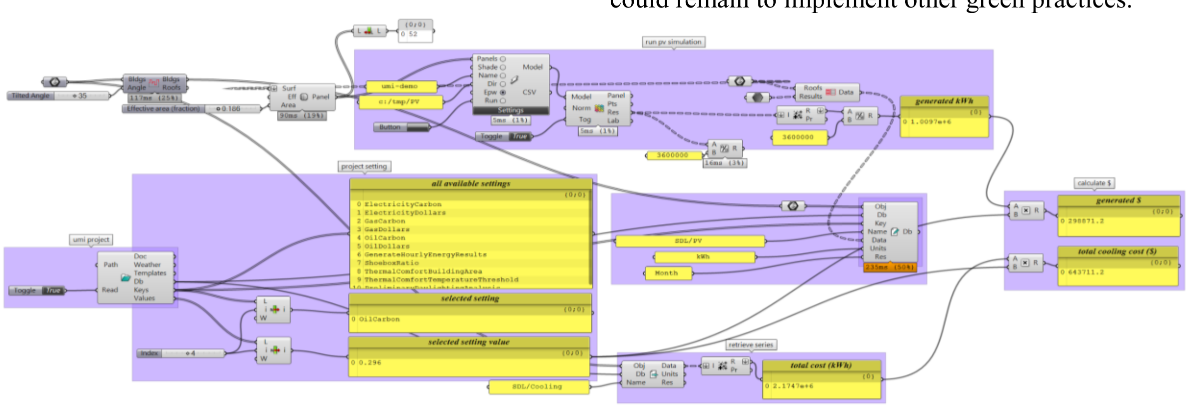

Figure 4. Workflow integration of umi and Archsim with the urban geometry manager

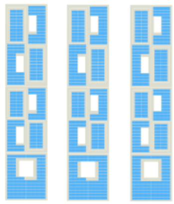

Figure 6. Grid-optimized PV array.

Figure 7. Excluded sections of a PV array.

Another aspect considered by the urban PVs manager is the tilted angle of the PVs, which is important when evaluating PVs performance and electricity production in different locations. When determining the optimized tilted angle for the PVs panels, sun exposure hours and equivalent sun vectors must be considered. When users input the equivalent latitude of a location, the angle optimizer calculates the relevant period of the year and extracts the sun vector for the optimal PVs panel angle. As can be seen in Figure 8, the optimized tilted array's sun vector in June shows the highest level of electricity production from the Boston PVs panels (at a latitude of 42.36). This means that the tilted angle optimizer automatically selects the sun vector from June to calculate the optimized PVs array.

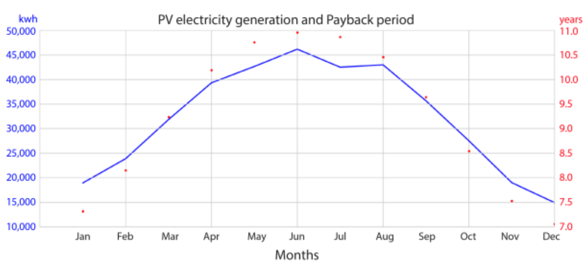

Figure 8. PV electricity production per month in Boston, Cambridge, MA.

Figures 9 and 10 show visualized panels with tilted angle optimizer components.

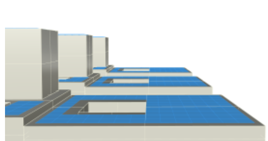

Figure 9. A grid-optimized PV array.

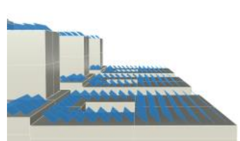

Figure 10. Tilted angle optimized PV array.

Both the grid and tilted angle optimizers are capable of being integrated or separately applied in PVs array designs. The generated PVs panel surfaces can be directly connected with the Archsim PVs calculation component for performance evaluation. For the comparison study conducted for this research, within a 12m x 18m roof surface in Boston, 1.6m x 0.9m PVs modules were applied to generate an optimized panel array.

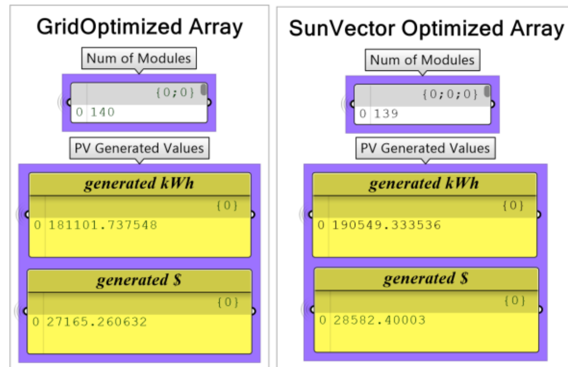

Figure 11. The annual electricity production of the grid and tilted angle optimizers.

This analysis determined that a tilted angle optimized array would offer a better level of performance than a grid-optimized array, assuming that a similar number of modules are equipped. Figure 11 shows that the vector-driven optimized array required the installation of 139 modules (the grid-optimized array used 140 modules) but produced more annual electricity than did the grid-optimized array. However, the relatively higher installation cost of the tilted PVs array over the price of a non-tilted PVs array revealed problems with the payback period and total amount of energy production. For further analysis of users' design decisions related to PVs arrays, the software is able to open two optimizers as separate components; this allows for more flexible design decisions.

Urban stormwater manager

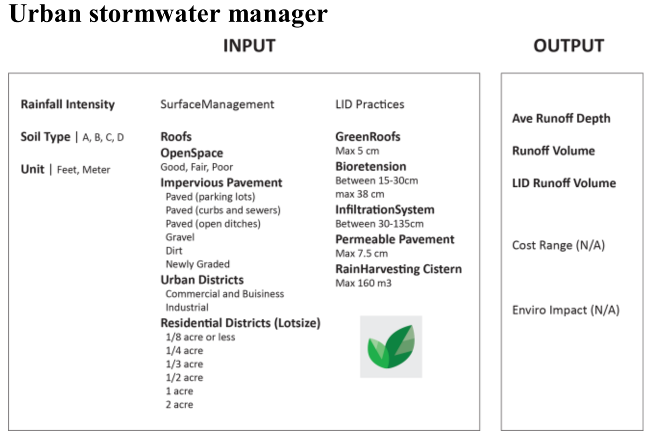

Figure 12. Inputs and outputs of the stormwater manager component.

Due to an increased concern regarding flooding and potential problems caused by stormwater runoff, the implementation of LID practices has garnered the attention of urban development authorities. This section introduces the stormwater runoff calculator, a sub-section of the urban ground-level surface manager. The urban stormwater manager is an interactive and intuitive tool for use in early urban modeling of ground surfaces. Urban stormwater management normally uses the National Resource Conservation Service (NRCS) curve-number method (Cronshey, 1986) developed by the US Department of Agriculture (DOA). This method was chosen for the current research because of its relatively comprehensive datasets and predefined curve values, which were internalized in a customized C# component. Possible inputs include the roof and district conditions, open spaces, impervious paving, and specific lot sizes in urban residential districts (see Figure 12). The applicable LID practices can be divided into five categories: green roofs, bioretention, infiltration systems, permeable pavement, and rain harvest cisterns (Chen and Tong, 2016). With respect to runoff depth, the overall runoff volume in both SI and IP units can be shown as the total runoff volume in response to typical and LID practices, respectively. As a result of the calculation, users can easily compare the results from a particular LID design by using the urban stormwater manager component.

CASE STUDY

This section demonstrates the feasibility and usage of the proposed workflow with the developed urban green technology manager add-ons for Grasshopper. To allow for further analysis of the proposed tools, it was essential to integrate another plug-in for Rhinoceros, *umi* (an urban energy modeling tool), and another add-on for Grasshopper, Archsim (an energy simulation add-on). All function-based components were embedded into the workflow and the results analyzed and visualized as a part of the case study conducted for this research.

Application of the urban PV manager

For several decades, urban planners and designers have expressed design concerns regarding urban horizontal surfaces. To design PVs for urban horizontal roof areas, feasible PV areas must be targeted; to accomplish this goal, the total energy use of the neighborhood and peak load energy consumption are crucial variables. In this section, the energy consumption levels of entire neighborhoods are analyzed as target areas for PVs, and the applicable areas of installation are demonstrated.

When the target electricity load in *umi* is specified, the number of PV arrays are automatically proposed. In this section, three strategies for PV installation are introduced.

- Option 1: Cooling load (peak month) offset by PV electricity generation
- Option 2: Total energy use (target month) offset by PV electricity generation
- Option 3: Total energy use (net zero) offset by PV electricity generation

The assumptions, therefore, are;

- Option 1: Each building consumes its own generated electricity.
- Options 2 and 3: The urban district grid system shares the energy from the redundant amounts of electricity produced by PVs.

Table 1 Input parameters for the PVs simulation

	PV assumption
Panel size	1.6m x 0.9m
Module efficiency	24%
Roof area of PV	Varied by building's energy use

The numbers above the panels of roofs (see Figure 13, Figure 15, and Figure 17) represent the percentage of the areas covered by PVs panels to produce the target amount of the electricity production.

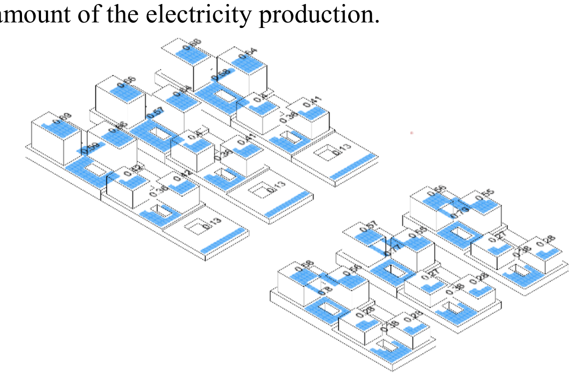

Figure 13. The proposed PV array for Option 1.

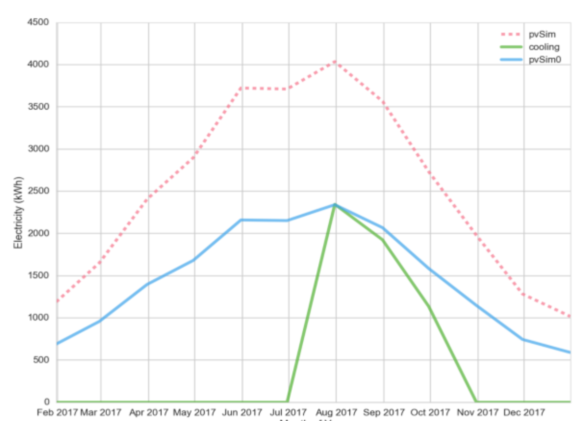

Figure 14. The PV electricity production results and monthly electricity consumption for Option 1(bd4)

For Option 1 (see Figure 13), the PV arrays are automatically proposed (1.6m x 0.9m x 468 panels) when the annual peak cooling load is equivalent to the proposed PV energy production (see Figure 14). In cases such as this, designers would be able to design green spaces on top of roof areas after designing PVs.

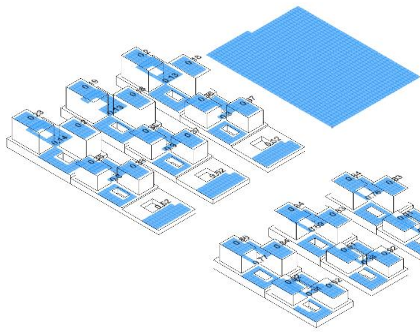

Figure 15. Proposed PV array for Option 2.

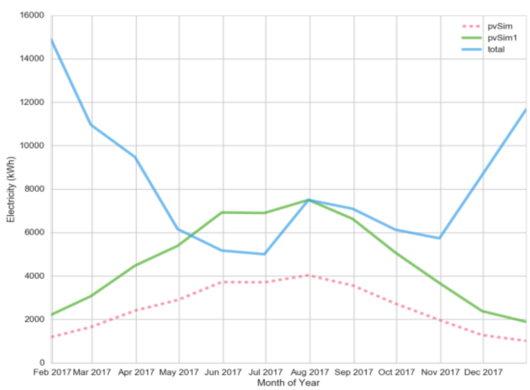

Figure 16. The PV electricity production results and monthly electricity consumption of Option 2 (bd4).

Option 2 (see Figure 15) suggests an excessive number of PV arrays (1.6m x 0.9m x 901 panels) to offset the annual energy consumption (target month: August). To achieve Option 2, it would be necessary to install more PVs (1.6m x 0.9m x 1587 panels) in urban areas (see Figure 16). For example, designers could apply more PVs to the rooftop of the garage and as part of the infrastructure to generate more electricity.

Lastly, Option 3 (see Figure 17) illustrates a net-zero energy use neighborhood. To offset the total annual energy consumption, the proposed number of PV arrays (1.6m x 0.9m x 2824 panels) must be installed. Thus, the optimized PV design from *umi* for building energy use would be suggested by the designer's intention. This function will be especially useful when users want to create net-zero energy use buildings or communities; designers could ask the tool to produce more electricity, targeting a balance between the total energy production and consumption.

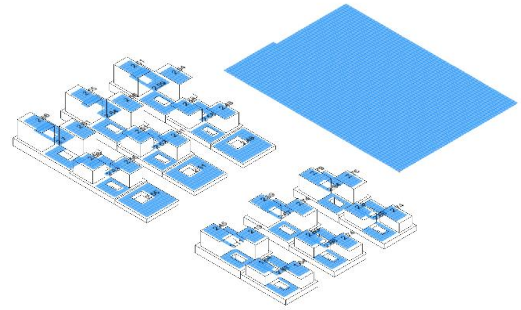

Figure 17. Proposed PV array for Option 3.

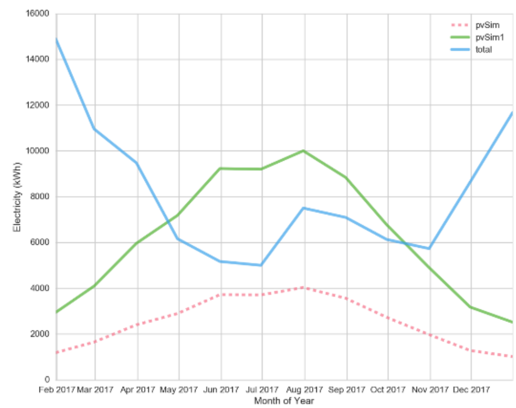

Figure 18. PV electricity production results and monthly electricity consumption for Option 3 (bd4).

Application of the urban stormwater manager

The urban stormwater manager requires the surface geometry and other input options for runoff calculations. Selected horizontal urban surfaces can be grouped by characteristics, such as roofs, open spaces, and impervious paving. Each surface can then be connected as a built-in "Brep" component in Grasshopper, and its conditions specified, such as by grass category or pavement type. Users can use the drop-down button to select the proper option for each category (see Figure 19).

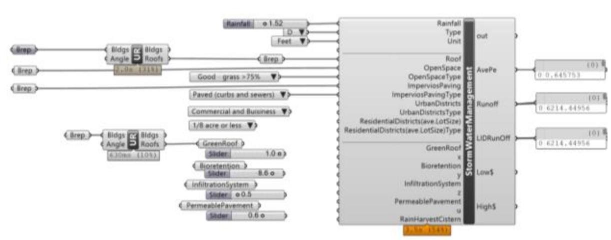

Figure 19. The feature implemented for the stormwater manager component.

After specifying the selected "Brep" component, users are able to input the percentage of rainfall and soil type, as well as the modeling unit, for the runoff calculation.

Figure 21 shows the types of different urban surfaces categorized according to two different options: without LID application (top), and with LID application (bottom). Table 2 compares the results of the two options: the existing condition (top) and LID design (bottom).

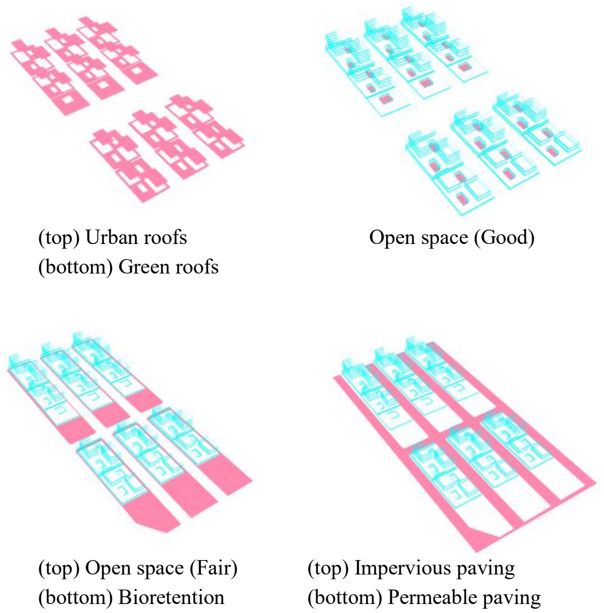

Figure 20. Existing (top) and LID (bottom) designs.

The merit of the stormwater manager component is its ability to partially change the areas of the existing conditions to LID practice-adapted circumstances. As can be seen in Figure 20, users can partially or entirely take the surface from the baseline design and apply it to LID practice. The case exhibited in Figure 20 (a lower portion of the roofs, entirely open space, and impervious paving) was replaced with green roofs, bioretention, and permeable pavement, respectively. By doing so, the total runoff volume decreased to 167m^3, as compared to the existing design.

In general, stormwater management is estimated and calculated based on the runoff penalties. The most common method of setting fees when using a graduated system is the Equivalent Residential Unit (ERU). According to the EPA, the ERU method is used by more than 80% of all stormwater utilities in the nation. In this case, the ERU cost for a typical design was $7,505, but the annual maintenance fee for LID practices was between $5,630 and $8,110. This means that if the LID practices were applied to reduce the amount of runoff water, the penalty would be equivalent to that of the existing design.

Table 2 Comparison of the Result of the Design Study

	EXISTING CONDITIONS	**LID DESIGN**
Design options	Figure 20(top)	Figure 20(bottom)
Annual runoff (m^3)	747	229
Runoff reduction	$1,218 (Blackhurst, 2010)	

CONCLUSION

To date, the contributions that green technology (PVs, green roofs, and LID practices) can make to sustainable practices and reductions in GHG emissions is apparent. The installation of PVs on roofs has the potential to support the energy use of entire building sectors. Furthermore, integrated PVs and green roof systems offer numerous benefits. For long-term technological development and integration, the installation of both PVs and green roofs are essential, both as a sustainable concept of surface design and new source of energy. By analyzing a case study, this research demonstrated potential designs for PVs on urban roofs, as well as integrated strategies for vegetation.

The current limited knowledge of green technology should not prevent urban designers from integrating these elements into their designs. For this study, a software platform was developed to overcome the conventional discrepancies between what current tools offer and users require. This platform considers both economic cost and essential environmental issues and evaluates PV electricity generation, runoff, and other impacts of green practices. The proposed software provides concise information on the benefits of green technology, suggesting urban block designs that contain both environmentally friendly outcomes and aesthetically pleasing geometries. It is believed that environmental analysis and parametric optimization strategies will greatly improve design quality and provide numerous green solutions from which designers might choose.

The contributions of this research include:

- The development of a simplified and integrated platform for PVs and green roof design software, with connectivity to energy simulation tools such as *umi* and Archsim.
- A demonstration of the sensitive inputs and outputs for performance evaluations of PVs and green roofs.
- An application of PV optimization to the performance evaluation of green technology, along with a description of its benefits in different urban energy use scenarios.

The limitations of this research are as follows:

- The weighted importance of different parameters requires further investigation.
- To encourage usage, the tool is simply designed.

This simplicity, however, comes at the expense of assumptions made in the form of default values. These assumptions might have an impact on the accuracy of the simulations produced. Future work should consider the influence of these assumptions on simulation accuracy and the possibility of inferring these default values from other input provided by users.

All in all, dexterous tools allow urban designers to actively participate in environmental analysis (EA) during the early design stage. Accordingly, the effort to implement EA tools should be supported by current practice. The software developed in this work is one conceivable method for engaging green technologies in the urban design process. In the end, urban districts could achieve net-zero neighborhoods or substantial reductions in energy use and stormwater runoff. In the future, an improved version of this software that features multi-objective analysis and a clearer purpose of use will be developed; this will cover a wider scope of green technology. The manifold ideas and their results will help us to achieve a more sustainable world, rethink our environment, and better plan our cities.

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