An innovative app for a parametric, holistic and multidisciplinary approach to early design stages

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Abstract

During early project stages, design teams need to explore a wide range of possible envelope configurations in order to identify those that best address the project constraints and objectives. Crucial aspects such as control of solar gains, use of blinds and renewable energy production are typically the subjects of extensive discussions among architects and facade, mechanical, electrical and PH engineers. Traditional methodologies used to inform the design on such matters are neither flexible nor time efficient, failing to meet the expectations of the team. Arup Solar is an innovative APP developed to overcome such inefficiencies and to provide a user-friendly way to aid the discussion between architects and engineers. The validated APP aims to investigate the relationships between envelope features (e.g. window to wall ratio, g values, etc.) and cooling strategies, as well as identify potential opportunities for renewable solar energy production. It allows for the exploration of a large number of design options instantaneously, visualizing results by mapping them on the 3D model of the building. The process of building any instance of the APP includes a first step where the NURBs modeler Rhino/Grasshopper is utilized to run a Radiance & DAYSIM solar analysis on any complex geometry. The resulting data (on each surface mesh) is then exported to the Unity gaming engine, where a set of pre-programmed features is automatically implemented and the graphic interface is created. The outcome is a stand-alone parametric application that can be potentially run on any device.

Keywords

total architecture, software development, design tool

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1 INTRODUCTION

Decisions made by the design team during early project stages can have a big impact on the final energy performance of the building (Granadeiro et al., 2013; Negendahl et al., 2015), as well as on its appearance and operation.During the concept stage, design teams typically need to explore a wide range of possible facade options, so that they can feel comfortable that the chosen solutions work within the project constraints. In spite of these demands, the use of building performance simulation in the architectural design process is hindered by three key obstacles (Zemella et al., 2014):

1. the resources required to create building models for energy simulation;
2. the time needed to accurately run and validate simulations on different geometrical options;
3. the lack of simple and straightforward communication of results.

Consequently, in a typical workflow, consulting engineers only simulate buildings later on in the design process, in order to verify a frozen design (Greenberg et al., 2013). The downside of this practice is that the amount of time and resources required to assess the impact of changes in parameters including, but not limited to, architectural configuration or mechanical systems, is large. The process is inflexible and does not allow for informative iterations. The typical software tools employed for Building Energy Simulation (BES) such as eQuest, IES-VE, Design Builder, OpenStudio are often used through extrusion of prismatic elements, which are in contrast with the current architectural trends. These models are employed later in the design process and are aimed at a much larger set of analyses. Other software tools are usually limited to solar incident radiation assessments due to the slow computational engine. Other examples such as Sustain (Greenberg et al., 2013) are still at the cutting edge of research projects, not yet ready for the market. Finally, many of these tools do not offer enough customization, computational precision or transparency.

There is a demand for software tools that help and support the whole design team during early design processes, in order to develop true performance-driven solutions. Reliability, flexibility, clarity and visual appeal are some of the key features of a software solution for this purpose. These new tools should then act as a platform on which the different members of the design team such as architects, facade engineers, mechanical engineers, electrical engineers and public health engineers can work together, saving time and resources, and striving for the real *"Total Architecture"* (Arup, 1970).
One aspects that has a significant impact on facade design is the control of solar gains through the transparent portion of the envelope. This is typically achieved by varying window to wall ratio and glazing g-value. Additionally, shading features of different types are often employed to mitigate gains where there is high solar exposure. Moreover, in order to achieve challenging objectives, such as the (nearly) Zero Energy Building, a significant amount of the energy demand of a building should be provided by renewable sources, including energy generation on site or nearby (European Parliament, 2010). The sooner these aspects are considered, the more likely it is that facade solutions that are aligned with the architectural intent can be found.

With regard to the above parameters, the exploration of the options should be facilitated by appropriate tools in order to inform the design in a proactive way. Such tools should be able to manipulate a large amount of data, enabling the design team to derive clear indications and results. However, there is a gap in the typical early stages workflow. There is a lack of tools available to adequately support the whole design team in defining the overall building energy performance strategies.
The work presented in this paper was developed with the aim of providing such a tool.
ARUP Solar is a new innovative APP that supports the design team in early stage development to overcome the inefficiencies described above.

2 ARUP SOLAR

2.1 PREVIOUS EXPERIMENTS

After testing available software tools for handling complex geometry, solar simulation and interactive data visualization, the conclusion was that none could meet the requirements described in the previous sections.

A number of experiments were carried out, including the combination of Ecotect results with an interactive data visualizer created by Java scripting, and the creation of a tailored tool in Excel to post process and interactively combine results from Energy Plus and Radiance. The downsides of these experiments were as follows:

1. the large amount of resources required to create the tools;
2. the long computational time to run the simulation because:
   a. Simulations with good sky resolution at the building scale take time;
   b. Scripts had to be developed to run Energy Plus and Radiance automatically more than 600 times and those analyses were limited to top floors without any obstructions;
3. the expertise required to use the tools;
4. the results were not expressed in a graphic, intuitive way and required extensive post-processing.

Grasshopper standardized the direct link between geometry (Rhinoceros) and BES (Energy Plus and Radiance) to break a first barrier to parametric assessments. However, despite the powerful visualization, Grasshopper was not able to handle such large amounts of data and interactively visualize them. An attempt was made to put results into layers where information was stored and the design team could visualize the results by means of Rhinoceros, but the process was neither flexible nor efficient. Another possible way was identified and is described in the following paragraph.

2.2 IDENTIFICATION OF ADEQUATE TOOLS

As mentioned earlier, the starting point was that an efficient approach to early design stage assessments was required to understand how solar radiation on the facades affects the architectural configuration, the mechanical system and the renewable energy fields. Following an analysis of how the main software tools for solar analyses worked, a combination of Radiance & DAYSIM was considered to be the most flexible and reliable solution for such applications. In addition, Radiance & DAYSIM can be run through the NURBs modeler Rhino/Grasshopper. This allows the geometry to be linked to Radiance & DAYSIM in a few steps by means of specific plug-ins such as Ladybug and Honeybee. However, Radiance & DAYSIM on their own do not allow users to derive clear design indications as their output is limited to radiation values and they do not offer an adequate interactive interface. Moreover, as stated above, Grasshopper does not offer sufficient computational power to post-process a large amount of data in real time. These points directed research towards more suitable engines that could overcome such limitations. Unity was found to be the right software for this use. Unity is a game engine widely known for its accessibility. Its unique nature allows a fast and responsive software that combines advanced calculation methods and rendering techniques. The algorithms were written using C# language in order to take advantage of its powerful parallel processing capabilities. Figure 1 offers an overview of the tools required to build the APP. The novel use of a game engine as design tool is one of the unique features of ARUP Solar. The next paragraph explains the workflow used to develop the final APP.

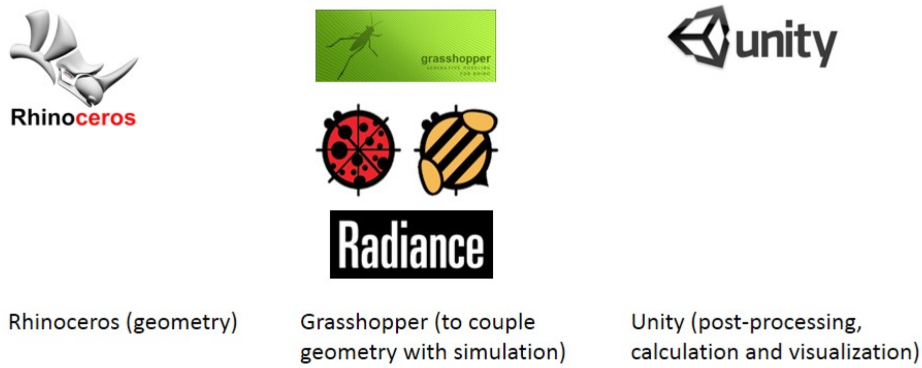

FIG. 1 Required tools to create the APP (Authors)

2.3 APP FRAMEWORK

The identification of this suitable software allows users to define the steps and the information to be exchanged through the different platforms. Figure 2 shows the main steps required to create the APP, which are summarized as follows:

1 create the geometry (STEP 1, Figure 2); this step is very important as the rationalization of the model is fundamental in order to run a successful simulation;
2 run the incident solar radiation analysis only once (STEP 2, Figure 2); this step allows the user to convert all the Rhinoceros scenes in a Radiance & DAYSIM file and assess the solar incident radiation on the geometry under investigation by defining the main Radiance parameters;
3 create the APP (STEP 3, Figure 2); when the simulation ends, the whole set of outputs is automatically exported from Grasshopper via scripting. The files are then copied into a Unity project where all the information is automatically post-processed.

One challenge was to overcome the interoperability between the different software used, as they do not read the same file formats and protocols. This led to the introduction of tailored scripts to derive the suitable outputs from Grasshopper to recreate the scene along the numerical results. The final step (STEP 4, Figure 2) is to run the APP on any device as Unity allows the user to choose the operating system on which the APP will run (Microsoft, MAC, Android, Linux...).

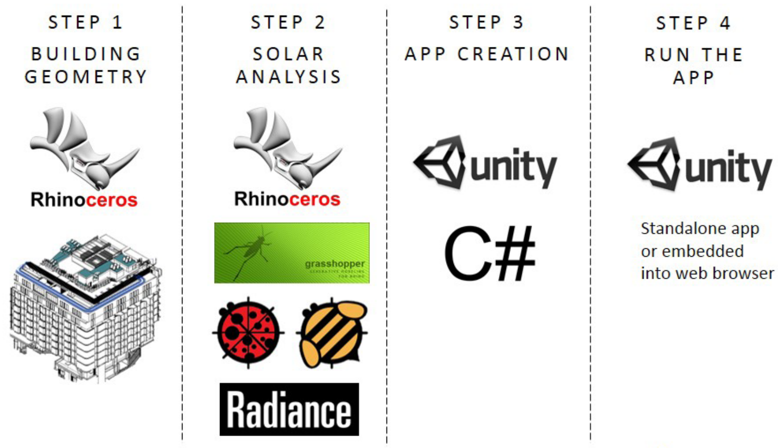

FIG. 2 Workflow to create the APP.

2.4 VALIDATION

ARUP Solar is a tool that post processes solar incident radiation values. A validation of the tool can be carried out by comparing the radiation levels derived from Radiance & DAYSIM (HoneyBee and Ladybug version 0.060 and 0.064) with the results provided by another validated software. Energy Plus version 7.2.0.006 was identified as reliable software to carry out this validation.

A previous validation of Radiance & DAYSIM using Grasshopper and Energy Plus was carried out by Waibel et al. (2016), showing good agreement on general trends.

A further validation was carried out by the authors using a building in central London as case study. (This is described in more detail in section 2.6). The image below (Fig. 3) shows the building (in black) and the urban context (in light grey).

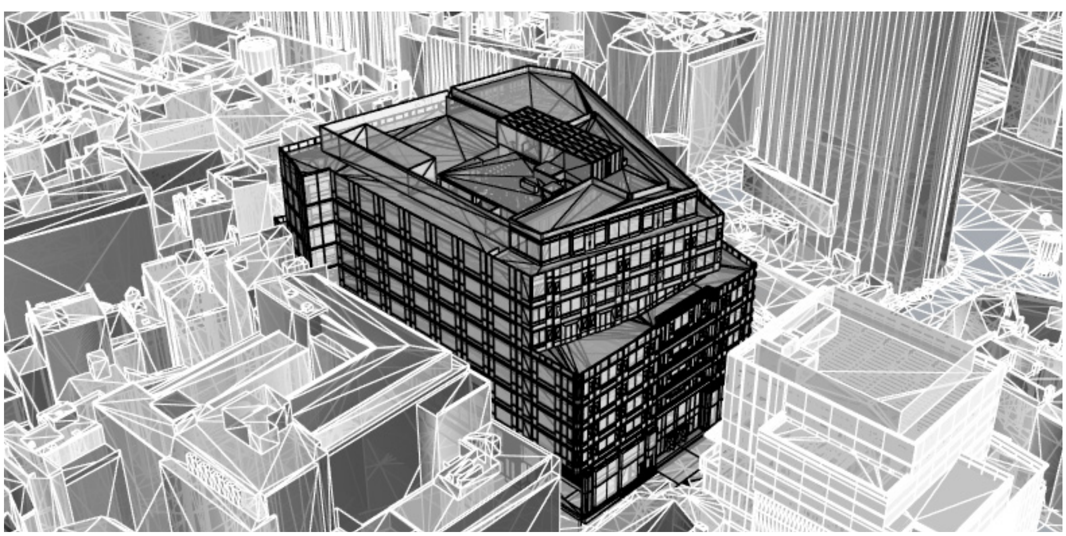

FIG. 3 Case study analized (real model)

The validation focused on three representative bays (6m x 3.5m), with different orientations and levels of obstruction as described in the following set of images. The images below (Fig, 4 and Fig. 5) show representations of a shading mask of the surface and localization of the assessed bay.

A shading mask represents a matrix of azimuth and altitude angles at which the percentage shading for the assessed surface was determined (Autodesk®, 2010). Ecotect Analysis 2011 was employed to assess the shading mask of the bays. Equidistant sun path polar projections overlap the shading mask to correlate the position of the sun with the shadows due to the obstructions. The key represents the percentage of surface that is shaded.

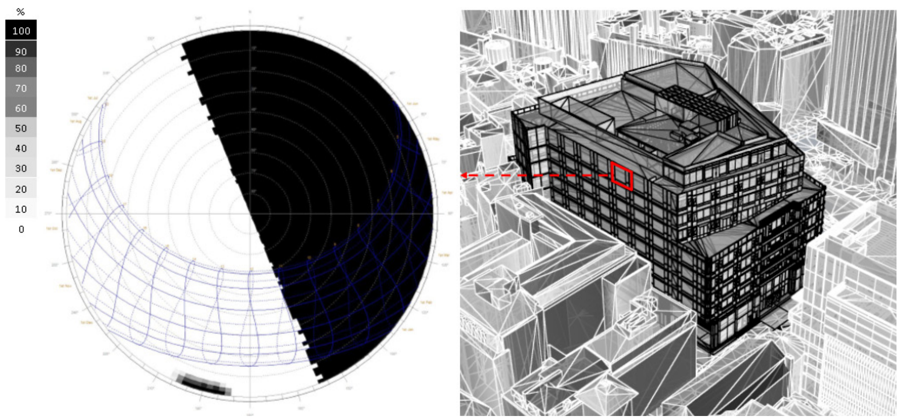

FIG. 4 West Elevation, shading mask and localization of the assessed bay.

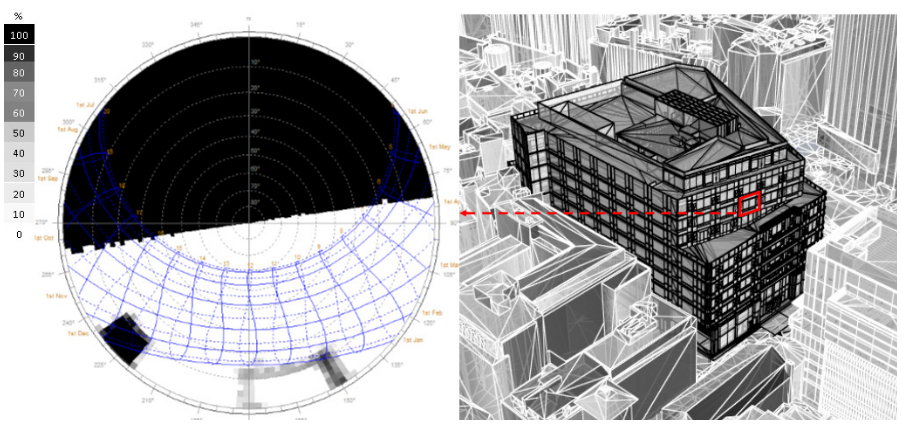

FIG. 5 South Elevation, shading mask and localization of the assesed bay.

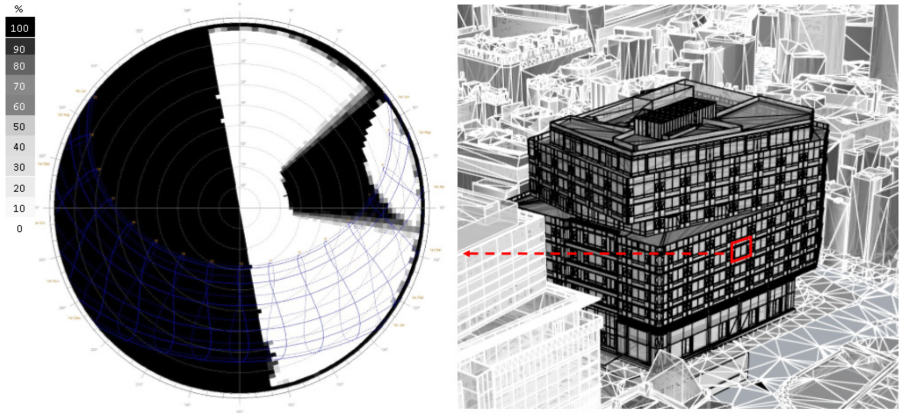

FIG. 6 East Elevation, shading mask and localisation of the assessed bay.

The simulation was carried out for a typical year. The weather file used was the Design Summer Year for London (DSY) by CIBSE (Chartered Institution of Building Services Engineers).

Radiance & DAYSIM were run by means of Grasshopper and Energy Plus directly from the latter's own interface (.idf).

The following Radiance & DAYSIM parameters were set within the subroutine of Grasshopper to perform the simulation:

1 Analysis Grid = 1.5m x 1.5m;
2 Quality = 2;
3 Ambient Bounces = 6;
4 Ambient Division = 2048;
5 Ambient Super Sample = 1024;
6 Ambient Resolution = 256;
7 Ambient Accuracy = 0.10;
8 Site Ground Reflectance = 0.2.

The following parameters were set within the .idf of Energy Plus:

1 Solar Distribution assumed as "Full Interior And Exterior With Reflection";
2 Calculation Frequency = 30 days;
3 Maximum Figure in Shadow Overlap Calculation = 15000;
4 Algorithm for Polygon Clipping = "Sutherland Hodgman";
5 Algorithm for Sky Diffuse Modeling = "Detailed Sky Diffuse Modeling";
6 Site Ground Reflectance = 0.2.

The correlations between the results obtained from the two models are shown in the graphs below (Fig.7, Fig. 8 and Fig.9).

It should be noted that the night hours were not considered to increase the accuracy of the calculations.

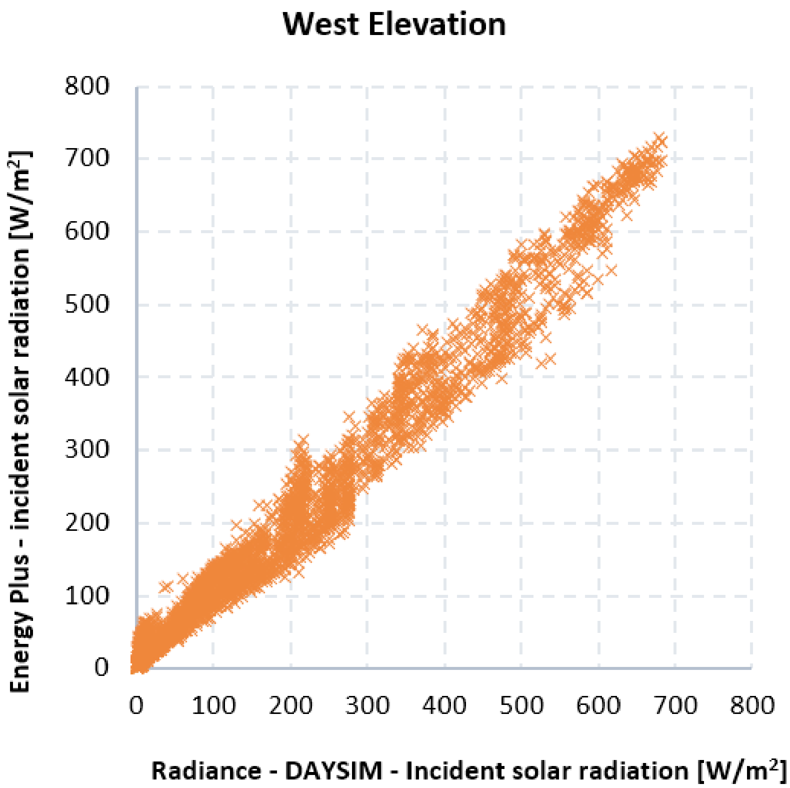

FIG. 7 Correlation West Elevation

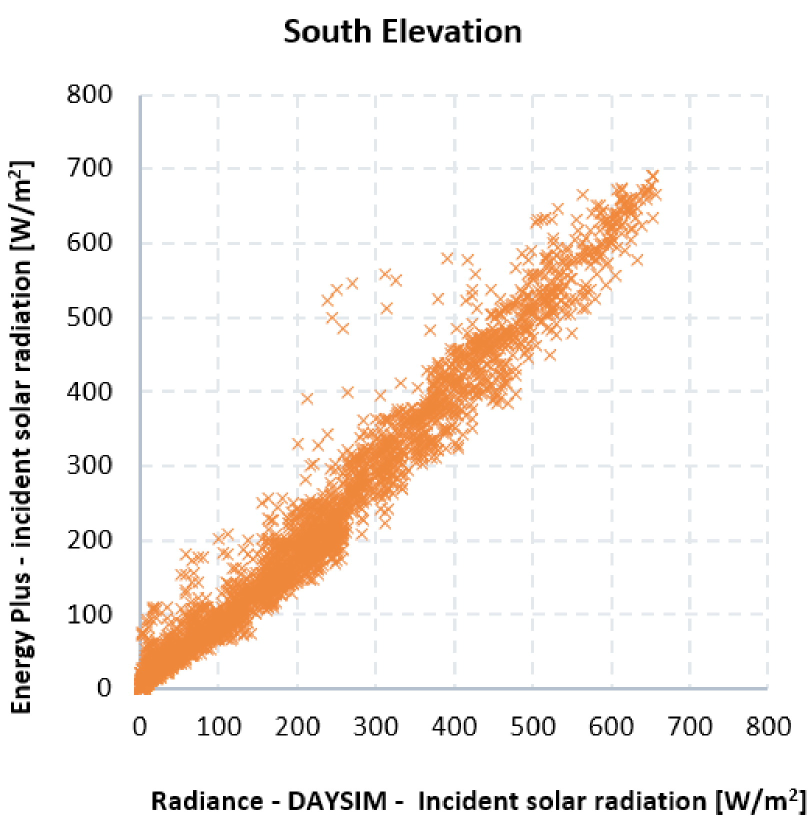

FIG. 8 Correlation South Elevation

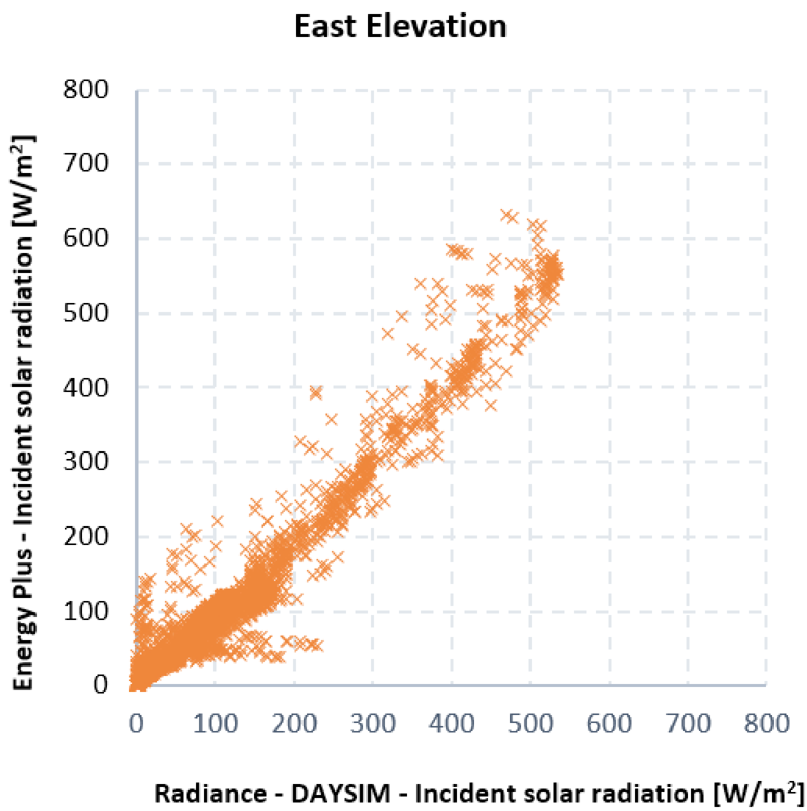

FIG. 9 Correlation East Elevation

	WEST ELEVATION	SOUTH ELEVATION	EAST ELEVATION	UNIT
R	0.99	0.98	0.97	-
R^2	0.98	0.97	0.95	-
RMSE	25	28	24	Wh / m^2
ΔPeak	-6.4	-4.8	-15.8	%
ΔCumul.	-3.0	1.6	1.5	%

TABLE 1 Results of the validation

Table 1 summarizes the correlation coefficient R, the coefficient of determination R^2, the root mean squared errors RMSE and the difference in terms of % between the two engines (Peak levels - ΔPeaks - and Cumulative levels – ΔCumul.) found.

The results show a good correlation between the two models, with a reasonable fit for most of the orientation. Some differences were expected due to the different approaches used to simulate solar radiation adopted by the software. Discrepancies were found when the facade bays experience of high levels of shading (i.e. the bay on the East elevation, during early hours of the day in the middle season - March and April).
The post-processed data was then used to assess solar gains, extra shading requirements and potential for new solar renewable energy as described in the following paragraphs.
All of the algorithms were based on validated mathematical models and were developed to provide conservative results to reflect the accuracy of the input typically available during the early design stage.

Solar gain was calculated with the static equation in accordance with CIBSE Technical Memorandum 37:2006.
PVs were described referring to the iNOCT method (Skoplaki et al., 2008) taking into account the overheating of the cell, the mounting typology and the real hourly efficiency of the system (Duffie et al., 2013).
Solar thermals were described by an implicit Euler method, which is a first order approximation, accurate in time and unconditionally stable (DiOrio et al., 2014). The efficiency of the panel was defined by a second order equation function of panel temperature and current incident radiation level (Quaschning, 2016; O'Hegarty, 2016).
In order to increase the accuracy of PV and solar thermal outputs, backwards ray-tracing tracked the relative angle between the surface normal and the incident solar radiation. This allowed for consideration of the angle-dependent optical properties of the glass (U.S. Department of Energy, 2016) and the angle modifier factor (Duffie et al., 2013).
The following paragraphs show the core functionalities of the APP and describe the case study in detail.

2.5 APP FUNCTIONALITIES

Once the APP is created it can be run on any platform (Unity does not have to be installed on the machine). Thanks to pre-coded post processing functions of the solar radiation data, the users can explore different design options. The features offered can:

1. visualize the incident solar radiation (hourly values, cumulative and peak values, in accordance with percentile and/or a certain period of the year);
2. calculate the solar gains according to glazing percentage and g-value, or visualize any of the three variables above as a result of the combination of the other two;
3. extra shading requirements to achieve solar gain target: hourly data plus performance indicators (e.g. amount of hours that extra shading features are typically required per day for each month);
4. estimate the amount of energy that can be produced by means of BiPV (Building-integrated photovoltaic);
5. evaluate the amount of energy that can be produced by means of BiST (Building-integrated solar thermal system) for hot water and HVAC utilities.

The final result is an APP where the data is visualized. The graphical user interface (GUI) presents a horizontal bar that shows core functionalities and a vertical bar with the settings (Figure 10). By selecting the buttons, it is possible to visualize:

1. GI, General Information (assumptions for the calculations);
2. TSP, Toggle Sun Path (On/Off);
3. RM, Recenter Model;
4. FD, Filtering of Data (certain hours, months);
5. S, Solar Gains calculation – the default method assesses the solar gains on 4.5m of perimeter floor area but this can be changed with different floor depths. In addition, instead of assessing them based on floor area, solar gains can be also calculated on facade area;
6. M, Geometrical Model;
7. IR, Incident Radiation;
8. SG, Solar Gains;
9. B, Extra Shading requirements;
10. PV, Photovoltaic calculation;
11. ST, Solar thermal calculation.

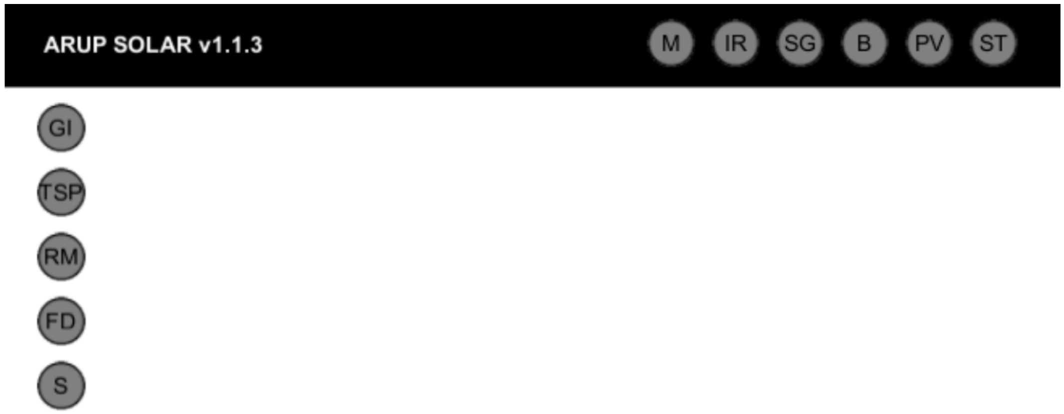

FIG. 10 Buttons to chose functionality to visualize (top horizontal tab) or general setting (vertical bar).

The functionalities are described in more detail in the following section, which describes a case study where the APP was tested.

2.5.1 Case Study

ARUP Solar was tested using real project applications during the development of the current version. One of the projects where the tool was employed was a new development in central London where a new office building will be built.
The building was characterised by two volumes and surrounded by other buildings. The ambition of the design team was to have low energy requirements, a high percentage of glazing and no external shading devices. The facade design had to reach a compromise among a number of conflicting requirements. The context of the surrounding buildings played a key role in the identification of the areas where clearer glass or more glazed areas were possible. In addition, by allowing more communication within the design team, the tool could save time and avoid misunderstandings, making the design decision process smooth and fast.

2.6 RESULTS OF THE CASE STUDY

Once the calculation was finished, the data was loaded and the .exe file selected. The first tab of the APP showed the Model Geometry of assessed scene with the buttons as presented in Figure 10.

A common feature of all the outputs is that by hovering over a mesh, specific information about that selected function is displayed. By selecting the Incident Radiation mode, the incident solar radiation (hourly values, cumulative and peak values in accordance with percentile and/or a certain period of the year) for each mesh or for the whole building is visualized (Fig. 11). In Figure 11, with the option “Peaks” being selected, the moments when the peak of incident radiation occurs and the intensity can be shown.

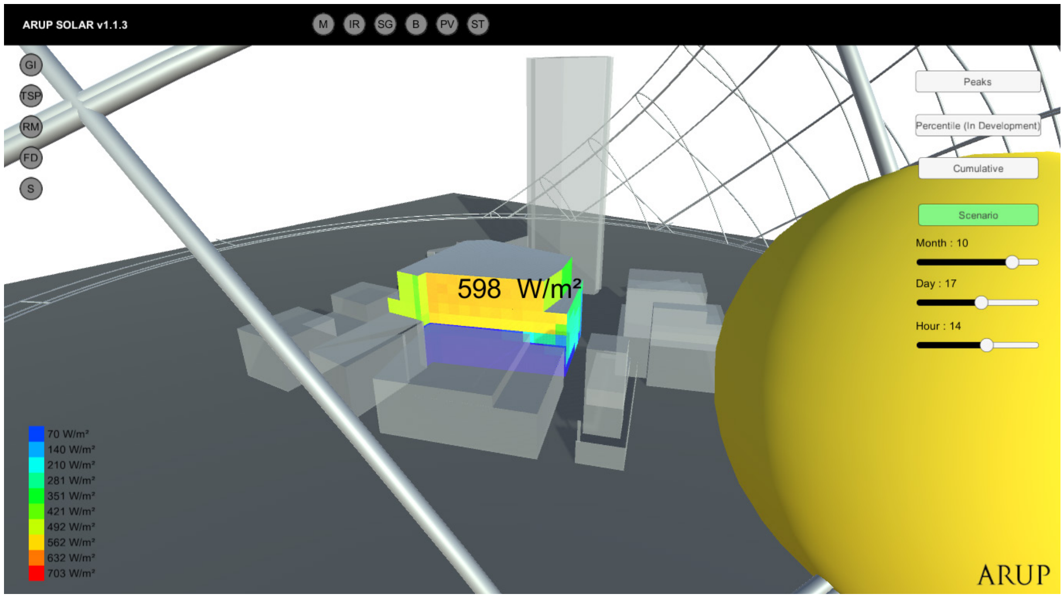

FIG. 11 Incident Radiation section

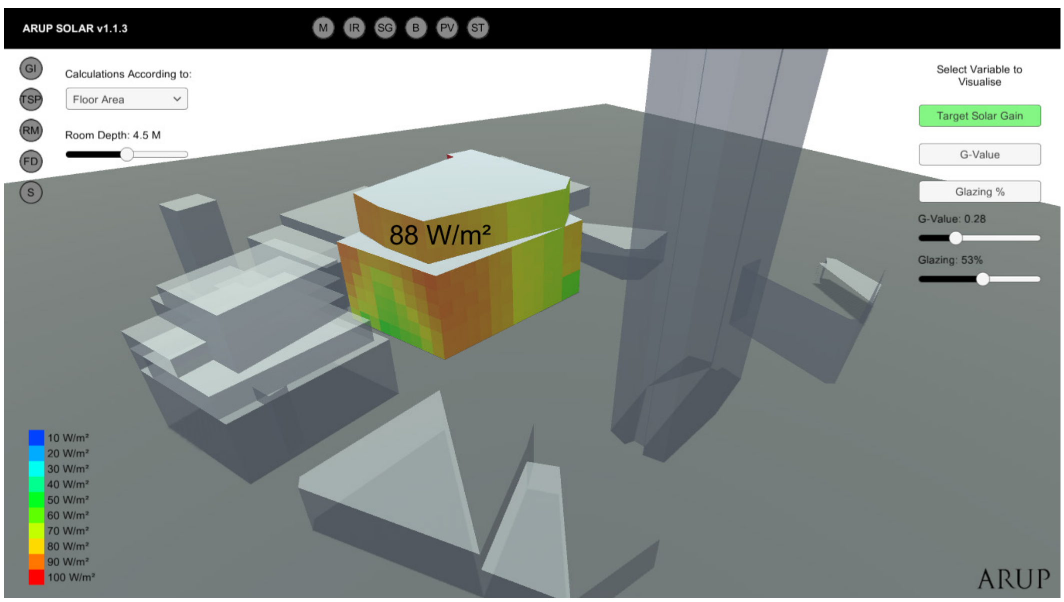

FIG. 12 Solar Gains section

In the Solar Gains mode, the solar gains according to glazing percentage and g-value can be calculated. Alternatively, any one of the three variables (i.e. glazing percentage, g-values and target solar gains) can be visualized in relation to the other two. (Fig. 12). Figure 12 shows a particular setting of g-value of the glass, percentage of window / wall, and depth of the facade zone. These can be easily changed by moving the corresponding sliders.

In the Extra Shading requirements mode, it is possible to identify the amount of time when additional shadings are required. The users need to input the Solar Gain Target, the glass g-value and percentage of window. In particular, when the use of extra shading in the form of blinds is required, clients typically want to know how often these will be deployed. Clear indicators support client's decision by visualizing the amount of time when blinds will have to be used (average daily usage per month and specific daily usage) (Fig. 13).

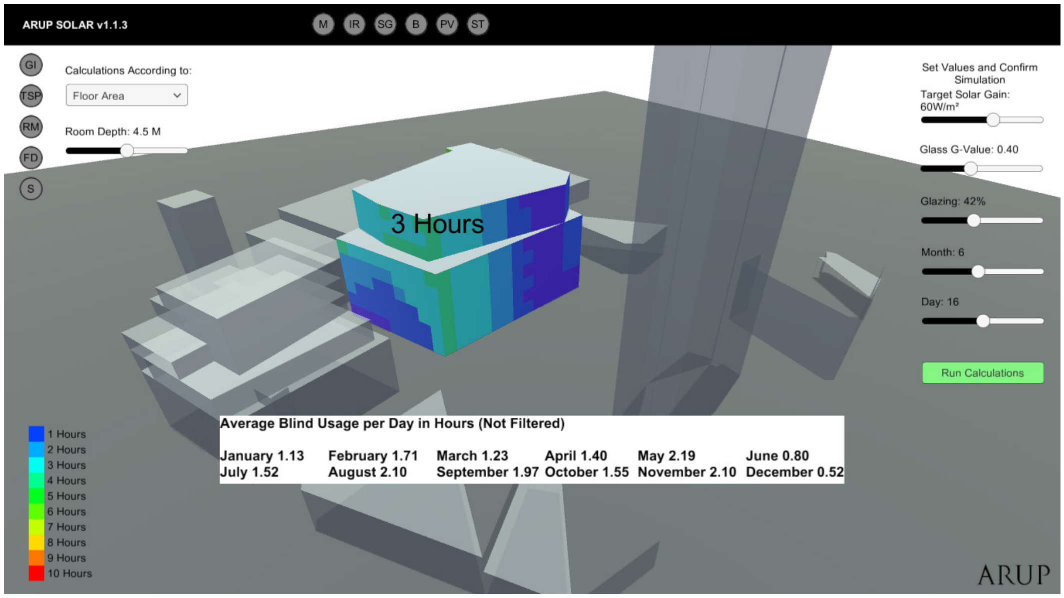

FIG. 13 Extra Shading requirement section

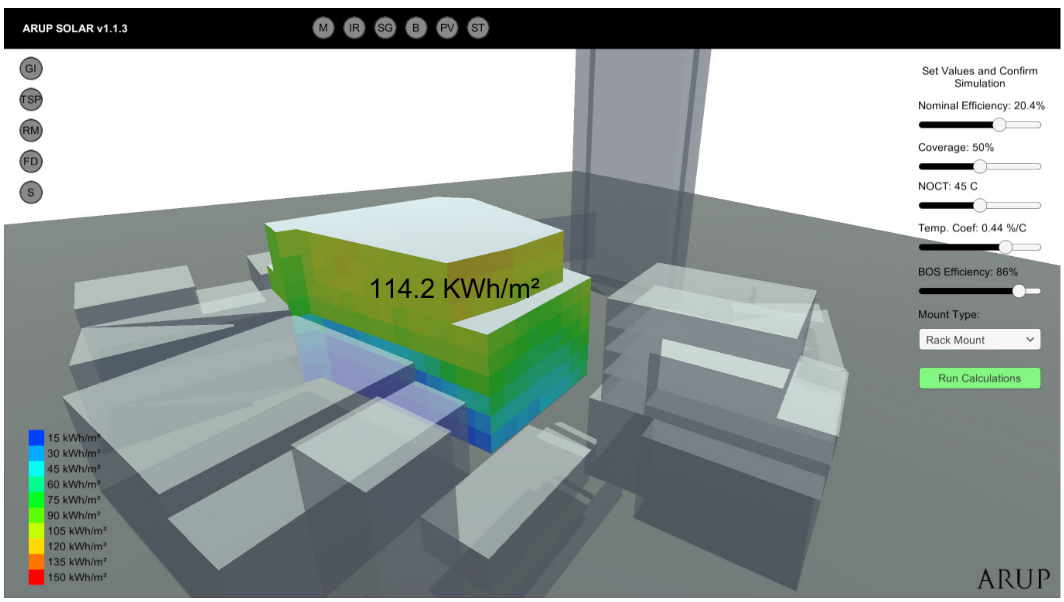

FIG. 14 PVs sections (Authors)

In the sections Renewable Energy, PVs and Solar Thermal (ST), the deliverable energy during a certain period can be assessed. Both these functionalities present algorithms based on relative angles of incident radiation, processes based on backwards ray-tracing and hourly temperature of the panels. Figure 14 shows PVs mode where the deliverable energy is displayed.

3 RESULTS AND DISCUSSION

This paper describes an innovative APP for a new approach to early design stage analyses that relies on interactive, flexible and user-friendly tools. ARUP Solar satisfies a requirement in the early stage workflow. The APP is built from the model geometry by means of Rhinoceros/Grasshopper that allows the link with Radiance & DAYSIM. For a specific geometry, the radiation analysis is required to run only once and Unity is used to post-process the whole set of results (substantially reducing computational times). The process to create the APP is straightforward and fast. In the case study, approximately 90% of the processing time was for the computation (STEP 2, Figure 2) of the solar incident radiation and the rest was for geometry creation and APP creation (STEPS 1-3, Figure 2). For more complex geometries, the time required to prepare the model could be longer.

The innovative use of game engine as a design tool improves the decision-making process with clear results mapped on the 3D model of the building.

The current tool is already powerful, stable, and quick. Furthermore, it allows the testing of an indefinite number of options (e.g. between g-value, window / wall ratio, target of solar gains / extra shading requirements). The APP also enhances the awareness of potential renewable energy generation through envelopes.

Some developments to improve the APP in the near future have already been planned, such as increasing the flexibility based on users' feedback and functionalities. In the mid to long term, the APP will be adapted for later design stages, so that the same approach can follow the development of projects. Thanks to its flexibility, the APP can easily become a tool where architects and engineers (facade, building services, electrical and PH) work together so that holistic design can become straightforward to achieve.

References

Arup, O., (1970). *The Key Speech*. ARUP digital publication. Retrieved from: http://publications.arup.com/publications/o/ove_arups_key_speech

Autodesk®, (2010). *Autodesk® Ecotect® Manual. Shading Masks.* San Rafael (United States).

CIBSE, (2006). *Technical Memorandum - TM 37, Design for improved solar shading control*. London (United Kingddom). Retrieved from: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7elAAC

DiOrio, N., (2014). *Technical Manual for the SAM Solar Water Heating Model.* National Renewable Energy Laboratory (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy). Retrieved from: https://sam.nrel.gov/system/tdf/SimpleSolarWaterHeatingModel_SAM_0.pdf?file=1&type=node&id=69521

Duffie, J.A., Beckman, W.A., (2013). *Solar Engineering of Thermal Process*. John Wiley & Sons, Hoboken (New Jersey). Retrieved from: http://eu.wiley.com/WileyCDA/WileyTitle/productCd-0470873663.html

European Parliament, (2010) *Energy Performance of Buildings Directive* 2010/31/EU. Official Journal of the European Union. Retrieved from: eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF

Granadeiro V, et all. (2013). *Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation*. Elsevier, Automation in Construction. Retrieved from https://www.researchgate.net/publication/257371570_Building_envelope_shape_design_in_early_stages_of_the_design_process_Integrating_architectural_design_systems_and_energy_simulation

Greenberg, D., et al. (2013). *Sustain: An experimental test bed for building energy simulation*. Energy and Building. Retrieved from . //dx.doi.org/10.1016/j.enbuild.2012.11.026

Negendahl K, (2015). *Building performance simulation in the early design stage: An introduction to integrated dynamic models*. Automation in Construction. Retrieved from: https://www.researchgate.net/publication/274736654_Building_performance_simulation_in_the_early_design_stage_An_introduction_to_integrated_dynamic_models

O'Hegarty, R., et al. (2016). *Review and analysis of solar thermal facade.* Elsevier, Solar Energy. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0038092X16301852

Quaschning, V., (2016). *Understanding Renewable Energy Systems*. Routledge, New York (United States).

Skoplaki, E., et al. (2008). *Operating Temperature of photovoltaic modules: A survey of pertinent correlations*. Elsevier, Renewable Energy. Retrieved from http://www.sciencedirect.com/science/article/pii/S0960148108001353

U.S. Deparment of Energy. (2016). *Energy Plus™ version 8.6 Documentation. Engeneering Reference*. National Renewable Energy Laboratory (U.S. Department of Energy). Retrieved from: https://energyplus.net/documentation

Waibel, C. et all. (2016). *Using Interpolation To Generate Hourly Annual Solar Potential Profiles for Complex Geometries*. Proceedings of BSO 2016. Newcastle (United Kingdom). Retrieved from: http://www.ibpsa.org/?page_id=797

Zemella, G., et al. (2014). *Evolutionary Optimisation of Facade Design. A New Approach for the Design of Building Envelopes*. Springer-Verlag. London (United Kingdom). Retrieved from: http://www.springer.com/us/book/9781447156512