URBAN SOLAR REFLECTION IDENTIFICATION, SIMULATION, ANALYSIS AND MITIGATION: LEARNING FROM CASE STUDIES

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ABSTRACT

Recent media attention has highlighted several cases where solar reflections from building facades caused serious impacts on their surroundings. Impacts range from general nuisance to property damage and human safety concerns. The trend in new construction of high window-to-wall ratios and increased use of reflective facade materials will presumably increase the frequency and impact of urban solar reflections. This paper reviews several solar reflection case studies performed by the authors conducted using a custom simulation tool. The assessment of reflection severity (both in a pre-construction, predictive context and a post-construction forensic context), mitigation effectiveness, and on-site measurement programs validating the predictions are all explored. Lessons learned during these studies which are applicable to the broader building performance simulation community are also discussed, including: selecting appropriate input data for simulations, the strengths and weaknesses of the various metrics used to describe reflection impacts, and effectively communicating findings to a lay-person.

INTRODUCTION

Experiencing impacts from reflected sunlight is often unavoidable for urban inhabitants. The majority of the time such reflections are simply a nuisance, however in recent years, well publicized cases of reflections causing dangerous visual impairment (Hayward, 2012), property damage (Wornick, 2012) and personal injury (Mayerowitz, 2010) have led to architects and designers wanting a deeper understanding of how their building will reflect solar energy and how that light and heat will impact the surrounding environment.

Over the past several years the authors have developed a custom simulation tool to better understand the impacts of solar reflections within complex urban environments (Danks & Good, 2016). This tool has been used for numerous studies of the impacts of a proposed building's reflections, as well as in forensic analyses, which have aimed to identify the sources of problematic reflections and evaluate the effectiveness of mitigation options. Field measurement programs have also been undertaken, with the aim of validating the simulation tool, as well as to provide context with respect to the intensities of existing reflections in a neighborhood and how those compare to the predicted intensities of reflections from a proposed building.

Due to the sensitive nature of the work performed, details which could identify the study buildings have been purposely omitted. Buildings shown in all figures have been modified to hide any unique features.

CASE STUDY 1: FOCUSED REFLECTIONS FROM A CONCAVE FACADE

During construction of a new building in the United States, it was discovered that at certain times the inward-curving (concave) curtain wall was focusing reflected sunlight to an intense spot that tracked across pedestrian areas in front of the building. This focal area was found to cause significant increases in temperature of objects in its path and unacceptable visual glare.

The initial study was a forensic analysis, which aimed to reproduce the issues observed on site, quantify the severity, and if necessary, identify the façade areas causing the problematic reflections and provide recommendations for mitigation measures. The area of concern was a drop-off area approximately 3,000 m² in area which would contain both pedestrians and idling vehicles. Architectural computer aided design (CAD) files detailing the geometry and orientation of the study building were simplified for simulation purposes but retained enough detail to accurately prescribe material properties to the façade and capture key details such as the vertical mullion fins which were approximately 30 cm deep. A model of the surrounding buildings was also created using information provided by the client and supplemented from publicly available sources. The surrounding buildings only act as obstructions to light in the simulations, thus they were modeled more coarsely, with details smaller than 0.5m neglected.

Simulating reflected light is critically dependent on the geometry of the reflecting surfaces. The original architectural 3D CAD model treated the curved concave façade as an idealized, continuously curved surface, but in reality the façade would be "faceted", i.e. multiple flat glazing units would be used. For most building simulation software this distinction is inconsequential, however when modeling reflected light, the difference between the two geometries can have significant impacts on the location, timing and intensity of the focused light. A smoothly curved surface will be much more efficient at focusing the reflections, leading to higher reflection intensities, which may be overly conservative. It can also influence the location of the focal areas. In this case, the affected area was close enough to the offending façade that these effects are relatively minor, but over longer distances, even slight differences in the orientation of the façade can change the location of a reflection impact by meters.

The reflective properties of the glazing then need to be determined. Since the façade causing the glare was already under construction, the exact manufacturer and model of glazing units were known. Reflectivity characteristics could then be determined using the industry standard software WINDOW, published by Lawrence Berkeley National Laboratory (LBNL) (Lawrence Berkeley National Laboratory, 2015). The primary glazing type was a high-performance glazing which featured a low-emissivity coating. These coatings are designed to selectively reflect thermal radiation, while allowing visible light to pass through. As such, while the glazing reflected approximately 15% of the visible light from the sun, when the entire solar spectrum (ultraviolet, visible and infrared) was accounted for, the glazing's overall reflectivity was nearly 40%. The design team had selected this glazing based on it being a "low-reflectivity" glazing, and was caught off guard by the difference.

Once the model was prepared, the simulations could begin. The area of interest was subdivided into a test grid positioned at 1.5m above local grade (i.e. a typical chest height for a pedestrian, or face height of a seated driver) with test points spaced approximately 0.5m apart. Reflections are a highly localized phenomenon, so high fidelity simulations are required to ensure that a focal area is not overlooked because the test point density is too low. However, fidelity must be balanced against the time it takes to run and post-process the simulation. The cumulative irradiance reflected from the façade and frequency of reflection occurrence was computed at one hour intervals over the course of a year as per (Danks & Good, 2016) on the test grid.

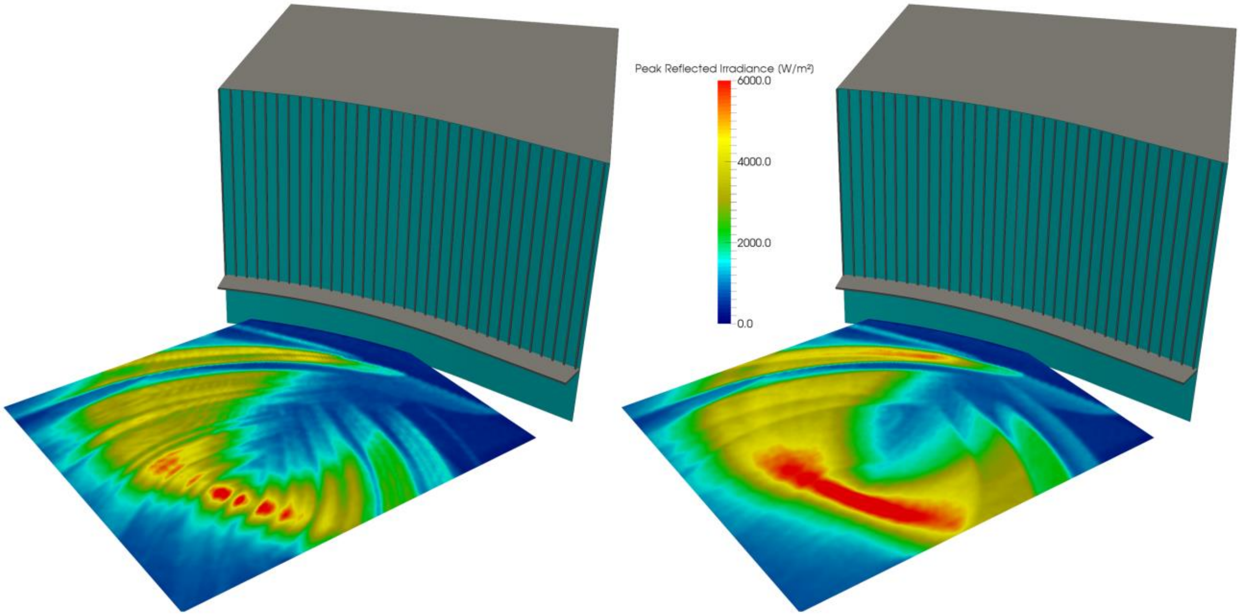

Figure 1. Comparison of predicted hourly peak reflected irradiance for 'typical' (left) and 'clear sky' (right) ambient solar conditions.

As per the reference text, the tool utilizes "clear-sky" solar data as an input. This type of input data is computed by first predicting the intensity of solar radiation at the top of the atmosphere at a given time and date, that intensity is then attenuated only by the air mass between where the energy enters the atmosphere and where it reaches the ground, which will change depending on the location of the sun relative to the receiving point as well as local factors like humidity. The effects of opaque cloud cover, however are not are not included in this estimation. There are many methods of varying complexity with which the clear sky attenuation can be computed. The method used by the authors (Gueymard & Thevenard, 2013), is the result of a research program sponsored by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE RP-1613), and was found to agree well with measured data. It is also a straightforward algorithm to compute, provides solar irradiance components (direct normal and diffuse horizontal) directly, and most importantly, the required input parameters needed to localize the attenuation, are available for thousands of locations around the world. Other methods do exist for computing clear sky data, however many require more detailed knowledge of the local atmospheric conditions than is typically readily available. Using clear-sky input data ensures that the full extent of the potential glare impacts are accounted for and intensities at a specific hour are not skewed down due to cloud cover, which in reality would be highly transient.

Figure 1 illustrates the results of two simulations in which the maximum reflected irradiance at each of the test points over an entire year is plotted. The plot on the left was computed using the Typical Meteorological Year (TMY3) file (Wilcox & Marion, 2008) for the site location, and the plot on the right shows the same results using "clear sky" solar data as the input to the simulation. Both results show areas where the façade creates peak reflected irradiance levels in excess of 6,000 W/m². However the results which used the "typical" solar conditions predict generally lower intensities and discrete zones where the most extreme focusing occurs; whereas the clear sky results show a more intense and continuous area of extreme reflection intensities. This is the result of the "typical" cloud cover which gets incorporated into the solar irradiance data in a TMY3 file. Cloud cover on a monthly or annual basis is relatively consistent; however the change in hourly cloud cover is much more variable. Energy modeling and other building science applications are usually focused on monthly or annual statistics, so hourly variations will balance and thus not impact results. Reflection analyses, on the other hand, are highly dependent on the intensities at a specific time and date. Lower hourly solar irradiance due to cloud cover can't be guaranteed in reality, and as the above results show, can lead to the under-prediction of the extent of a glare problem. In this case it is evident in the TMY3 simulations that a focusing problem exists, but for a scenario where the focusing events are short in duration, the potential danger could be missed entirely by a coincidental cloud.

With the degree of the focusing problem confirmed, a detailed analysis of the most intense focal areas was then conducted. The results of a minute-by-minute analysis found that the most extreme focusing events occurred in late afternoon during spring and fall and would take approximately 10 to 15 minutes to fully pass over a given point. A large portion of the curtain wall was identified as contributing to the focusing effect, meaning that large scale mitigation measures would be necessary.

In collaboration with the project design team, options for mitigation were conceived and their effectiveness tested through simulation. Over 40 simulations were conducted to understand how various combinations of glazing modification, façade mounted shading and/or grade level shading reduces the reflected irradiance. Ultimately, a grade level shading structure in combination with an anti-reflective coating on the glazing and additional mullion fins was decided upon. Further simulations were also conducted to understand the level of reflected irradiance the grade level shading structure would be exposed to, so that decisions on the structure's materially and detailed design could be better informed. The structure's design was modified to ensure that it intercepted reflections before the focal point, reducing the impact of the reflections on the shading device. It was also recommended that the surfaces be light colored and nonglossy to minimize heat gains and secondary reflections. In addition to the reflection simulations, physical testing was performed on site to benchmark the accuracy of the simulated results before fully committing to the mitigation measures.

The details of the on-site testing program can be found in (Danks & Good, 2016) but in short the simulation tool predicted the intensity and timing of the focused reflections satisfactorily, but tended to predict a smaller focal area, resulting in shorter durations (10-15 minutes) than what was seen in the measured data (20-25 minutes). Twenty-five focusing events were recorded with peak intensities ranging from 1,500 to over 4,000 W/m² providing further evidence of the extent of the focusing problem and validating the results of the preliminary studies.

Several temperature measurements of various surfaces were also taken before and after exposure to the focused reflections. These were taken to provide context for the intensity of the reflections and to justify our use of irradiance as the metric used to define the severity of a reflection's impact as opposed to temperature. While temperature is an intuitive metric that a lay-person can easily understand, the temperature of a surface is highly dependent on a host of environmental factors aside from the irradiance it's exposed to. While temperatures can be estimated a priori from the predicted reflected irradiance levels, it would require making numerous assumptions regarding the ambient wind and thermal environment as well as the material properties of the heated surface. Given the highly complex and transient nature of urban wind flows and the huge variety of possible materials, which may change significantly over the life time of a building, making appropriate assumptions is challenging and if done improperly may provide decision makers with a false sense of security.

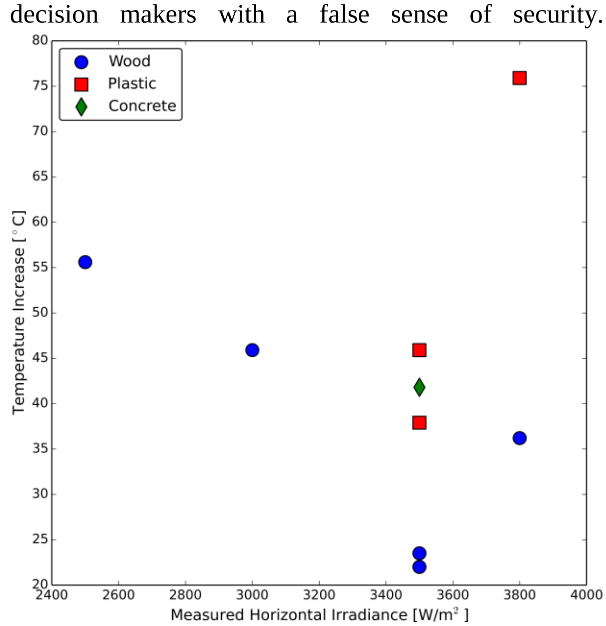

Figure 2. Measured temperature gains vs. reflection intensity.

Figure 2 plots the measured temperature gains of three different material types against the maximum intensity of the focused reflection event to which the materials were exposed. The wood object was the untreated pine support stand the measurement equipment rested upon. The plastic object was the light grey plastic weather-proof enclosure of the data logger mounted to the stand. The concrete surface was a nearby section of the poured concrete sidewalk. The wood and plastic surfaces were oriented vertically, while the concrete was horizontal. All the exposure times are approximately 20 minutes and occurred at ambient temperatures ranging from -10 to 20°C. While on-site limitations prevented gathering a more significant number of data points, the available data does illustrate why surface temperature gains are not necessarily an appropriate analogue for reflection impacts. Five temperature gain measurements were conducted during two adjacent days where peak reflections of approximately 3,500 W/m² were measured. An analysis of meteorological data from a nearby airport showed that the day with the higher temperature gains occurred when the wind was blowing from a direction which was obstructed by surrounding buildings. This would limit convective cooling of the surfaces which in turn presumably led to increased temperatures.

The most extreme temperature increase measured during the study was seen after the plastic enclosure was relocated on the stand. This increased the surface area exposed to the reflections. Under a reflection which was only 8% more intense than the ones discussed previously, the temperature gain increased by 65%. This underscores how variable surface temperatures can be, depending on not only exposure to irradiance, but also ambient conditions, material properties and even orientation, size and shape of the surface in question.

With the severity of the focusing problem directly measured, and the simulations showing satisfactory agreement with what was recorded, the mitigation measures were confidently implemented.

CASE STUDY 2: REFLECTIONS FROM PHOTOVOLTAIC PANELS

The next case study explores a case where the concern was reflections from a large array of photovoltaic (PV) panels adversely impacting the surrounding airspace. In the past, PV panels have been blamed for significant reflection impacts on the surrounding environment (Hayward, 2012).

PV panels are designed to absorb as much solar energy as possible and considerable effort is made in their design to minimize the amount of light reflected by the outer layer of the panel. Nevertheless, the glass used in PV panels will still reflect light. For light striking at near-normal angles to the panels, the fraction of light reflected is typically less than 5%, however as light strikes the panels at glancing angles, the fraction of light reflected increases rapidly and can result in a 4-5 fold increase in the fraction of light reflected, (Paretta, et al., 1999), (Ho, Sims, & Yellowhair, 2013). Much like the "low reflectivity glazing" from Case Study 1, the potentially high reflectivity of PV panels was not initially considered by the design team.

In this case, the visual impact of the glare was the primary concern rather than the absolute intensity. There are currently no universal guidelines for external glare impacts on typical urban environments, yet a Solar Glare Hazard Analysis Tool (SGHAT) (Ho, Ghanbari, & Diver, 2011) has been established for solar energy production facilities near airports to define the impact of reflected light on an individual based on its potential to cause "after-images" in a viewer. The use of this metric is currently required by the Federal Aviation Administration (FAA) for determining visual glare impact from PV panels near airports before they can be installed (FAA, 2013). The authors use a slightly modified version of this metric to account for the assumed task an individual would be undertaking when impacted by the reflection. As an example, reflections falling within the field-of-view of drivers or pilots would be considered more impactful than those falling on pedestrians due to the increased risk to others posed by the reduction in situational awareness.

Three-dimensional models of the development and the PV panels were developed. The PV panels were assigned a nominal reflectivity of 4% at normal angles of incidence, with off normal reflectivity defined as per (Ho, Sims, & Yellowhair, 2013). A volume of airspace 500m in radius and 500m tall above the site was defined as the study area and hourly simulations over an entire year were conducted to determine the frequency of ocular impacts based on the (Ho, Ghanbari, & Diver, 2011) criteria.

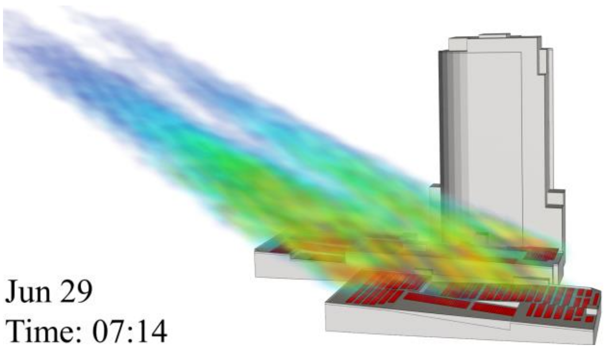

Figure 3. Point-in-time rendering of reflection impact from a PV array

Figure 3 illustrates a point-in-time rendering of the predicted reflections emanating from the PV panels. It highlights the need for large initial study domains, as reflections can travel significant distances and still be able to impact a viewer. Even in dense cities, reflections can travel unimpeded for multiple blocks if they are aligned with roadways.

Based on the results of the simulation it was found that while the reflections from the PV array did cause some minor visual impact on nearby buildings, the source of the reflections was too far away to have any significant impact on building occupants, drivers or pilots.

CASE STUDY 3: REFLECTIONS FROM FLAT AND CONVEX FACADES

Whereas Case Study 1 is a rather dramatic example of a solar reflection study and Case Study 2 explored reflections from a relatively unusual building element; Case Study 3 represents a more characteristic reflection study, which would be done during the early design stages of a proposed building. The goal of such a study is to provide the architect and building owner with an understanding of how the proposed building will reflect sunlight, and how those reflections will impact the neighborhood. The need for such a study is usually triggered by the request of an authority or as a due diligence exercise by the architect and/or owner.

In this case study, the proposed development featured several extensively glazed facades which were both planar and convex in shape. The building was located in the downtown of a major American city, putting it close to highways, parks, historic neighborhoods, and other locations which would be sensitive to reflected light.

The models of the study building and surrounds were prepared similarly to what was described in Case Study 1. However, in this case, due to the distances involved, how the convex façade was facetted would affect the results. The original continuously curved façade provided by the client was modified to clearly define the correct size of the facets. Figure 4 illustrates the predicted annual reflection frequency at hourly increments for a convex façade modeled as smoothly curved, as well as facetted with facet widths of 5 and 10m. It is clear that the idealized nature of the smoothly curved façade acts to scatter the reflections much more efficiently than what would be seen in reality. Even moving from a 5m to a 10m facet noticeably changes the results.

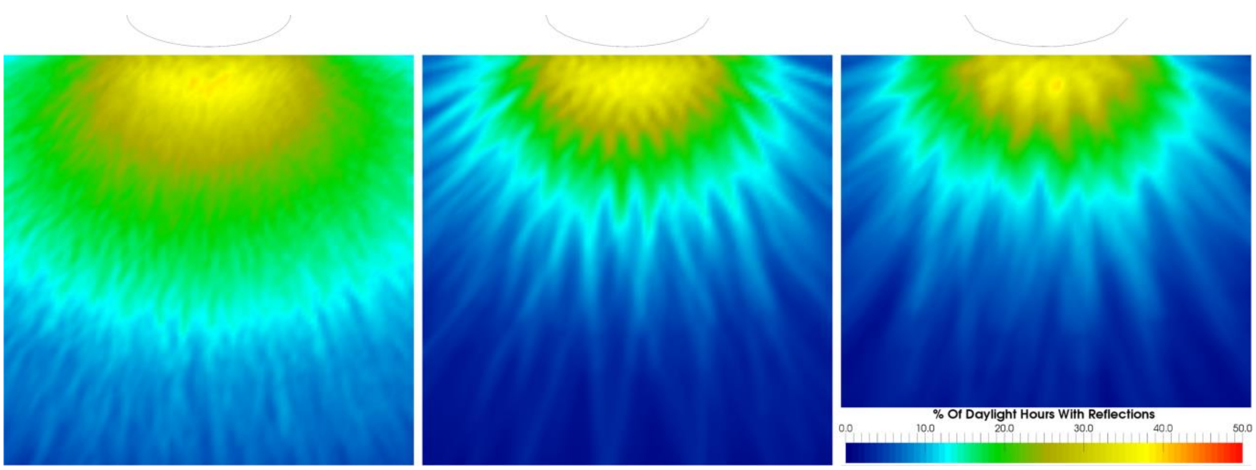

Figure 4. Hourly Glare frequency plots for an idealized convex facade (left), a convex facade with 5m facets (center) and a convex facade with 10m facets (right)

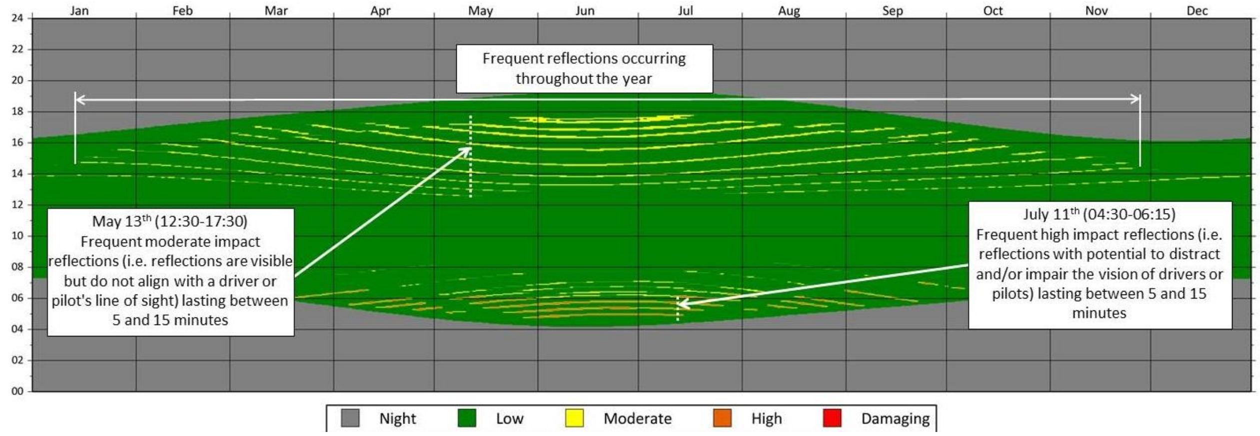

Figure 5. Example annual glare impact plot

The area of interest was determined to be a 500m radius around the study building and clear sky solar data was computed for the study site. This domain was divided into a 2m test grid placed at 1.5m above the ground and analyzed at hourly time steps for an entire year. This initial screening analysis identified areas where reflections occur frequently and/or areas where peak reflection intensities or visual impact are predicted to be high. The results of this screening analysis are combined with geographic information of the neighborhood to select specific locations which warrant further study. Locations such as street intersections, highway on/off ramps, parks, outdoor seating areas and the facades of nearby buildings are common choices.

At these specific locations, the visual and thermal impacts of the building's reflections are reassessed at 1 minute increments for the entire year. This allows for a very detailed understanding of the frequency, intensity and duration of the reflection events. Figure 5 presents an "annual glare impact plot" which is an effective way to distill such a vast amount of data into something easier to understand. One can clearly see the extent of the frequent, short duration reflections caused by the facetted convex façade which occur throughout the year. The reflection impacts are presented using the authors' modified version of the Ho et al. methodology. Where "high" impact reflections are defined as those bright enough to cause after-images and fall within a driver's line of sight. Moderate impacts are those which can cause after-images but fall outside of a driver's line of site, or impact those assumed to be engaging in low risk activities (walking, sitting, etc.).

The majority of the points were found to experience typical levels of glare impacts from the development. However, one area of the façade was found to be reflecting sunlight along a busy roadway during the morning rush hour in such a way that it would cause a noticeable impact on drivers. The angle at which the light was reflecting was computed and it was found that vertical mullion fins of modest depth would be adequate to break up the high impact reflections affecting the street.

LESSONS LEARNED

While the presented case studies represent a novel form of building simulation, several lessons learned during these projects are applicable to the broader building science simulation community, and generally fall into three categories.

Input Data

A simulation's results are only as good as its input data. Having a good understanding of any assumptions and limitations inherent to the inputs is critical. As an example, meteorological data underpins many types of building simulation, and aside from selecting the closest available data set, little thought is often given on the appropriateness of the data for a given location or task. In Case Study 1, cloud cover included in the TMY3 file lead to a significant reduction in the scale of the reflection impacts. If the TMY3 file had been used as the input for the mitigation simulations, the potential exists for cloud cover to mask an unmitigated reflection. It is important to realize (particularly for novice simulationists) that the typicality of the TMY3 (and other) weather data is terms of monthly and annual average values of key parameters (Su, Huang, Xu, & Zhang, 2009). Variations and trends in data at shorter or longer timescales will not necessarily (nor should be expected to) be "typical".

Similarly, how a building is modeled can also potentially influence the results of a simulation. It is usually not desirable (or even possible) to model a study building exactly. Simplifying the geometry is often necessary to ensure simulations can be run in a timely fashion, but it is important to understand how sensitive the simulation results are to those simplifications. As shown in Case Study 3, different methods of simplifying a building façade led to drastically different results. Likewise, small scale features like the mullion fins, which are ordinarily neglected in building simulation, may be vital features to include when studying external reflections from a façade.

Output Metrics

Often the raw output of simulations is in a format which is not necessarily easy to understand for a lay-person (i.e. megajoules of energy used). Consequently, in many cases derived metrics are used instead to provide more clarity to the results (i.e. energy use intensity) or to make them easier for lay-people to understand (i.e. expressing energy savings as an equivalent savings in oil, CO_2 or currency). While these metrics make communicating the results easier, they can contain inherit assumptions which, if poorly understood, can skew the perceived results.

This is the reason the authors' preferred metric for reflection intensity is the raw irradiance values in W/m² as opposed to a derived metric like temperature or in units of "suns" (i.e. the reflected irradiance normalized by the ambient solar irradiance). Many assumptions need to be made in order to derive the (more intuitive) temperature gain information, and as shown in Case Study 1, actual surface temperatures are extremely sensitive to a variety of other environmental factors which are highly variable in a complex environment like a city. Likewise, expressing reflected intensity as a fraction of the ambient solar levels can also be misleading. Ambient solar intensity varies over the course of a day and throughout the year, a reflection which is twice as intense as the sun at dusk may be an order of magnitude less intense than a reflection which is twice as intense as the sun at noon, but both would be considered "2 suns" while potentially resulting in different impacts on people or property.

Many metrics exist which aim to describe the level of impact *visible* glare has on an individual and generally are used in the study of night time road lighting or indoor glare. However, most are unsuitable for daytime outdoor glare assessment due to assumptions within the methodology or because of their formulation. As an example, the commonly used Threshold Increment (TI) metric, which can be thought of as the increase in an object's contrast required to maintain its visibility after a glare source is introduced, is only valid for average road luminance values between 0.05 and 5.0 cd/m² (CIE, 2000). During the day, typical road luminance values are several orders of magnitude above this range (BSI, 2003), making this metric invalid for use with solar reflections. A similar metric has been suggested by Hassall (Hassall, 1991), where the so called "veiling luminance" (a measure of disability glare) is limited to no more than 500 cd/m² for motorists. There is an assumption in this limit that glare only occurs during late dawn or early twilight time frames, when a driver's eyes would be adapted to a 500 cd/m² luminance level (Schieber & Harms, 1998), rendering that limit overly conservative for glare occurring at other times of day.

Indoor glare metrics have similar drawbacks. Many define the severity of glare based on the ratio of the brightness of the source to the overall brightness of the field of view. A light source as bright as the sun will dominate both terms, driving this ratio close to 1 and result in a net *decrease* in glare discomfort (Jakubiec & Reinhart, 2012). Much like the TMY3 weather files, all of these metrics are suitable for use within their intended scope, but cannot be universally applied to any scenario.

The authors' preferred metric derived from (Ho, Ghanbari, & Diver, 2011) is explicitly designed for assessing the impact of glare from the sun outdoors. It is also easily relatable to a lay-person, as the "after-images" the metric references are a common experience. Perhaps its biggest advantage is its explicit endorsement by a major governing body, (FAA, 2013), making it distinctive among glare metrics.

Communicating Results

The interaction between the built and natural environments is complex. Maintaining an open dialogue with the clients throughout the study process is critical. In the context of reflection studies in particular, first-hand knowledge of the city and neighborhood can provide insights into locations which may be particularly sensitive to reflected light that may not be immediately obvious to an outsider. Similarly, a preexisting reflection problem can dramatically influence a community's perception of new reflections, so again having open lines of communication can help ensure the results are presented appropriately. When presenting unfamiliar topics, providing context to a reader is very important. The authors have found that overlaying results on site drawings or other maps aids in the understanding of the scale of reflection problems in a city. Photographs showing glare instances can also be used to provide context with respect to the intensity of a reflection. However, care should be taken that the photographs are suitably calibrated since improperly calibrated images can potentially exaggerate the impact of glare.

While presenting the results on pedestrian height planes is a useful way to illustrate the reflections, in situations like Case Study 2 it may make more sense to present the results volumetrically. The advantage of illustrating the results in this fashion is that the path the reflections take through the air is immediately apparent, as is the source of the reflection. The angle of the reflection is also clearly shown which when combined with instantaneous reflection intensity values, effectively illustrates the relationship between a material's reflectivity and the angle of incidence of the light.

As noted above there are no universally accepted guidelines for how much glare is "acceptable". In scenarios like Case Study 1 where the level of focusing is extreme it's obvious when there is a problem, but it can be challenging for clients to understand results when there is no definition of what is "typical" glare in a city. Experience in viewing and modeling urban reflections will lead to a level of intuition and understanding of what is "typical", but initially this can be difficult to communicate to clients and building authorities. In some cases the authors have performed preliminary investigations which measured the intensity, timing and duration of existing glare events in a given location. This helps by providing context to the clients and authorities on how the predicted reflections from a proposed building compare to what already occurs, and can also serve as a benchmark or calibration for simulation results.

Lastly, it is also important to remember that an individual simulation is usually one piece of a larger design, and that recommendations to mitigate one issue can have downstream impacts. Adding vertical fins, for example, reduces glare impacts but may lead to issues related to wind loading, snow/ice buildup or aero-acoustic noise, so a holistic approach to the problem is preferred.

CONCLUSIONS

The authors have developed an innovative simulation tool which can predict the impact solar reflections from the built environment will have on their surroundings. Three case studies were presented showing the range of uses in which the tool can be applied. Despite the novel nature of the problems being simulated, the lessons learned by the authors while performing the work can be generally applied to all those who work in the field of building simulation.

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