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Computer simulation of sunlight concentration due to façade shape: application to the 2013 Death Ray at Fenchurch Street, London

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Reflected sunlight from the Walkie-Talkie building in 20 Fenchurch Street, London, was reported to have caused the melting of plastic components of a car parked at street level in late August of 2013. The incident was explained by the concave-shaped south façade of the building, which converges solar radiation into a hotspot. In this study, we test the sunlight concentation hypothesis with a lighting simulation. A geometry model with material properties was created, and different weather situations were modelled. The results are illustrated in irradiance maps indicating time, position and peak heat fluxes. The highest simulated flux on the day of the incident was 3320 $\mathrm{Wm^{-2}}$ (10 to 15 fold increase compared to direct solar radiation). Additionally, the specific time and day for maximum heat fluxes between June and December were determined . For the worst scenario, which was avoided becuase the sky was partially cover with clouds that day and the hotspot did not fall on street level, the simulations showed that the peak heat flux would have reached well over 4000 $\mathrm{Wm^{-2}}$.

Keywords: glare; lighting simulations; sunlight; urban enviroment

1. Introduction

According to the principles of sustainable buildings, summarized by the *Conseil International du Bâtiment* (CIB) in 2010, a sustainable building should 'have its environmental impact minimised over service life' (CIB 2010). One obvious environmental impact of a building is its energy demand. To minimise the cooling load inside a building, most modern building envelops are made of a spectrum selective glass to achieve optimal energy consumption. It maximizes the transmission of visible light while reflecting wavelengths in the infrared part of the spectrum which greatly contribute to the incoming heat (Lechner 2015). However, this mechanism may lead to environmental problems such as discomfort glare and unexpected thermal load on surrounding areas (Shih and Huang 2001). Several serious cases have attracted public attention recently. The building at 20 Fenchurch Street (also known as the Walkie-Talkie colloquially) a high-rise building in London, was criticized for concentrating the reflected solar radiation at its south façade in 2013. The Vdara Hotel (Las Vegas, USA) and the Walt Disney Concert Hall (Los Angeles, USA) are two other famous cases of sunlight concentration in the surrounding (Henley 2013). A series of studies on the topic of heat and glare caused by glass facades were conducted. The first one was by Schiler and Valmont who conducted a study on the thermal and lighting impact around the Walt Disney Concert Hall. An infrared thermometer gun was used to record the temperature at a spot of interest, and digitized photographs and computer simulations were used to analyse potential glares (Schiler and Valmont 2005). Lobaccaro and Frontini used a real case in Lugano, Switzerland to develop an approach to sustainable urban planning method using parametric solar design optimization to maximize the solar access of the building and evaluated the solar influence on the neighbouring buildings (Lobaccaro and Frontini 2014). Yang et al. introduced a method to analyse reflected sunlight from building envelope using forward ray-tracing to localize critical positions, and applying backward ray-tracing to quantify the reflected daylight received (Yang, Grobe, and Wittkopf 2013). Disability glare caused by photovoltaic panels to an air traffic control tower was studied using backward ray-tracing by Jakubiec and Reinhart (2014), finding good agreement between simulations and measurements.

The objective of the present study is to reproduce the sunlight concentration phenomenon at 20 Fenchurch Street using the backward ray-tracing computational simulation tool Radiance (Larson and Shakespeare 2004). The simulations explore the relationship between the sunlight, the building and the surrounding environment. The impact of reflected irradiance on the surrounding environment in different weather conditions is also evaluated.

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Furthermore, the date and time for the worst sunlight concentration scenario are found. The presented simulation framework will enable building designers to prevent accidents resulting from sunlight reflections by adjusting their design and thus to avoid cost-intensive retrofitting of the building.

2. Scenario description

The Walkie-Talkie is a 160 m high skyscraper, located in the financial district of the City of London. A photograph of the building and its surroundings is shown in Figure 1. The construction work finished in 2014 but even by the time of the sunlight concentration incident in 2013, the building had become an iconic volume and shape in the skyline of London (Lane 2015).

News about plastic parts (wing mirror, panels and badge) of a car parked at street level near the building being melted was first reported in early September 2013 (Verity 2013). The south façade of the Walkie-Talkie has a concave shape covered with highly reflective glass panes to reduce the energy consumption inside the building. The reflected solar radiation converges at street level, as indicated schematically in Figure 2. The sunlight concentration caused the melting of plastic parts, carpets and doormats to catch fire and scorching of bike seats (Duell and Webb 2013). Surfaces exposed to hotspots created by the building were reported to reach temperatures of up to 91.3°C. Land Securities claimed that the problem could last for two hours a day and might occur during two to three weeks of the year (Verity 2013). The architect of the building at 20 Fenchurch Street told the media that he knew reflected sunlight could cause problems but that there was a lack of tools and software to assess and prevent these problems. The actual temperature of hotspots induced by the building was more than twice as high as the estimated temperature (Wainwright 2013). Independently of the present study, a permanent solution to avoid this phenomenon from happening again has since been implemented, consisting of sunshades attached to the south façade (Molloy 2014). This solution added extra cost to the project, and substantially altered its aesthetics.

Glass has been widely used in building construction industry since the late twentieth century (Lyons 2014). In order to meet the demand of reducing energy consumption inside buildings, the glass façades are generally spectrally selective by adding an additional low-emissivity (low-e) film layer on the glass. Spectrally selective glass can filter out infrared and ultraviolet radiation, maximizing the transmission of visual light (Lechner 2015). Since ultraviolet and infrared radiation lies outside the visible spectrum, it does not add to the lighting of spaces inside the building, but does contribute to the heating of internal surfaces (Modest 2003). The whole south façade is defined to be solar coated double glazing (Land Securities and Canary Wharf Group PLC., 2012). It can be assumed that the solar coating is low-e. Traditionally, outer panes are made of toughened glass while inner panes are made of low-e glass to perform environmentally (Xianfeng, Junping, and Xiaoqing 2011). Irradiation on a semi-transparent media can be reflected, absorbed or transmitted (Incropera et al. 2007). In the case of the Walkie-Talkie, the south façade is similar to a parabolic mirror that can reflect and concentrate solar radiation into a convergent hotspot. Hence the dominant

Figure 1. The Walkie-Talkie located at 20 Fenchurch Street, London, in February 2018 as seen from the south. Copyright by N. Theasby 2018 (licensed under CC BY-SA 2.0).

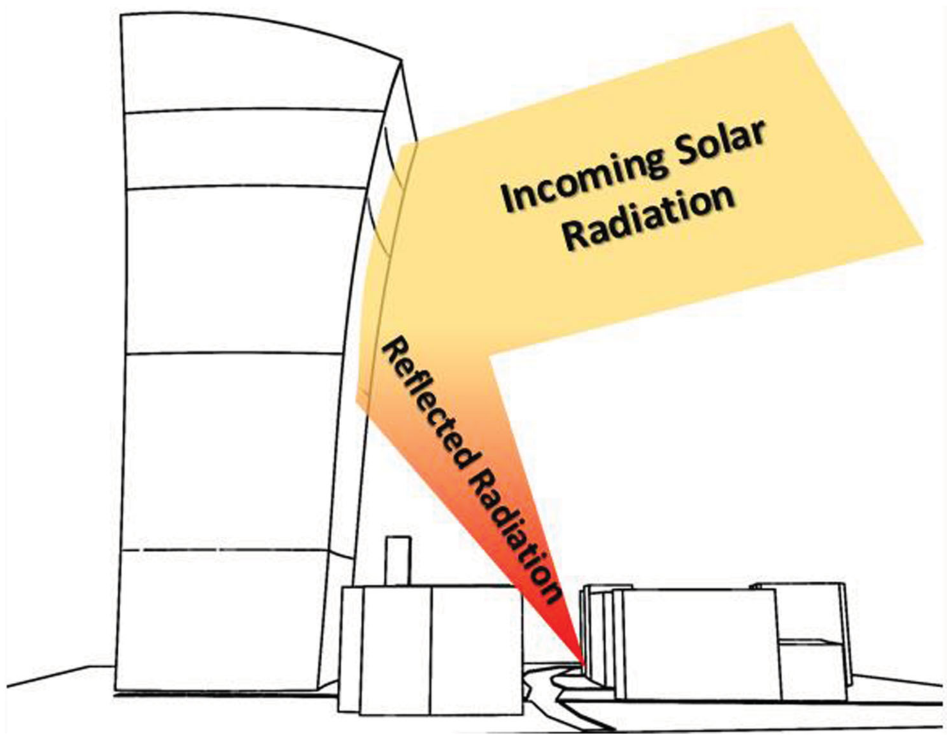

Figure 2. Schematic illustration of solar rays being reflected off the south façade of the Walkie-Talkie and concentrating at a hotspot at street level.

reason for the phenomenon under study is the reflection of solar radiation also referred here as sunlight.

The total reflectance of a double glazed façade, ρ_{total}, is obtained from the transmittance of toughened glass (τ_0) and the reflectance of toughened and low-e glass (ρ_0 and ρ_i, respectively) (Howell, Menguc, and Siegel 2016),

$$\rho_{\text{total}} = \rho_0 + \frac{\rho_i \tau_0^2}{1 - \rho_0 \rho_i}. \quad (1)$$

Reflectance and transmittance can be found in the BSI Standards (BSI Standards EN 410:2011, 2011). For the characteristics of the glazing of the Walkie-Talkie, the reflectance of the façade was calculated to be 27%.

3. Modeling framework

Radiance is a suite of programmes for the analysis and visualization of lighting phenomena. It was initially created as an advanced rendering technique in lighting design at the Lawrence Berkeley National Laboratories (Larson and Shakespeare 2004). Radiance can solve a wide range of lighting phenomena such as object modeling, rendering, intensity calculation, image processing and display. Radiance has the capability of simulating complicated light behaviour accurately by using backward ray-tracing. This technique is described as the process of 'render[ing] following view rays from the virtual focus of the eye or camera through pixels in an imaginary image plane into the environment', so that it can provide accurate numerical results as well as realistic renderings. Radiance is recognized for its performance and flexibility (Larson and Shakespeare 2004).

The basic procedure of the computational lighting simulation consists of several steps. The first step is the definition of the geometry of the scenario to be modeled. Itincludes the building itself, and the area in front of the south façade that may suffer from sunlight concentration. A total of 17 surrounding buildings, 6 roads and adjacent pedestrian areas were created using the 3D modeling software Rhinoceros (McNeel and Associates 2015). Since the main cause of the hotspot phenomenon is the concave south façade of the building, its envelope was created in detail, while the shapes of surrounding buildings were simplified. For the Walkie-Talkie, only four floor-plan blueprints and one side view were found, and the model was thus created by extrapolation and a loft tool. The complete scene geometry model can be seen in Figure 3. The actual geometry of the building is quite complicated (e.g. individual glazed panels deform from their original shape). Thus the geometryimplemented in this study is just a reasonable approximation.

The second step is to define the material properties for each surface of the scene geometry model. There are around 30 material types in the Radiance material package (Larson and Shakespeare 2004). According to the

Figure 3. Complete geometry of the scenario as modelled in Radiance.

arguments exposed in Section 2, the reflectance of the envelope of Walkie-Talkie was set to be $\rho_{\text{total}} = 0.27$. The reflectance of roads, pedestrian areas and façades of surrounding buildings are modeled as 0.1, 0.1 and 0.3 respectively based on the material database of Radiance (Jaloxa 2011).

Once the materials were defined, the view point and view direction of the result image were defined. The whole scene of the final simulation results is illustrated in Figure 4. The view point was chosen as being located on the top of the Walkie-Talkie and directed downwards in front of the south façade where the hotspot had been reported. Four locations of interest were marked with dotted lines and numbers. There is a bicycle parking lot at location 1. It was reported that bicycle seats were scorched by the focused solar rays. Location 2 indicates three parking bays where the affected car was parked at the time of the incident. Location 3 is a café that suffered the shattering of tiles at its front due to the heating caused by the hotspot. The doormat at the barber's shop at Location 4 ignited, which left a scorched mark (Duell and Webb 2013). The surrounding buildings and main streets are also indicated.

The fourth step is to decide the time and period of simulation. The scene of the adjacent area in front of the south façade of the Walkie-Talkie from 11:00 am to 14:00 pm GMT on August 29th, 2013 was replicated to demonstrate what had happened on that day when the plastic parts of the affected car melted. This specific time period was selected based on observations that during this period the hotspot induced by reflected solar radiation passed through the region where the reported heating damages occurred. Although these events first attracted the public's attention, it might not have been the worst situation created by the reflected radiation in terms of peak heat flux. It is not correct to assume the amount of reflected radiation is maximized when the sun directly faces the south façade, because maximum irradiance occurs when the sun is not directly facing the south façade. Therefore, a series of simulations were performed to identify which sun position and what day corresponds to the worst case scenario.

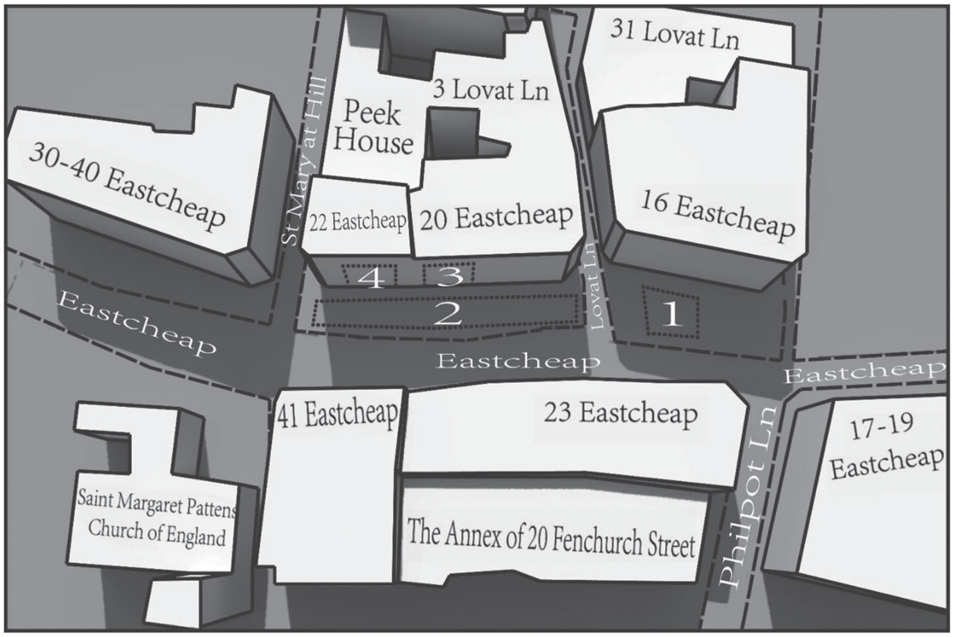

Figure 4. View of the model of the surrounding buildings with the indicated view point. Four locations of interest are indicated. Damage to objects due to the action of the hotspot has been reported at those locations.

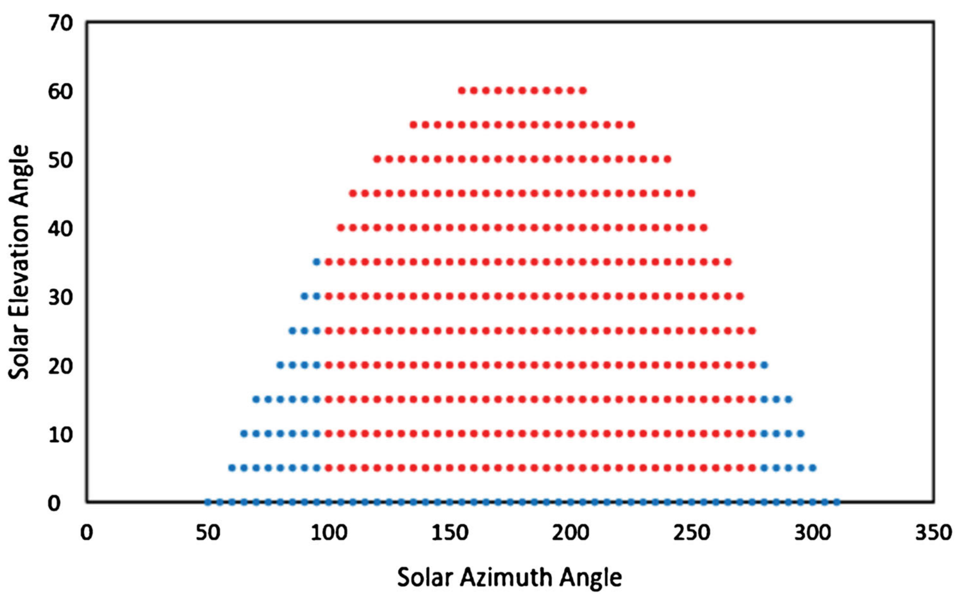

Figure 5. The annual solar path (discritized in 5 degrees) illustrates all possible sun positions in the sky viewed from the Walkie-Talkie. Red dots mean the sun faces the South façade; blue dots mean the sun does not face the South façade (no direct solar irradiance). Units are degrees (°).

According to the solar path diagram, the sky dome was discretized into 461 segments, as shown in Figure 5.

In some sun positions, the sun does not face the south façade of the Walkie-Talkie and no reflected solar rays can be observed on the ground, therefore only 364 sun positions (red dots in Figure 5) were simulated. The model of these simulations was simplified so that only the south façade of the Walkie-Talkie and the ground were created. The value of the peak heat flux received at ground level for each simulation was recorded. With that information, a falsecolour intensity map of peak heat flux with various sun positions was plotted, as presented in Figure 6. The brightest region is at the solar elevation of 30° and an azimuth angle ranging from 185° to 200°. Comparing this plot to the sun path diagram in Fig. 5, it is observed that the sun passes the brightest region on the 12th of October 2013.

Once the direct solar radiation had been analysed, an appropriate sky model was selected. Three sky luminance distribution types were considered and implemented in Radiance: a clear sky, an intermediate sky and an overcast

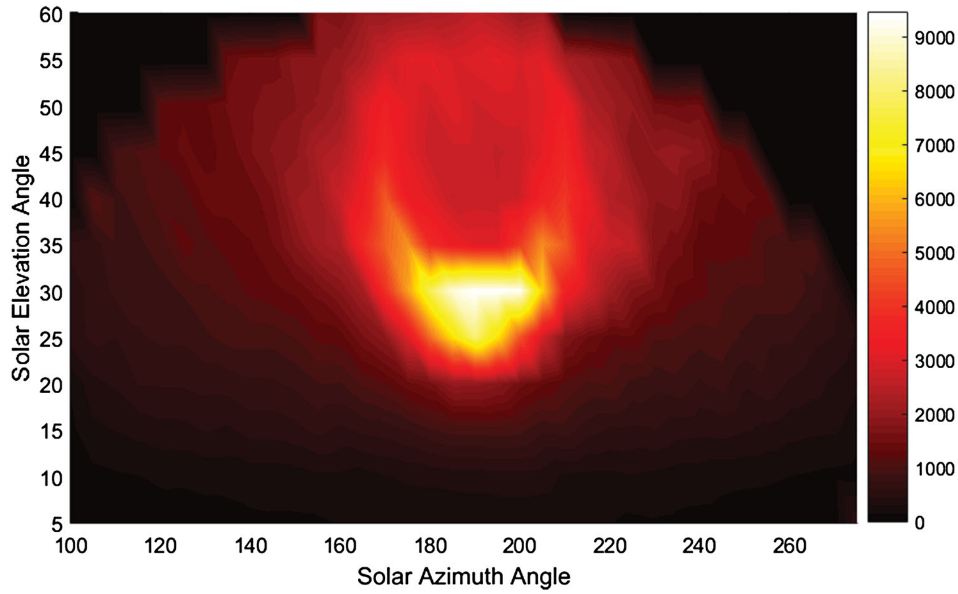

Figure 6. Falsecolour intensity map of peak flux received on the ground with various sun positions.

Table 1. Relationship between CIE sky models and cloud account.

Sky luminance distribution type	Descriptions	Amount of clouds (okta)
CIE Standard clear sky	Less than 30% of the area of sky is covered by clouds	0,1,2
CIE Standard intermediate sky	Between 30% and 70% of the area of sky is covered by clouds	3,4,5
CIE Standard overcast sky	The entire sky is covered by clouds	8

sky. The models are built based on the CIE (Commission Internationale de l'Eclairage) standard (CIE Technical Committee 3-15 2003). These three sky models represent three different weather conditions in terms of the amount of cloud. In meteorology, the cloud amount is the fraction of sky covered by clouds measured using a cloud base and recorded in okta units. Oktas range from 0 to 8, and are defined as the fraction of the sky occupied by clouds. Zero okta represents a completely cloud free sky whereas 8 oktas represent a fully clouded sky (MetOffice 2017). The CIE standard sky models and cloud measurements are related in Table 1.

The heat flux incident at ground level is maximum if sunlight is not obstructed by clouds, so that among the three different sky models, the *clear sky* is the worst scenario. In the *intermediate sky* model, sun rays are partially obstructed by clouds, which block about 30–70% of the light. Whereas no direct solar irradiance is received by either façade or ground in the *overcast sky* because the sun is completely blocked by clouds.

Table 2. Cloud amount collected by Met Office.

Time	Cloud amount 29th of Aug.	Cloud amount 12th of Oct.
11:00 am	0	3
12:00 pm	2	5
13:00 pm	2	4
14:00 pm	0	2

The data of cloud blockage on the 29th of August and 12th of October 2013 were obtained from the Met Office (MetOffice 2017), and are listed in Table 2. According to the historical data, it can be concluded that in real condition, from 11:00 to 14:00 on the 29th of August 2013, the sky can be regarded as a *clear sky*, whereas on the 12th of October 2013, it can be considered as an *intermediate sky*.

The previously defined model combinations were then compiled using binary representation and the results sent to the calculation process. Finally, to visualize and analyse the results, an irradiance map was rendered and outlined using the Falsecolour Radiance sub-programme, whereas the peak heat flux value can be read using Radiance's `wxfalsecolor` programme. The process of validation of the simulations was divided into three parts. The sky luminance was verified using a simple model consisting of a sky dome and an area on the ground. The reflection process of the simulation was validated by a simple plane model and comparing the results to the theoretical calculation. The mechanism of light and heat convergence was verified by simulating first in Radiance a validation case for a simple parabolic dish.

The order of magnitude of the maximum temperature of an object under heating can be estimated by assuming that the incoming radiation is completely absorbed (with heat capacity c $\mathrm{Jkg^{-1}K^{-1}}$ and mass m kg), from a simple energy balance to yield the expression,

$$q''_{\mathrm{rad}} A \cdot t = mc\Delta T, \qquad (2)$$

where q''_{rad} is the incoming radiative heat flux (in $\mathrm{Wm^{-2}}$), A is the area receiving the radiative flux (in $\mathrm{m^2}$), t is the total time of exposure and ΔT is the temperature increase in K (Incropera et al. 2007). Equation (2) only holds for thermally thin objects (i.e. objects thin enough so that heat conduction within the object can be neglected). In larger objects local surface temperatures can be higher than estimated using Equation (2), as heat is not instantly transferred into the interior of the object.

4. Results and discussion

4.1. Incident on August 29th, 2013

The first group of simulation results is used to replicate the scene on the 29th of August 2013, when parts of the passenger car were melted. The *clear sky*, which was the real weather condition on that day, was applied. The results were mapped for every 20 min. A sample of the results for different times is presented in Figure 7.

Due to incomplete information regarding geometry and material properties, the model was created by estimation and site visits, so that some uncertainty is expected in the results. Scattering and absorption caused by water vapour, dust, ash and other particulate matter in the air were neglected, becuase their effect is very small for the short ray lenghts under study.

Synthesising each image, four interested locations can be identified, and the quantitative results are tabulated in Table 3. The values marked with ∗ are interpolated, while the remaining values are directly read from the results image.

Three parking bays are affected by a hotspot during 2 h in the early afternoon (rows 2 and 3 of Table 3), which agrees with the statement from Land Securities ‘it can last for two hours a day’ (Duell and Webb 2013). Other locations are affected for 30 min in average. The last four rows of Table 3 indicate the average heat flux and the peak heat flux received in each location during the affected period along with the time and location. The highest average heat flux and peak flux is received at the parking bays. The barber’s shop receives the peak flux at the right corner of the shop, which is consistent with burn marks observed at the right corner of the doormat at the entrance.

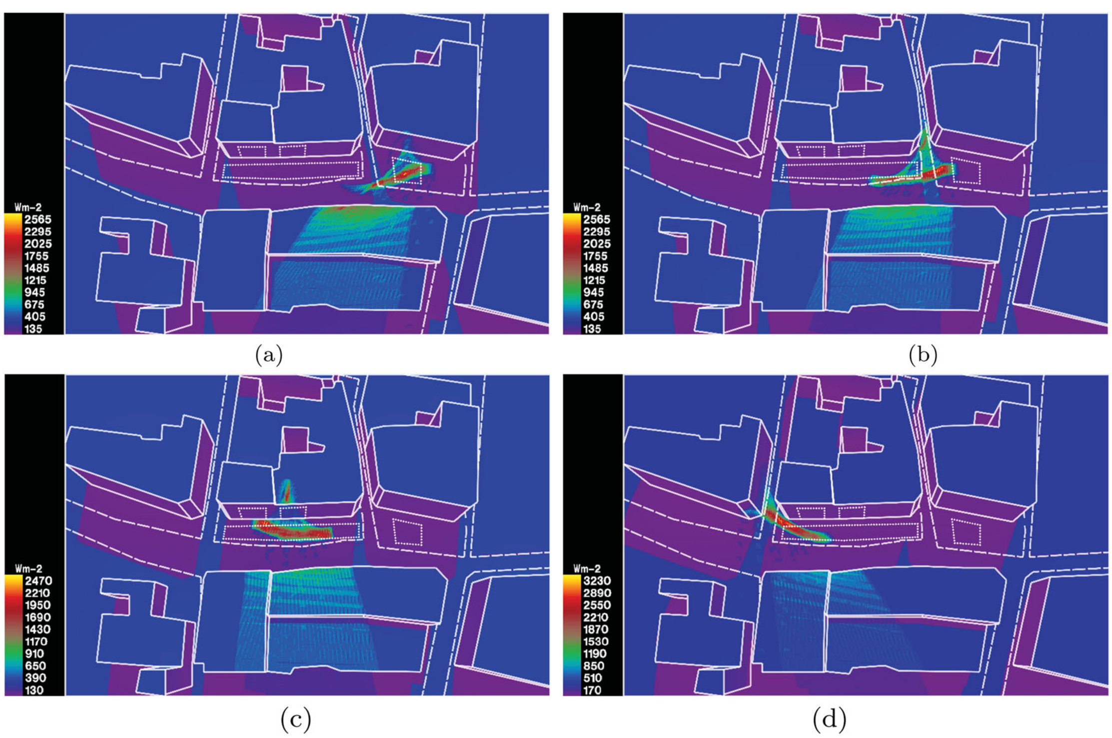

Figure 7. Heat flux predictions for 29th of August, 2013. (a) 11:40 am. The peak heat flux is 2696 $\mathrm{Wm^{-2}}$ and can be observed at the bike parking lot. Severe radiation partially affected the crossroad of Lovat Ln and Eastcheap. (b) 12:00 pm. Most of the hotspot lies at the crossroad of Lovat Ln and Eastcheap, which may have caused glare problems in the traffic. The parking bay now starts to be affected by the hotspot. (c) 12:40 pm. The line-shaped hotspot lies in the parking bay. Part of the hotspot affects the café, and a corner of the barber’s shop starts to suffer from intensified radiation. (d) 13:20 pm. The peak flux increases to 3320 $\mathrm{Wm^{-2}}$ and can be observed at the left side of the parking bay. Most of the hotspot now lies on the crossroad of St Mary at Hill, and starts to hit the nearby building at 30–40 Eastcheap opposite the lane.

Table 3. Summary of the predictions for the event on August 29th, 2013.

Location	1. Bike parking place	2. Parking bays	3. View Cafe	4. Re-style barber's shop
Time when hotspot hits the location	11:20 am	11:50 am*	12:25 pm*	12:40 pm
Time when hotspot leaves the location	12:00 pm	13:45 pm*	12:50 pm*	13:10 pm*
Affected duration by hotspot (min)	40	115*	25*	30*
Average heat flux received (Wm^{-2})	2200*	2500*	1000*	2200*
Peak heat flux received (Wm^{-2})	2696	3320	1200*	2552
Time of peak flux occurs	11:40 am	13:20 pm	12:30 pm*	12:40 pm
Location where the peak heat flux received	Centre of bike parking place	Left parking bay	Right part of the caf	Right corner of the shop

The incident of car mirror can be analysed in view of the results in Table 3 and Figure 7. The total amount of energy accumulated within an object can be estimated from the net heat flux and the time of exposure to that flux. The radiative heat flux is obtained directly from the Radiance simulations, while the time of exposure can be estimated analysing Figure 7. For this purpose, the hotspot was defined as the peak heat flux ±20%, and its size was estimated by counting the pixels of the picture that received an incident radiation within that range. The average displacement speed of the hotspot was then obtained from comparing the position of the hotspot in a sequence of simulations. The time a small object would have been exposed to the hotspot can thus be calculated from those two parameters.

While a reliable calculation of the temperature would require a more detailed model, the rough estimate of Equation (2) yielded temperatures well above the melting temperature of polymers, thus confirming that the shape of the façade of the Walkie-Talkie could have produced a hotspot capable of melting the wing mirror of a car parked across the street. The estimate using Equation (2) is also consistent with reports of people frying eggs in a pan on street-level tiles.

The high value of the peak heat fluxes predicted at street level in Table 3 are troublesome indeed. According

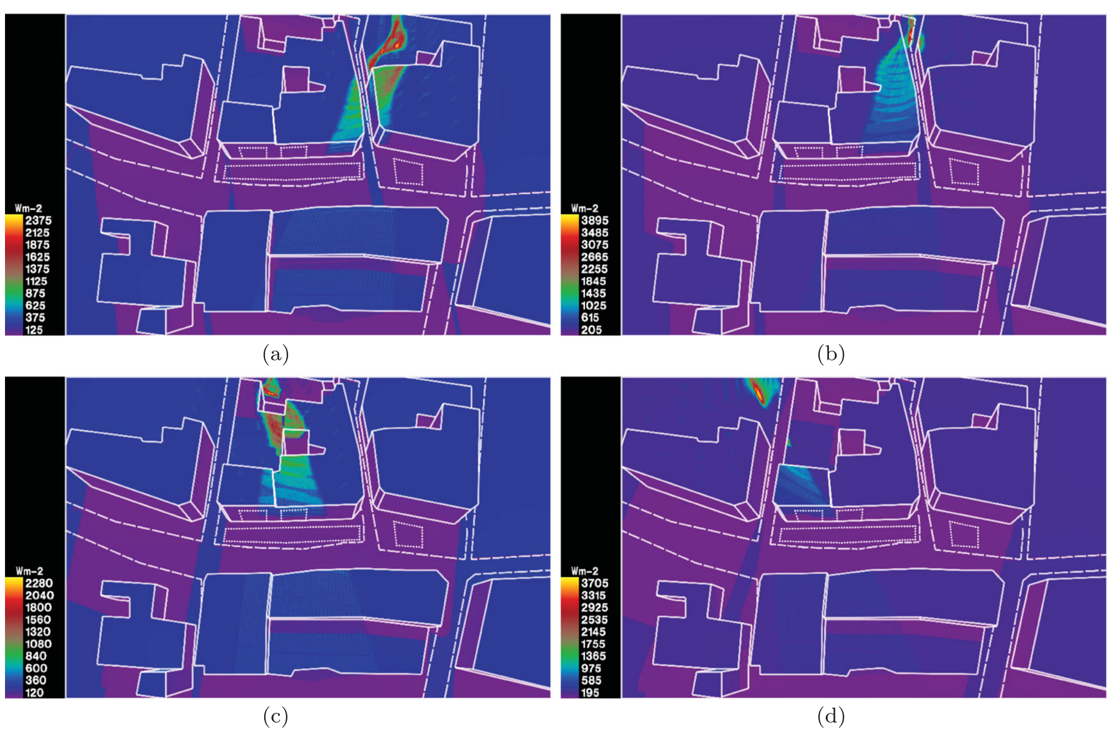

Figure 8. (a) 11:40 am. The reflected radiation is distributed over 16 Eastcheap, 31 Lovat Ln and 20 Eastcheap. The hotspot lies on the rooftop of 31 Lovat Ln but in a different region. (b) 12:00 pm. The reflected radiance is mostly distributed on the rooftop of 20 Eastcheap. The concentrated heat flux, which is as high as 4088 Wm^{-2}, can be observed on Lovat Ln. (c) 12:40 pm. The reflected radiance is mostly distributed over the rooftop of Peek House, 22 Eastcheap, 20 Eastcheap and 3 Lovat Ln. (d) 13:20 pm. The entire hotspot is on the building of 32 St Mary at Hill, which is not modeled in the simulation. Some of the irradiance reaches the rooftop of 22 Eastcheap.

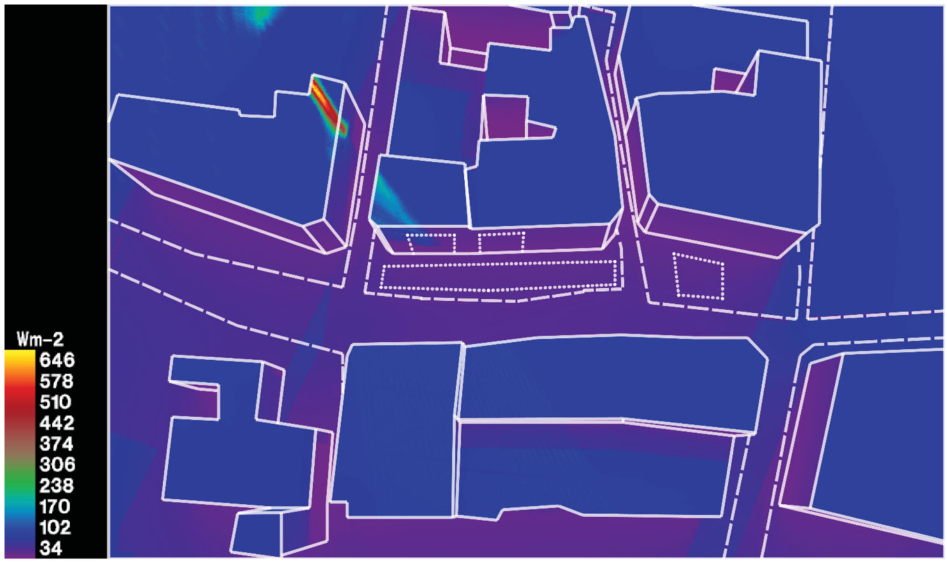

Figure 9. Heat flux predictions for 13:40 pm on 12th of October using an *intermediate sky* model.

to the British Standards, people may tolerate exposure to a heat flux of 2500 Wm^{-2} for up to 30 s before skin damage occurs (British Standars Institution 2003). Pedestrian comfort is affected by much lower heat fluxes.

4.2. *Worst case scenario*

In this section, the potential damage that could result from the peak radiative heat flux in the worst case scenario is analysed. As established previously, the highest direct radiation occurs on the 12th of October. The results of this worst case using a *clear sky* are presented in Figure 8.

The highest heat flux of around 4176 Wm^{-2} occurs at 13: 40 pm, and is almost 25% higher than the peak heat flux on the 29th of August. However, Figure 8 shows that for most of the time, the hotspot lies on the rooftop of buildings, thus causing less impact on pedestrians and cars parked at street level. Additionally, according to the weather data collected from Met Office (shown in Table 2), the weather condition on the 12th of October 2013 was intermediate, so that around 60% of the sky was covered by clouds. Therefore, the hotspot phenomenon was weakened and was not noted by the public. Figure 9 shows the simulation result at 13:40 pm on the 12th of October using intermediate sky model to replicate the real case. The peak heat flux is 678 Wm^{-2}, which is six times smaller than the peak heat flux with the clear sky model.

5. Conclusions

The main objective of this study is to quantitatively reproduce the 'Death Ray' incident produced by the façade of the Walkie-Talkie building in the City of London, using computational simulations. Additionally, an evaluation of the heating hazard was conducted by performing a simplified heat balance with the simulation results. A computational model of the building and its surroundings were developed, and simulations were performed using Radiance, a widely validated lighting simulation tool. The geometric model was created based on site visits and architecture drawings . The material properties of glazing façade were selected for reflection calculations. The sun position was analysed in order to evaluate the proper time and period when the incident could have occurred. This study corroborated the hypothesis that the concave-shaped south façade of the Walkie-talkie could have caused the melting of plastic parts of a car parked at street level opposite the building.

It was found from simulations that the car wing mirror could effectively have melted by exposure to the hotspot, reaching temperatures well above the melting point of plastic for periods of up to 1h. The simulated heat flux at the hotspot corresponded to a 10–15 fold increase compared to direct solar radiation. Additionally, the time and day when the highest peak flux was identified. Fluxes of over 4100 Wm^{-2} can be reached, according to the simulation results. This is higher than the critical heat flux that people can tolerate for prolonged times. It was further shown that the highest peak flux occurred at a hotspot that converged over the rooftops, and did not reach street level. The effect from different weather conditions was also incorporated into the analysis.

Possible uncertainties arise due to limited information regarding the geometry model and surface parameters of the façade (reflectivity of double glazing etc). The methodology presented here is accurate and feasible, and could be added to building design and so reduce the probability of hotspots occurring.

Acknowledgments

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