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SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA

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Dissertation Thesis Abstract

URBAN SOLAR REFLECTIONS IDENTIFICATION, SIMULATION AND ANALYSIS

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ABSTRACT

This dissertation thesis intends to advance the understanding of solar reflections in the urban realm, to analyse the current state-of-the-art, and identify threshold limits according to which the influence of new proposed building development could be evaluated. To be able to measure the impact of existing reflective constructions on the visual comfort of pedestrians, a digital camera was calibrated, which enables to capture the luminance of the environment and use the captured hight dynamic range (HDR) pictures for further analysis. Furthermore, this thesis attempts to develop a new simulation method for the evaluation of solar reflected glare and its impact on the neighbourhood. The method was theoretically developed by Gil, but it was never developed for simulation purposes. The program combination, which was developed during this thesis, *generate_hemisphere.bash* and *calculate_solar_radiance.bash* enables to create a hemisphere description corresponding to solar positions at any desired geographical location.

Keywords: glare, solar reflected radiation, simulation of daylight, calibration of a digital camera

ABSTRAKT

Táto dizertačná práca má za cieľ poskytnúť prehľad súčasného výskumu v oblasti porozumenia slnečných odrazov v mestskej oblasti, analyzovať súčasný stav v oblasti vyhodnocovania a predikcie výskytu negatívnych slnečných odrazov, a identifikovať prahové limity, podľa ktorých by bolo možné vyhodnotiť vplyv novonavrhovaných budov. Aby bolo možné zmerať vplyv slnečných odrazov existujúcich konštrukcií na vizuálny komfort chodcov, bola kalibrovaná digitálna kamera, ktorá umožňuje zachytiť jas prostredia a použiť zachytenú snímku s vysokým dynamickým rozsahom (HDR) na ďalšiu analýzu. Ďalej sa táto práca pokúša vyvinúť novú simulačnú metódu na hodnotenie odrazeného slnečného žiarenia a jeho dopadu na okolie. Túto metódu vyvinul po teoretickej stránke Gil, ale nikdy nebola aplikovaná na simulačné účely. Prínosom tejto práce je nová metóda generovania a modelovania Slnka ako zdroja žiarenia pre simulačné účely. Kombinácia v rámci dizertácie vyvinutých programov *generate_hemisphere.bash* a *calculate_solar_radiance.bash* umožňuje vytvorenie opisu hemisféry zodpovedajúceho slnečným pozíciám v ľubovoľnom požadovanom geografickom mieste.

Kľúčové slová: oslnenie, simulácia denného osvetlenia, kalibrácia digitálnej kamery

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INTRODUCTION

One of the main objectives of urban planning, and building regulations is to ensure common access to sunlight and fresh air, and to define guidelines for function and general accessibility of the built environment. As the natural interest of developers of individual properties is to exploit the maximum of what is available, this can lead to a conflict with the neighbourhood and the general public. With the recent rise in awareness of the environmental interdependence of all processes in complex systems such as cities, where "*the effects of an intervention in one area can produce changes in another…"* (Pollock, 2016), the assessment of the potential microclimate impact arising from a development is becoming a part of the planning process. This is also an important factor in achieving energy conservation and support the overall sustainability of cities.

An urban microclimate is a consequence of natural parameters and anthropogenic actives. The natural parameters such as the air temperature, humidity, wind speed, solar radiation gains and sunlight availability are sensitive to 3-dimensional changes in the urban development (Dimoudi *et al.*, 2013; Sharmin, Steemers and Matzarakis, 2017). The evaluation of impact of the resulting change in the natural parameters is then dependent on the identified anthropogenic activities (Attaianese and Duca, 2012).

Research in the field of urban microclimate is mostly focused on the investigation of the air flow enabling air exchange in urban canyons, to ensure the pedestrian wind comfort and to mitigate the urban heat island (UHI) phenomenon (Moonen *et al.*, 2012). In recent years, the awareness of the importance concerning the control of solar reflections from a built environment was highlighted due to several publicized cases. Complaints ranged from nuisances and an increase in thermal loads of the neighbouring buildings (Schiler and Valmont, 2005), to severe skin burns (Daily Mail, 2010; Hodge, 2010), air-traffic obstructions (Hayward, 2012), property damage (Wainwright, 2013) and blinding of drivers (Ferro, 2013). This is due to the trend in new constructions with high window-to-wall ratios, with an increased use of façade materials with high reflectance and with complex geometry. These new trends increase the probability of urban solar reflections. However, there are no universally accepted criteria defining the acceptable limits concerning the control of solar reflections (light as well as thermal irradiance) in the urban realm (Danks, Good and Sinclair, 2016). New building constructions with a curvilinear design with an increased use of high reflectance materials, may result in an adverse solar reflection phenomena occurrence, that may have a severe impact on the neighbouring area. Despite the risks, there are no universally accepted criteria for acceptable limits, and there is no accepted evaluation process to estimate the impact of sun reflections which results in the lack of regulation.

1. Summary of the literature review

Ideally, a good simulation evaluation method should be simple and quick enough, so that users can apply it in the pre-project planning phase of a building proposal to identify potentially disturbing reflections at an early stage. The results can then lead to adjustments to the project while still in the planning phase. However, based on an analysis of contemporary simulation methods available for the prediction of glare occurrence the following conclusions can be drawn:

- There is no generally accepted simulation method for the prediction of glare occurrence in the urban realm.
- High dynamic range photography can be used for the measurement of glare in the field of view in the exterior.
- All the proposed methods published rely on computation heavy calculations, (resulting in hours of simulation times necessary to gain results for a standard user).
- The methods currently available, are not developed for a quick intermittent evaluation of draft building designs.

Furthermore, the following lessons can be learned in regard to used weather conditions for the simulation:

- To evaluate a scene for a *„worst case scenario"* for the occurrence of glare and solar reflections, the scene should be evaluated for sunny clear sky conditions, not under the conditions gained from weather data files.
- Due to analemmatic symmetry, it is sufficient to evaluate only half a year of the sunny clear sky conditions.
- Due to the change of sun positions between hours and days, a *„bigger"* step size can be chosen in between the simulation of the selected days (from seven up until 21 days), but a smaller timestep should be chosen for sun positions within a day (a step of minutes not hours).
- As new constructions will change the solar conditions in the neighbourhood, the evaluation should be based not only on the analysis of absolute irradiance and radiance values, but in terms of relative change in the conditions. Therefore, the simulation should be run for two cases – without the planned construction, representing the current state, and with the planned construction. An analysis of the absolute difference should be then performed.

To more technical conclusions in regard to the simulation process belongs:

- Backward raytracers are more efficient when simulating with big light sources, but forward ray traces are more precise when working with caustic rays, which are important for reflections.
- The simulation time is one of the biggest handicaps of all currently used simulation methods.

For the identification of glare, specific viewpoints have to be evaluated as glare evaluation is dependent on the space angles subtracted by glare sources and their distribution within the view. Therefore, they have to be carefully chosen by the evaluator. As the identification of these hot spots is difficult, first an analysis of the irradiance of surfaces should be performed. Then after an identification of "*hot spots*" in those places, an analysis on annual glare occurrence should be performed.

One different evaluation approach was proposed by Gil (2016), who proposed a method that promises a greater simplicity than the previous approaches, whilst providing a graphical output. Based on the application of the Sunlight Availability Protractors, the view of the sky is identified in order to identify the solar reflections that are geometrically possible. It promises to yield the duration of solar reflections that can get to the observer. If the method is developed for the purpose of 3D simulations, the limitation imposed by sloping surfaces would be removed. However, the method was never developed for simulation purposes.

To implement this method in a simulation process it is necessary to:

- Develop a 3D hemisphere generator, which would produce sky hemisphere patches that would represent sun positions in time (such as in Sunlight Availability Protractors) for any arbitrary location.
- Develop a calculation programme that will be able to calculate and export radiance values for the respective hemisphere patches.
- Find a method of accounting only for light rays parallel to the sources normal.

2. Research goals

The main goal of the dissertation thesis is to analyse the current state of understanding of solar reflections in the urban realm, to identify used threshold limits according which the influence of a new proposed building development could be evaluated, to calibrate a digital camera that would enable to evaluate the luminance of the environment in the field of view, and lastly, to develop a new simulation method for the evaluation of solar reflected radiance and its impact on the neighbourhood.

To be able to measure the impact of existing reflective constructions on the visual comfort of pedestrians, this dissertation thesis had a partial goal - to calibrate a digital camera, which would enable to capture the luminance of the environment and use the captured hight dynamic range (HDR) pictures for further analysis of the visual comfort. A second partial goal of this thesis was to develop a new simulation method for the evaluation of solar reflected radiance and its impact on the neighbourhood. The simulation method is based on the theoretical model proposed by Gil, which was never put in practice (Gil, 2016). The aim of the method was to offer a more time effective simulation process, whereas it promised to enable the identification of:

- critical elements that have a high potential to contribute to the occurrence of adverse effects of the solar reflected radiance;

- critical time periods, based on the position of the sun (elevation and azimuth) and the resulting angle of incidence of solar rays;
- critical positions in the neighbourhood, where the solar radiance reflected from the proposed building development could result in undesired phenomena, such as heat islands and glare occurrence.

3. Used methods

To identify limits of solar reflections and identify existing methods for the evaluation of the solar reflected radiation in the urban realm, a literature review was performed on existing available studies that focus on solar reflections. This was achieved using an internet-based search concerning relevant scholarly articles in the databases of Web of Science, Scopus and Google Scholar. Within these databases, a search on identifiable keywords and their combinations was performed. The search terms used were “solar reflection, urban realm, daylight simulation, solar glare”. The sources found were then briefly scanned for relevancy, and sources considered unfit were removed from the accumulated collection.

A similar source search was performed while searching for relevant existing standards and regulations that address the problematic elements of solar reflected radiation in the urban realm. The search was performed in the databases of the International Organisation for Standardisation (ISO), American National Standards Institute (ANSI), European Standards (EN) and European Committee for Standardisation (CEN). This was complemented by a web-based search using the Google Search engine. The keywords used were “glare, material properties, daylighting, solar reflections”. When a relevant standard or regulation was identified a full version was acquired if possible. If not, a search for a scientific publication reviewing the standard was performed.

In this thesis the simulation tool Radiance was used. Radiance is a physically-based backward raytracer developed by Gregory Ward and the Lawrence Berkeley National Laboratory (LBNL) (Ward, 1994). In this thesis, the integrated extension of Radiance, photon mapping, was also used. It is a forward raytracer which enables an efficient simulation of specular scattering from daylight redirecting components and was developed by Ronald Schregle (Schregle, 2004).

Furthermore, to be able to calibrate a digital camera that would enable to acquire high dynamic range images(HDR) that would enable to capture the luminance intensity distribution in the field of view to evaluate the visual comfort in the environment, the OpenCV libraries were used (OpenCV, 2020).

Lastly, all codes used for the calibration, simulation or evaluation in this thesis were prepared using BASH or Python programming language. The research process and research methods applied in this thesis are summarized in Figure 1.

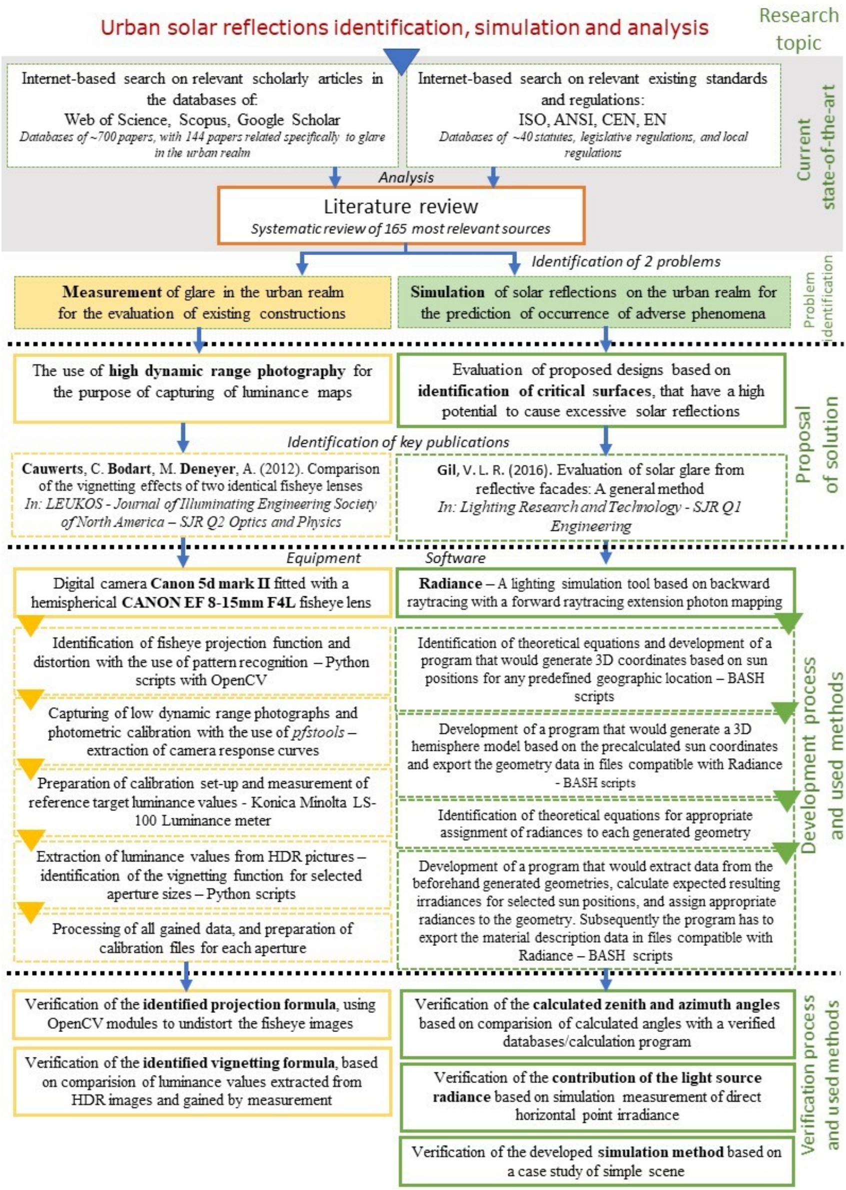

Figure 1 Research methods and research process applied in this thesis

4. High dynamic range imaging for daylight glare analysis – calibration of a digital camera

High dynamic range (HDR) photography is a validated method for capturing high resolution luminance data, which can be subsequently used for the evaluation of the visual quality of the luminance environment and analysis of visual perception (Debevec and Malik, 1997). This technique has been successfully used to capture luminance maps of building interiors (Jacobs, 2007; Hirning *et al.*, 2013; Hirning, 2014; J. Alstan Jakubiec *et al.*, 2016; Suk, Schiler and Kensek, 2016a; Goovaerts, Descamps and Jacobs, 2017), to capture sky luminance distributions (Inanici, 2010; Tohsing *et al.*, 2013; Cauwerts and Piderit, 2018), and to evaluate the quality of luminance distribution in the exterior (Brotas and Wienold, 2014; Jakubiec and Reinhart, 2014; Suk, Schiler and Kensek, 2016b, 2017; Hjorth and Wochele, 2017). If HDR imaging is coupled with fisheye technology, it enables the assessment of luminance distribution ratios in the human field of view (FOV), which can be used for the evaluation of glare risk (Inanici and Navvab, 2006; Suk and Schiler, 2013).

For the purpose of this thesis, the calibration and application of this technique is based upon best practices laid out by Inanici and Jakubiec (Inanici, 2006; John Alstan Jakubiec *et al.*, 2016), both of whom have with their teams tested, validated and presented steps for a successful employment of this technique for the evaluation of the daylight environment.

A digital camera (Canon 5d mark II) fitted with a hemispherical CANON EF 8-15mm F4L fisheye lens was used to take the low dynamic range photographs. Before the measurements, a calibration process was employed. This consisted of:

- determining the fisheye lens projection type and distortion;
- obtaining the camera response curves;
- determining the vignetting effect of the lens (correction of the brightness decrease observed from the centre to the edges of the picture);
- photometric calibration.

During the process of calibration, the following calibration functions were extracted:

- the camera response curve;
- the projection formula;
- the vignetting function for four apertures – f/4, f/4.5, f/5, f/5.6.

During the process of photometric calibration, a function converting the pixel values (from 0 to 255 for the RGB channels) produced by the camera to photometric quantities (radiance values) was produced. This process allows to merge low dynamic range pictures with different exposures into a high dynamic range image.
To relate the pixel values to the real world luminances, a series of LDR pictures with

different exposures of an interior scene with daylight, with exterior view was created (Inanici, 2006).

The response curve was recovered using *pfshdrcalibrate*, a program belonging to the *pfstools* (Mantiuk *et al.*, 2007). The algorithm applied was *Robertson* (Robertson, Borman and Stevenson, 2003). The resulting curves are polynomial functions that: *"model the accumulated radiometric non-linearities of the image acquisition process"* (Inanici, 2006), such as A/D converter, gamma correction and white balance. It depicts the relation between the amount of the incoming light and image pixel values of a digital camera, Figure 2. The process is known as radiometric self-calibration, and the curve has to be acquired for each camera separately.

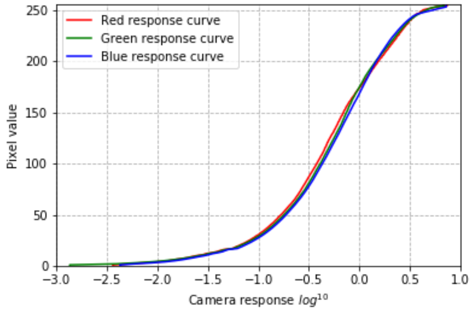

Figure 2 Camera RGB response curves for aperture f/4

A mapping function (projection formula) is described as a relation between the angle θ of the incoming light beam, the focal length f, and the distance r of the optical axis form the centre of the image. Even though it is mostly defined by the manufacturer, there are still significant deviances due to the manufacturing process. The projection formula was gained using pattern recognition libraries of OpenCV. Based on the polynomial projection model it was then further identified that the lens produces theoretically a distorted equidistant projection, Figure 3.

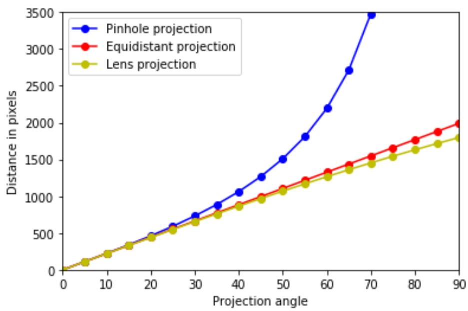

Figure 3 Comparison of the projection formulas

For the final evaluation of the captured luminance a remapping function was determined, which corrects the actual lens projection into an ideal equidistant projection. The remapping function was determined by a polynomial regression model using the method of least squares via Python scripts. The remapping function is defined as follows:

$$r_{remap} = 0.5617\, r''^3 - 0.1209\, r''^2 + 0.9211\, r'' - 0.0005159 \qquad (1)$$

where r'' is the pixel distance from the image centre of the original image taken by the fisheye lens, and r_{remap} is the corrected distance from the centre, equivalent to an equidistant mapping function. The remapping function is applied to each HDR picture before the luminance and glare analysis via a .cal file.

The vignetting effect in photography is the gradual decrease in luminance recorded, decreasing from centre to the peripheries. It is caused by the loss of light rays due to lens properties and obstructions, resulting in the rays being scattered or absorbed, and not reaching the sensor through the lens body (Kordecki, Palus and Bal, 2016; Edmund Optics Inc., 2020). To compensate for the loss of intensity of the captured luminance vignetting curves were identified, and their inverse functions are used as a multiplication filter for the captured HDR pictures.

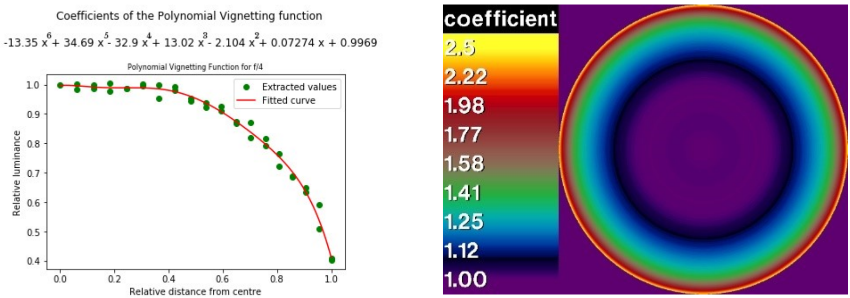

Figure 4 Vignetting curve for the f/4 aperture with a corresponding falsecolor representation of a filter

After the calibration procedure it is possible to use the captured images as luminance maps. These can be used for the evaluation of glare with the use of the Radiance tool *evalglare* (Pierson, Wienold and Bodart, 2018).

5. Development of a simulation method for prediction of solar glare occurrence from building façades

This thesis attempts to develop for simulation purposes the theoretical method developed by Gil (Gil, 2016). The method should enable an efficient evaluation of solar glare occurrence from reflective buildings in the urban realm. However, the method was never developed for simulation purposes, and therefore never properly evaluated. This thesis attempts to do so.

The proposed computational programs generate a sky hemisphere part covering the sun positions during a year at any location in the world[1]. This is done with the developed program *generate_hemisphere.bash*. Furthermore, for each generated sky patch a respective radiance description is calculated, that would result in a corresponding direct horizontal irradiance from the sun during clear sky conditions. This is done with the developed program *calculate_solar_radiance.bash*. The workflows of both of the programs are managed in a UNIX Makefile. To generate a hemisphere for any desired geographic location, it is necessary to input the data on the latitude, longitude, meridian (or time zone), elevation, and the radius of the hemisphere that is expected. It is further possible to define the step in the sun positions in minutes, and the desired step in regard to days. The programs will proceed to generate the patches and export them in a folder. For each location a separate invocation of the Makefile has to be run. The format of the files exported is compatible with the requirements for material and primitives description for the Radiance simulation software (Ward, 1994). The hemisphere with its material description can be used with a Radiance scene, substituting the sun source for simulation purposes.

To validate the two programs an analysis and comparison of results was performed in regard to:

- the zenith and azimuth angles calculated;
- the difference between the expected calculated direct horizontal irradiance and values gained by simulation;
- the simulation results in comparison to other simulation methods for the solar radiance.

The analysis was performed for four selected locations. The locations (with their respective latitude and longitude, and a selected date) are listed in Figure 5.

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[1] The computational program has a limited functionality for latitudes beyond ±66,5°, where polar night and day occure, and should be used for those with caution.

Table 1. The generated hemispheres for Bratislava and Helsinki with an hour long step between sun positions during a day and a 14 day step between generated positions can be seen in Figure 5.

Table 1 The four selected locations for the analysis

Location	Latitude	Longitude	Date	Computation time for generating a hemisphere model	Computation time for generating a material description
Bratislava (SK)	48,2°	17,2°	21.3./22.3.	2 m 7 s	3 m 59 s
Helsinki (FI)	60,2°	24,9°	21.9./22.9.	2 m 4 s	4 m 10 s
Cape Town (ZA)	-33,9°	18,4°	1.8./2.8.	1 m 56 s	3 m 4 s
Stanley (FK)	-51,69°	-57,84°	21.6./22.6.	1 m 18 s	3 m 24 s

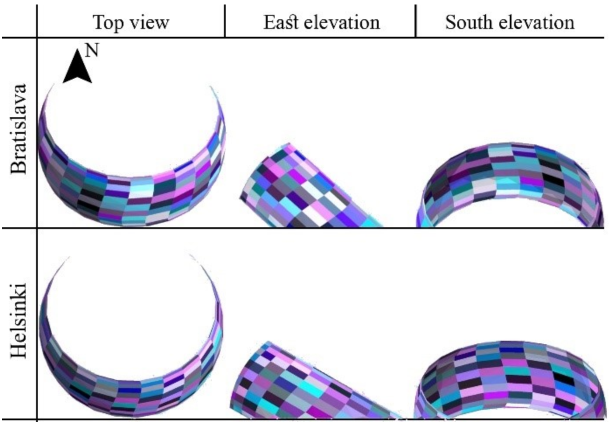

Figure 5 3D models of the generated hemispheres

The zenith and azimuth angle analysis was based on calculating the root mean square error. As the reference values were used values gained from the freely available NOAA Solar Position Calculator (National Oceanic and Atmospheric Administration), which is based on the equations from the Astronomical Algorithms book by Meeus (Meeus, 1998; NOAA, 2020). The calculator should provide locations that are theoretically accurate to within a minute accuracy. As the program *generate_hemisphere.bash* uses simplified algorithms, which are generally used for calculations while evaluating insolation, small deviances are expected. As it can be seen in the results in

Table 2, the generated solar positions are within a 0.5° degree accuracy, which is considered acceptable for the simulation purposes.

Table 2 Zenith and azimuth angle values RMSE

in degrees	**Zenith angle**			**Azimuth**		
	RMSE	**Max abs. deviation**	**Min abs. deviation**	**RMSE**	**Max abs. deviation**	**Min abs. deviation**
Bratislava	0.433	0.515	0.346	0.330	0.517	0.012
Helsinki	0.036	0.515	0.346	0.037	0.080	0.030
Cape Town	0.081	0.122	0.042	0.173	0.368	0.028
Stanley	0.019	0.033	0.000	0.055	0.060	0.040

The hemispheres and the respective sun materials were then used to calculate the direct horizontal irradiance at the point P [0,0,0], using a simulation evaluation in Radiance with *rtrace*. This was done for all the generated patches for each location (**Error! Reference source not found.**). The reference values used were the one c alculated for the respective zenith angles. The irradiance values gained by the measurement at a sensor point in P [0,0,0] deviated by max. 3.88 % percent from the calculated value, what is well in the area of acceptance for simulation purposes, Table 3.

Table 3 Comparison of direct irradiance values

	RMSE	**max % deviance**
Bratislava	18.92 cd/m^2	3.88 %
Helsinki	16.71 cd/m^2	3.51 %
Cape Town	20.37 cd/m^2	3.29 %
Stanley	18.04 cd/m^2	3.19 %

The goal of the method is to enable the first step described by Gil in his method (2016):

"*The first step consists of creating an image with direct normal illuminance values. The picture needs to be generated using a sky with a sun path that includes the solar intensities for each and every possible sun positions… The software should then create a picture where the reflective surfaces mirror the sun path.*"

However, due to the properties of the *light* material description, which is a Lambertian source emitting light in all directions, this does not work with a traditional definition of the source. To work only with direct rays, it is necessary to use *photon mapping* (Schregle, 2019). *Photon mapping* is a forward raytracing extension to the Radiance, originally developed by Schregle (Schregle, 2004). With the *mkpmap* utility it is possible to generate only a direct photon map, which accounts only for direct illumination, Figure 6. It will enable to visualise the area of impact, however as stated in the reference manual the tool is (Schregle, 2019): *„intended for debugging and validation of photon emission from the light sources, as the quality is too low for actual rendering.“*

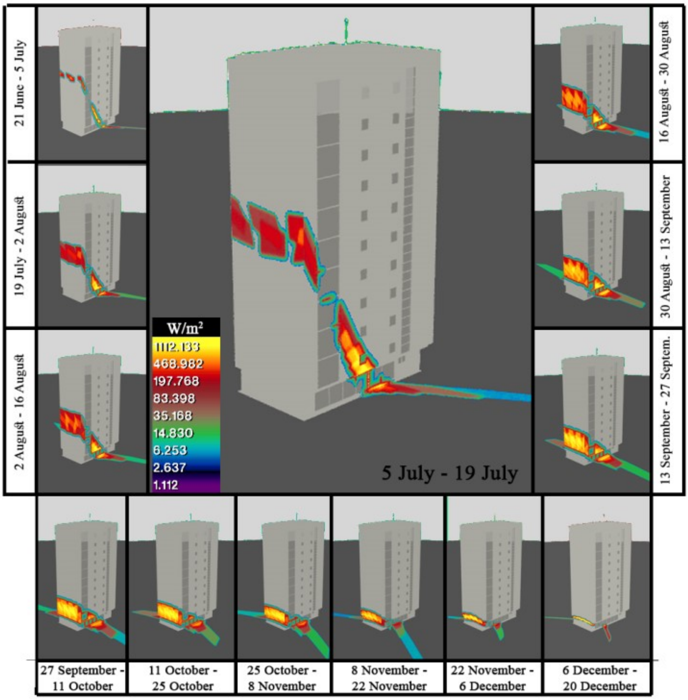

Figure 6 Direct projection of hemisphere patches for a location in Bratislava

The falsecolor renders represent the irradiance gradient, whereas it becomes clear that there are no peaks visible on all the standard irradiance renders. One would expect that at least a little rise in irradiance in the identified projections would be visible, if the theoretical method proposed by Gil is sound. However, this is where the shortcomings of the method proposed by Gil become visible.

The method suggests that the identification of the projection of sun will enable the evaluation of glare. This is not true, as the reflections causing glare, are not the literal reflections or the Sun circle. They are the reflections of rays which are redirected into the view of the observer. Even though one can clearly distinguish the Sun on the sky as a small circle subtracting less than 0.5 sr from the sky's hemisphere, the direct rays emitted from the Sun, do not subtract such a small part (as in a) Figure 7). In reality the Sun is more than a 100 times bigger then Earth. The rays are emitted from the Sun in all directions, but as Earth is a small target surface in comparison to the Sun, the rays arriving at the surface are theoretically parallel (as in b) Figure 7). Glare in the urban realm is then caused by the rays reflected from buildings towards the observer (as in c) Figure 7).

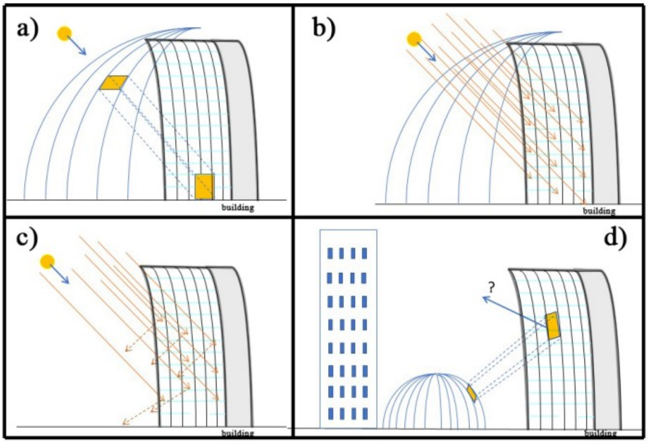

Figure 7 Comparision of theoretical model proposed by Gil, with actual geometry of sun rays

Even though Gil mentioned that the picture should be generated using a sky with sun paths, upon closer inspection of the pictures provided in the article, in his theoretical work he uses the hemisphere as if it was projecting outwards, and not inwards (as in d) Figure 7). This could be done using the *generate_hemisphere.bash* program by simply identifying the start day of creating the hemisphere to be 1.1., as this would force the program to create the patches in a reversed order, effectively having a normal pointing outwards. It would be then possible to use the created patches to emit rays outwards of the hemisphere. The second assumption that would have to be made is the fact that the projection outwards is in a reversed order – East is sunset, and West is sunrise, and the same applies to South and North. As the direct normal irradiance is dependent only on the zenith angle – the expected irradiances could be turned to radiances of the patches.

This is where other problems arise. Even if one would be only interested in the projection of the hemisphere, the method would fail to account for shading from the surrounding structures (as in d) **Error! Reference source not found.**). Furthermore, i f one would like to somehow arrive at the expected irradiance values at the projected patches, one would effectively reinvent backward raytracing, as there is no other way of figuring out the irradiances, only by following the ray to its origin.

Sadly, it has to be concluded, that the method proposed by Gil for the evaluation of glare in the urban realm, was based on faulty assumptions. Even though it is possible to create a simulation based model based on the theory, its implementation will not bring any advantages for the evaluation of glare occurrence.

Even though the method proposed by Gil has been proven to have major flaws, the developed programs (*generate_hemisphere.bash, calculate_solar_radiance.*bash) can be used in the future in multiple ways. It is possible to use the method for a more visual presentation of the sun positions on the hemisphere in a scene. As with *rtrace* it is possible to save the data on ray origin, direction and source[2], the data can be used for creating a visual representation of the rays. It is possible to use the programs for standard simulation purposes with Radiance, where the generated hemisphere will be used as the source of the direct irradiation. The limitations of this application are described in section **Error! Reference source not found.**. Furthermore, the h emisphere can be used as an effective way of creating photon ports, for exterior scenes. The results of this application can be used in **Error! Reference source not f ound.** (photon mapping with patches as photon ports). A proper definition of photon ports is essential when one wants to use photon mapping in the exterior, where the light source is the sun. This is due to the fact that emitting photons from the source primitive presents a challenge; there is no local geometry associated with these directional sources. The photons are essentially emitted then from the scene cube. The *mkpmap* spends a lot of time integrating flux from all the light sources, to figure out how many photons to emit per source (and per partition thereof) beforehand. This is aggravated if photons are emitted from the scene cube surfaces in the absence of ports, as there can be several 10k partitions per side. As most of the photons will get lost in the scene, this results in a low performance. The photon ports are an effective workaround. However, the photon ports have to be defined in line with the source, otherwise the produced results would be biased. The program *generate_hemisphere.bash* is therefore an effective way of creating these photon ports, as the size and the radius can be personalized and the patch is created on actual sun positions.

6. Conclusions

In this thesis a comprehensive overview of the state-of-the art research in the field of the solar reflected radiation in the urban realm was presented. In general, it can be concluded, that contemporary there is no international consensus on how to evaluate or predict the contribution of planned constructions towards the negative phenomena of solar reflected glare and irradiance. There is a multitude of studies trying to propose workflows and limits, some more some less successfully. The most important lessons that have to be highlighted are:

- For the prediction of occurrence of adverse phenomena caused by solar reflections it is necessary to work with the worst-case scenario, which is a theoretical year with only sunny clear sky conditions. Standard weather files are therefore not useful for the evaluation.

[2] Backward raytracing works in a contra intuitive way where rays are spawned from the observer to the origin

- The angles of incidence of the sun rays are critical for a successful assessment, therefore a smaller step (in minutes, and not hours) for the generated sky conditions within a day is necessary. On the other hand it is sufficient to work with a 7 up to 21 days step between the generated sky conditions.
- The same is true for the evaluation of already existing building arrangements, where negative impacts of solar reflected glare were identified. If so called hot spots were identified, the angle of incidence of the sun rays is critical, and the time periods selected for the data gathering are critical.
- Due to analemmatic symmetry the analysis can be done just for a half a year – between summer solstice and winter solstice.
- An analysis of the solar reflections and their spatio-temporal impact of new proposed constructions should be performed for any constructions with big continuous facades, where the materials planned to be used have any directional properties, causing specular peaks, such as metal claddings and continuous glass facades. The design feature here is the continuity of the surface, and not just the general shape. If a façade has no overhang such as exterior shades on each floor an analysis in the phase of planning should be considered necessary.

In this thesis was further a calibration process of a digital camera presented that will enable future research in the field of luminance distributions in the field of view. The process brought the following results:

- Successful implementation of the pattern recognition programs, which enabled to identify the distortion projection formula of the lens. This way a higher number of evaluation points was gathered, and a higher precision was achieved, compared to other recommended methods for the identification of the projection formula.
- Necessary calibration data, to compensate for the lens distortion and the light sensitivity falloff that occurs towards the lens peripheries.
- The whole workflow description and development of all necessary programs that will enable future capturing and analysis luminance distribution in the field of view. The calibrated .hdr pictures can be used for glare assessment, for a continuous analysis of yearly sky distributions for the analysis of daylighting conditions.

Based on the presented calibration the following future work is being considered:

A repetition of the luminance measurements under clear sky conditions, and in a room with high illuminance, with a higher angular resolution of the reference targets, especially in angles close to 90° from the centre of the projection. This is due to the fact that there is a loss of sharpness of the picture in the peripheries and a higher density of reference points would enable a more precise derivation of the vignetting functions. Furthermore, the different light conditions in under the clear sky and in the interior would enable to create separate calibration packages for an even more precise evaluation.

A development of a fully automated workflow that would enable a continuous collection and analysis of the luminous conditions in a selected evaluated position.

Last but not least a simulation program and workflow was developed based on a theoretical method developed by Gil (2016). Unfortunately, the simulation method enabled to identify major flaws in the theoretical work, and lead to a conclusion that the method is not applicable for the desired purposes. However, the work performed brought contribution in the following:

- A new method for generating and modelling the sun for the simulation purposes. The program combination of *generate_hemisphere.bash* and *calculate_solar_radiance.bash* enables the creation of a hemisphere description corresponding to solar positions at any desired geographical location.
- A new method of generating photon ports that can be used for simulation purposes, when working with photon mapping in the exterior. This can simplify the workflow and result in more precise definition of photon ports in exterior scenes where sun is used as a light source.

The following limitations and future work is suggested:

- To make a separate function file that will modify the way the light is emitted from the generated patches. This way the 7° angle deviation of the triangle normal could be corrected and the light falloff could be compensated. The patches could then be used as photon emitters directly, not just as photon ports, simplifying the simulation process, and overcoming the problem of implementing virtual sources in photon mapping.
- To find a better algorithm for the tessellation of the patches, again correcting for the angular discrepancies.

To summarize the results, this thesis has contributed:

- to the research field by disproving a theoretical model, and by creating a comprehensive overview of the current state-of-the art in the research field of analysis and identification of solar reflections in the urban realm;
- to the practice by summarizing the boundary requirements for the evaluation of new proposed construction designs and their impact o the distribution od the solar radiation in the neighborhood with simulation, by calibrating a digital camera, that can be used in the future for studies of glare in the field of view, by developing a new simulation process by developing a new simulation model of the sky hemisphere.

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LIST OF PUBLICATIONS

During the research throughout the authors PhD studies, a number of papers has been published based on the work presented in this thesis, which was cited thirteen times by several authors The publication are listed here for reference.

Publications in international journals registered in Current Contents

ŠUJANOVÁ, Paulína - RYCHTÁRIKOVÁ, Monika - MAYOR, Tiago Sotto - HYDER, Affan. A Healthy, Energy-Efficient and Comfortable Indoor Environment, a Review. In *Energies [Open access]*. Vol. 12, iss. 8 (2019), online, [37] s., art. no. 1414. ISSN 1996-1073 (2018: 2.707 - IF, Q3 - JCR Best Q, 0.612 - SJR, Q1 - SJR Best Q). V databáze: CC: 000467762600007 ; SCOPUS: 2-s2.0-85065501504 ; DOI: 10.3390/en12081414. (Citation: 11)

Chapters in scientific monographies published by an international publishers

PAVLENDOVÁ, Gabriela - LUKOVIČOVÁ, Jozefa - ŠUJANOVÁ, Paulína. Historical Buildings Deteriorating Safety Risks And Electroosmotic Dewatering. In Techniczne i materialne aspekty bezpieczeństwa. 1. vyd. Czestochowa : Oficyna Wydawnicza Stowarzyszenia Menedžerów Jakošci i Produkcji, 2017, S. 128-155. ISBN 978-83-63978-69-3.

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HARTMAN, Peter - ŠUJANOVÁ, Paulína - HRAŠKA, Jozef. Circadian characteristics of special glazing. In *Athens Journal of Sciences*. Vol. 1, no 4 (2014), s. 241-254. ISSN 2241-8466. (Citation: 1)

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RYCHTÁRIKOVÁ, Monika - ŠIMEK, Richard - ŠUJANOVÁ, Paulína - HÚSENICOVÁ, Jarmila - CHMELÍK, Vojtech. Audiovisual comfort in shopping streets covered by structural skins. In *Proceedings of the TensiNet Symposium 2019 : Softening the Habitats. 3-5 June 2019, Milan, Italy*. 1. vydanie. Milan, Italy : Maggioli SpA, 2019, S. 614-623. ISBN 978-88-916-3245-6. V databáze: DOI: 10.30448/ts2019.3245.30.

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Professional works in international proceedings (conference and non-conference)

SZABÓ, Daniel - ŠUJANOVÁ, Paulína - GLORIEUX, Christ - RYCHTÁRIKOVÁ, Monika. Impact of Building Facade Properties on Noise Levels in Street Canyons. In *Euronoise 2018 [elektronický zdroj] : conference proceedings. May 27-31, Heraklion - Crete, Greece*. 1. vyd. Madrid : European Acoustics Association, 2018, USB kľúč, s. 967-969. ISSN 2226-5147. (Citation: 1)

INTERNSHIPS

May 2018-June 2018	**"PapaBuild" H2020-MSCA-RISE-2015 project 690970**
Host Organisation	Technologisches Gewerbemuseum Wien, Department of Acoustics and Building Physics
Supervisor	Dr. Herbert Müllner
Activities	Calibration of a digital camera
January 2019-April 2019	**"PapaBuild" H2020-MSCA-RISE-2015 project 690970**
Host Organisation	KU Leuven, Department of Architecture
Supervisor	prof. Monika Rychtáriková
Activities	Research in the field of interior environmental quality
August 2018-October 2018	**"PapaBuild" H2020-MSCA-RISE-2015 project 690970**
Host Organisation	University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Electroacoustics

Supervisor	prof. Dr. Sc. Kristian Jambrošić
Activities	Development of a Revit plug-in for simple acoustic simulations
May 2018-July 2018	**“PapaBuild” H2020-MSCA-RISE-2015 project 690970**
Host Organisation	Technologisches Gewerbemuseum Wien, Department of Acoustics and Building Physics
Supervisor	Dr. Herbert Müllner
Activities	Development of a Revit plug-in for simple acoustic simulations

May 2017 – August 2017	**Erasmus + internship**
Host Organisation	KU Leuven, Department of Architecture
Supervisor	prof. Monika Rychtáriková
Activities	research in the field of simulation of adverse effects of solar radiation in the urban environment

February 2016 – May 2016	**Mobility project between higher education institutions EEA/EHP SK06-II-01-004**
Host institution	University of Liechtenstein, Institute of Architecture and Planning
Supervisor	prof. Peter Droege
Activities	research in the field of energy-savings potential, and the quality of daylighting for buildings with integrated photovoltaic technologies

April 2015 – June 2015	**Erasmus + internship**
Host institution	Slovak Liaison Office for Research and Development (SLORD)
Activities	collecting and providing information on opportunities provided by EU research and cooperation programmes (mainly H2020 programme), preparation of dissemination materials, preparation of contributions to the information portal

January 2015 – February2015	**COST STSM Action TU1303-24438 internship**
Host institution	Swiss Federal Laboratories for Materials Science and Technology
Supervisor	dr. Tiago Sotto Mayor
Activities	theoretical research on building climate control