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DAYLIGHT PERFORMANCE OF ADAPTED INDUSTRIAL BUILDINGS

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Abstract. *This paper assesses the potential of historical industrial buildings to be reused as office spaces. Belgrade's industrial heritage has been classified according to the criteria that influence visual comfort, including glazing area, floor depth, and orientation. Daylight performance of two representative buildings has been analyzed using daylight factor, point in time illuminance and spatial daylight autonomy. Potential improvement strategies that would not have a negative impact on the historical character of buildings have then been discussed. Further studies include increased internal surface reflectance and introduction of roof-lights. The impact of roof-lights on the annual cooling and heating load has been addressed in parallel.*
Since LEED is the dominant sustainability assessment tool in Serbia, preliminary compliance with LEED v4 Daylight credit has been assessed for all options.
The methodology and findings can be applied to a wide range of industrial buildings in similar climatic conditions.

Key words: *industrial reuse, office buildings, daylight, LEED, Belgrade*

1. INTRODUCTION

Belgrade and Serbia have a large number of vacant industrial buildings built prior to the Second World War. While some are permanently or temporarily listed (placed on the statutory list of buildings of special architectural or historic interest), the majority has no legal protection. Key heritage sites are planned to be reused for culture and hospitality related functions. Meanwhile, the unlisted buildings are in danger of being torn down. Many of these are in central locations and have the physical properties that make them suitable for adaptive reuse as offices.

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Adaptive reuse is one of the key strategies of urban regeneration. In the case of industrial buildings, it does not only help the social and economic rehabilitation of neighborhoods, but also aids in understanding our industrial background and historical production processes.

This paper is based on a study of locational and physical characteristics of Belgrade's industrial heritage, which covered over 70 buildings. The buildings selection mostly coincides with an industrial archaeology database developed by the Museum of Science and Technology in Belgrade [1]. The analysis aids in understanding which buildings are most suitable for reuse as office space. The work presented in this paper focuses on the characteristics influencing daylighting performance.

Daylight design is an important component of any retrofit. Most adaptive reuse projects include changing the components that affect daylight penetration. In addition to their thermal properties, today's windows have a different performance in terms of both quantity and quality of light compared to original single glazed windows. Internal organization of a building has to take into account this change in daylight levels, and often additional strategies should be applied to increase the daylight performance of a space to levels satisfactory for office use.

Energy used for artificial lighting in offices can be substantial. In commercial offices in the UK, 15% of final energy consumption is associated with lighting [2]. This also has an impact on the total cooling load. In addition to energy conservation, daylight connects building occupants with the outdoors and helps the reinforcement of circadian rhythms.

2. Daylight Performance Criteria

A minimum level of illuminance is necessary for a clear vision without tiredness, while an excessively abundant illumination can be uncomfortable. The recognized scale of illumination for office tasks is either:

- 300 lux for mainly screen-based tasks, which can include minor paper-based tasks such as note-taking or
- 500 lux for mainly paper-based tasks.

Large spatial variations in illuminance around the task area can lead to visual stress and discomfort.

Daylight potential of a space has traditionally been assessed using daylight factor. This is the ratio of available illuminance in a space to the illuminance outside under an overcast sky. The daylight factor calculation does not take into consideration the location or orientation of the building. British Standard 8206-2 [3] states that an average daylight factor above 2% across a space should result in that space appearing to be predominantly daylit. An average daylight factor greater than 5% indicates that electric lighting will not normally be required during daytime [3].

In recent years the profession has moved toward dynamic daylighting metrics, which are location-based (use actual weather data) and annualized (summarize performance over the entire year). Daylight autonomy (DA) is a daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in a space is met by daylight. DA of 50% means that for 50% of the occupied time daylight levels at a point are above the target illuminance. A target illuminance of 300 lux and a threshold

DA of 50% in short DA_{300lux}[50%], are values currently promoted by the Illuminating Engineering Society of North America [4] for common workplace environments.

Today, daylight analyses are included in all environmental performance rating systems. LEED version 4 Indoor Environmental Quality credit 'Daylight' could be met by a simulation of spatial daylight autonomy (sDA), illuminance calculations or by measurement [5]. The credit requires a demonstration of sDA_{300lux}[50%] for at least 55% (1 point), 75% (2 points), or 90% (3 points) of regularly occupied area. It should also be demonstrated that annual sunlight exposure $_{1000,\ 250}$ ($ASE_{1000,\ 250}$) of no more than 10% is achieved. Alternatively, in order to achieve 1 point, 75% of regularly occupied floor area should have illuminance levels between 300-3000 lux at 9 a.m. and 3 p.m., both on a clear-sky day at the equinox. To achieve 2 points, the same should apply to 90% of regularly occupied floor area. LEED defines regularly occupied space as an area where occupants perform focused activities for more than one hour per day. WELL Building Standard [6], an assessment tool with a primary focus on wellbeing of occupants uses the same requirements in its 'Daylight Modelling' credit.

Due to LEED being the dominant environmental performance tool for office buildings in Serbia [7], this methodology will be used to compare buildings daylight performance.

3. Classification of Belgrade's Industrial Heritage

Industrial production in Serbia started with state-owned companies that produced weapons and ammunition (gunpowder mill in Strugari from 1806 and cannon foundry in Belgrade from 1808) [1]. These were accompanied by smaller foundries, and workshops for the manufacture of leather goods. By the mid-19th century Belgrade saw the first production systems based on mechanical/rotary drive source for primary strategic products - military and food. Later, during 1880s there has been a significant development of industries for civil purposes.

During World War I a good part of the industry has been damaged or destroyed. After the war, the total number of industrial buildings on the territory of Serbia has been reduced to only 70 [1].

In 1930 Belgrade had 170 industrial enterprises with 14,000 workers [1]. Between the two wars, the most developed industries in Belgrade were textile, metal processing and food industry [1].

Central or well-connected locations, durable construction and large open spaces make industrial buildings attractive to commercial investors. Generous floor to floor heights and period features make them attractive to office tenants. These buildings are likely to have substantial thermal mass, and some have favorable floor depths for daylight and natural ventilation.

In order to select representative cases for analysis, Belgrade industrial heritage has been categorized according to factors influencing daylight illumination:

- Window to wall ratio
- Building depth
- Orientation and
- External obstructions.

3.1. Window to wall ratio

According to their window to (gross external) wall ratio, Belgrade industrial buildings could be classified in four main categories:

- Below 10%,
- 10-20%,
- 20-30%, and
- Above 30%.

Mills, sawmills and brickyards are likely to have a window to (gross external) wall ratio below 10% (Fig. 1). The majority of analyzed buildings have a ratio between 10 and 20 percent. This group includes buildings from all industrial sectors. A window to wall ratio between 20 and 30% is likely to be found in production facilities which used to have workstations with occupant's requirements similar to those for office work. Very few buildings have a window to wall ratio above 30%.

International standards find the values from 19-60% appropriate for office use. ASHRAE Standard 90.1 [9] baseline building scenarios assume 19% window to wall ratio for office buildings smaller than 465 m^2, 31% for office area between 465 and 4650 m^2 and 40% for larger offices. These values are considered to offer a good balance between heat gains and losses, without compromising the daylight requirements. WELL Building Standard [6] in 'Daylighting Fenestration' credit considers acceptable glazing ratios to be between 20 and 60 percent.

Buildings with window to wall ratio below 10% are not suitable for office use, and will not be considered further in this study. Very few buildings that have a ratio above 30% are likely to offer satisfactory daylight conditions. For this reason, the study will focus on buildings with window to wall ratio between 10 and 20 percent, and 20 and 30 percent.

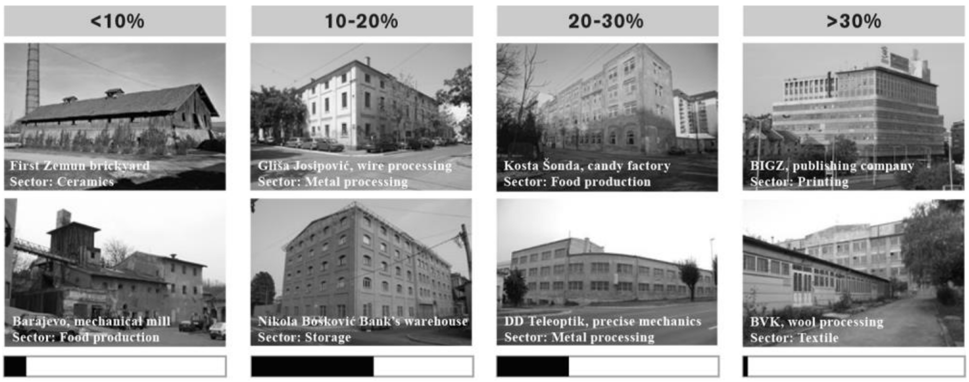

Fig. 1 Belgrade's industrial heritage - window to wall ratio categories
(Sources: Images: Kulenović, 2010 and Museum of Yugoslav History [8])

3.2. Building depth

According to building depth Belgrade’s industrial heritage could be classified in 3 main categories:

- Up to 15m,
- 15-25m, and
- Above 25m.

Most industrial buildings fall within the first two categories.

Purpose built office buildings usually have floor depths between 15 and 19 meters. Larger depths could be difficult to plan and are likely to have comfort issues.

3.3. Building orientation and external obstructions

Building orientation is usually predetermined by the street grid. In the case of Belgrade’s industrial buildings it varies from building axes facing the four main orientations to being rotated by 15 or 45 degrees either side of North.

External obstructions vary from case to case, and are not the focus of this study.

4. Main Climatic Data Influencing Daylight Availability

Daylight strategies depend on the availability of natural light, which is determined by building’s location. Belgrade’s latitude is 44°N. Days can last from 7 hours in winter to 15 in summer (Fig. 2).

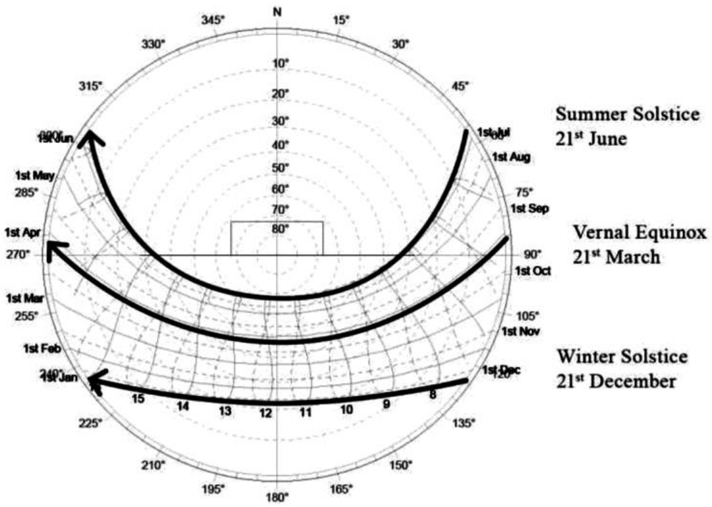

Fig. 2 Sun-path diagram for Belgrade

Mean global horizontal radiation values vary from 41 W/m^2 in December to 263 W/m^2 in July [10]. Horizontal surfaces receive at least two times more solar radiation than any vertical orientation (Fig. 3).

Skies are predominantly sunny during summers, and overcast or cloudy during winters. Midseason months would have at least 40% sunny skies (Fig. 3).

Daylight availability varies from very little in winter to high levels during summer months.

With peak temperatures above 30°C for 6 months a year, there should be a balance between allowing enough daylight in a space and minimizing solar gains during warmer months.

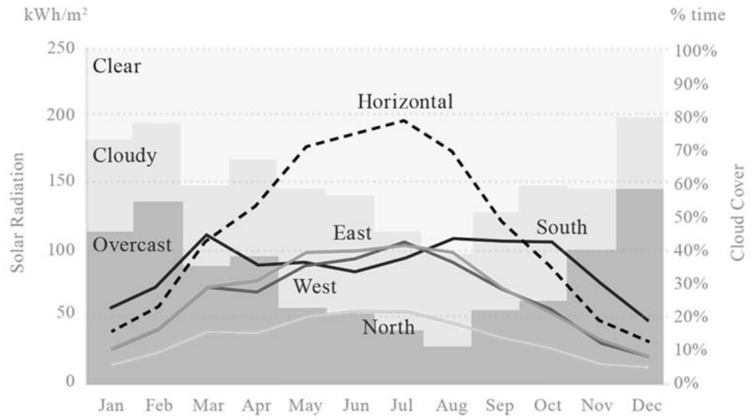

Fig. 3 Mean monthly solar radiation levels for different surface orientations and monthly sky cover (Source: after National Renewable Energy Laboratory, 2015)

5. Methodology

Two case studies that are representative of a large number of Belgrade industrial buildings have been selected for further analysis.

Daylight performance has been assessed using daylight factor, point in time illuminance, and spatial daylight autonomy. The simulations were done using DIVA (Design, Iterate, Validate and Adapt), a daylight modelling plug-in for Rhinoceros [11].

After the initial daylight assessment, a number of parameters that could influence the daylight performance were analyzed. Optimal strategies that increase daylight levels without having a strong impact on building's historical character or energy performance were explored.

6. Case Studies

The case studies chosen for analysis are the warehouse of Nikola Bošković Bank and the candy and chocolate factory Kosta Šonda. The first case study was originally built for storage, has a window to wall ratio between 10 and 20 percent, and a floor depth between 15 and 25 meters. It is oriented due North, with its longer elevations facing East and West. The second case study building was built for manufacturing, and has a glazing ratio between 20 and 30%, a floor depth below 15 meters and its main axis is oriented 15° away from North.

6.1. Nikola Bošković Bank Warehouse

The warehouse was built in 1920s in reinforced concrete. It had been severely damaged during WWII and rebuilt after 1945 [12].

Today, the building is owned and occupied by an IT company. It comprises approximately 1100 square meters of office space on each of its five levels. The building underwent a major refurbishment in 2000. The works included facade and structure improvements, new services and BMS system, and an internal fit-out.

The building is surrounded with low rise buildings, except to South, where it is facing a 3 and a 4-storey building (Fig. 4). The obstruction angle for the first floor windows is approximately 45 degrees, and direct sun does not reach these windows during winter months.

The building has windows on all four facades. The average window to wall ratio is around 15%. Original wall thickness varies between 45 cm on ground, first and second floor and 30 cm on upper levels.

The window sill height on ground floor is 1.5 m, and the window height is 1.8 m (3.3m above the floor level). On the upper levels the sill is 1m, and window height 1.5 m. Floor to floor height on ground floor is 4.52 m and on upper floors 3.52 m. On the top level the height varies from 2.7 to 5.2 meters.

Fig 4. Nikola Bošković Bank's warehouse
(Sources: Map: after Google Earth, 2015; Photo: Kulenović, 2010;
Drawings: after Historical Archives of Belgrade, 2015)

6.2. Kosta Šonda

Originally built as a candy and chocolate factory around 1900, the building's use has been changed to workers' apartments, graphic school and souvenir production workshops. Today it is used as the headquarters and production facility for a fashion brand. Offices are located on ground and first floor, while leather and textile workshops and warehouse space are on upper floors and in other buildings within the complex.

Each of its four levels has a GIA of approximately 600 m^2. The width of the building is only 11.2 meters. The building was last refurbished in 2007, this included envelope improvements and interior fit-out of office levels. Windows are currently glazed with aluminum framed double glazing.

The building's window to wall ratio is around 24% on East and West facing facades (Fig. 5), and 9% on South facade for the analyzed level. To the North, the analyzed part is connected to an existing building which has different floor levels.

The surrounding buildings have a negative effect on daylight levels only during winter months.

Window height on all levels is 1.8 meters, sill height varies from 0.8-1.05 meters. Floor to floor height is 5.3 meters on ground level and between 4 and 4.3 meters on upper levels.

Fig. 5 Kosta Šonda
(Sources: Map: after Google Earth, 2015; Photo: Kulenović, 2010; Drawings: after Historical Archives of Belgrade, 2015)

7. Daylight Performance

Daylight performance has been assessed using daylight factor, point in time illuminance and spatial daylight autonomy as per LEED v4 requirements.

For both case studies, daylight levels have been assessed on the first floor, since ground floors are partly occupied by reception and amenity spaces. External obstructions have been included in the model. For the ease of comparison, the analyses do not include furniture or any non-structural partitions. The whole floorplate is considered to be a 100% regularly occupied space.

The initial studies are looking at a typical refurbishment scenario, which somewhat reflects the current situation for both case studies. The original windows have been replaced with low emissivity double glazed windows. Assumed visible light transmittance for external glazing is 0.65 which combined with a dirt depreciation factor of 5% (minimum in IES [4]) and a frame factor of 10% results in transmittance of 0.55. Assumed reflectance values are 0.2 for floors, 0.5 for walls and 0.7 for ceilings (as recommended in IES [4]).

7.1. Daylight factor

Only 10% of Nikola Bošković Bank warehouse's floor area is likely to have a daylight factor above 2%. 29% of Kosta Šonda's floor area is likely to have daylight factor above 2%. It can be concluded that under overcast sky condition (approximately one third of the year), both buildings do not receive sufficient daylight (Fig. 6).

Daylight factor analyses are informative for general performance of buildings, regardless of orientation. Conclusions can be made on the performance of other buildings with similar floor width and glazing ratio.

7.2. Point in time illuminance (LEED v4)

In order to assess daylight performance under sunny sky conditions, the study uses LEED v4 illuminance path (Fig. 6). The illuminance analysis for 21st September for Nikola Bošković Bank's warehouse shows abundance of daylight immediately adjacent to the windows (above 3000 lux). These values are alerting to possible glare issues on East and West facade, and glare blinds should be provided as a mitigation measure. The task area that is likely to achieve the targeted illuminance levels between 300 and 3000 lux is around 16% for both 9 a.m. and 3 p.m. simulations. Most of the internal floor plan receives under 300 lux.

Kosta Šonda shows a better performance under the same criteria (Fig. 6). Percentage of the tested area that is likely to receive 'good' daylight (between 300 and 3000 lux) is 58% at 9 a.m. and 74% at 3 p.m. From the same area, 6% at 9 a.m. and 10% at 3 p.m. is likely to receive illuminance above 3000 lux.

7.3. Spatial daylight autonomy (LEED v4)

Spatial daylight autonomy is the preferred metric for analysis of daylight sufficiency, due to its dynamic character. Daylight conditions are based on typical meteorological year (TMY) data, with an analysis time period from 8 a.m. to 6 p.m. (3650 hours, 1825 hours for 50%).

Only 10.8% of floor area of Nikola Bošković Bank is likely to reach the targeted sDA_{300lux}[50%] (Fig. 6). Kosta Šonda meets the target in 19% of its floor area.

The analysis did not model internal blinds, and will therefore not comment on the ASE values.

8. Daylight Improvement Strategies

The analyses show that achieving the recommended daylight levels in industrial buildings is difficult with a window to wall ratio between 10% and 20%.

Buildings with narrow floor depths are more likely to achieve desired illuminance levels by using daylight. Buildings with a depth above 15 meters would require additional strategies to increase daylight levels.

To keep their original aesthetics, allowed interventions on external envelope of historical industrial buildings are very limited. Even in the case of unlisted buildings, the application of external shading or light redirection devices is not considered good practice. These additions can significantly alter the preserved appearance of the building.

The most common strategies that could increase daylight levels inside deep plan industrial buildings are a careful selection of internal surfaces and an increased area for daylight penetration. This is often limited to introduction of roof-lights and rarely smaller atriums or courtyards.

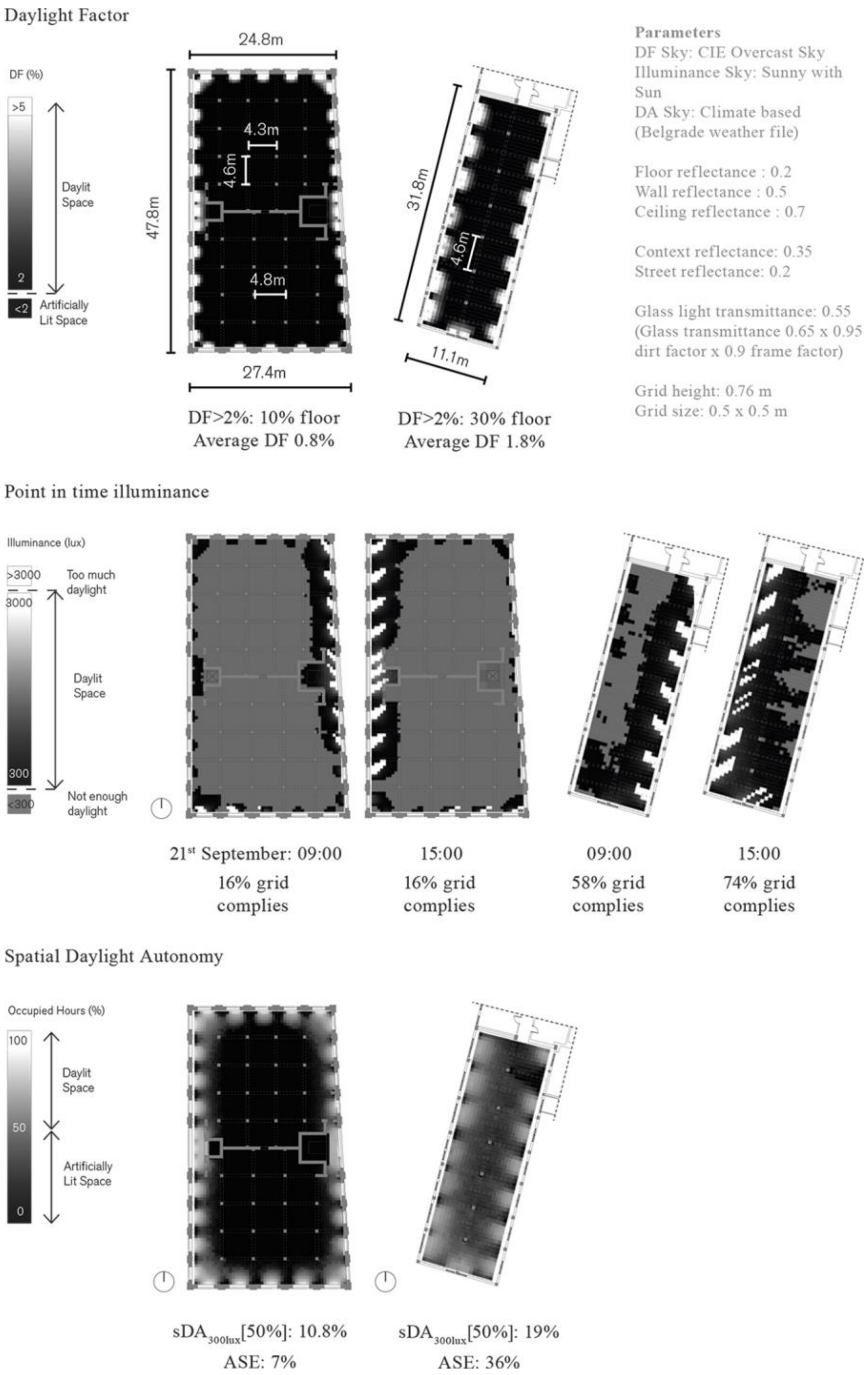

Fig. 6 Base case daylight performance
(Source: Drawings after: Historical Archives of Belgrade)

8.1. Increased surfaces reflectance

When done in conjunction with daylighting goals, effective selection of finishes can substantially improve daylighting performance. Choosing bright interior finishes helps increase daylight levels in a space, and shape the perception of brightness (psychological effect).

The analysis increased the wall reflectance to 0.8 and assumed highly reflective ceilings (reflectance: 0.9). This resulted in 12% increase in average daylight factor, and about 18% increase of the area that will appear daylit (DF over 2%) (Fig. 7).

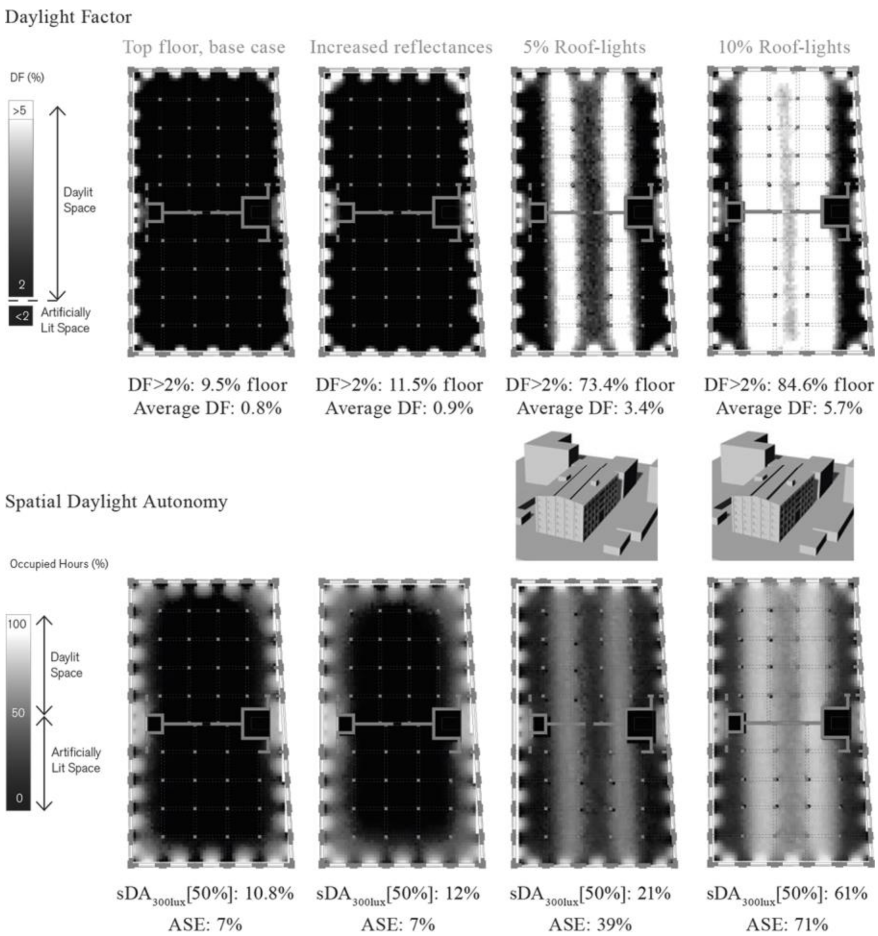

Fig. 7 Improvement options
(Source: Drawings after: Historical Archives of Belgrade)

8.2. Introduction of roof-lights

Roof-lights have a potential to improve the daylight environment of the space below, but also have structural and thermal liabilities. While in the case of industrial buildings it is often structurally possible to glaze significant portions of a roof, the resulting cooling loads in summer or heat losses in winter can be substantial. Solar radiation falling on a horizontal surface during summer months is about 2 times higher than on any facade orientation (Fig. 3). Building energy codes therefore typically restrict the roof-light area for commercial buildings. UK Part L2B [13] limits the prescribed skylight area in extensions to existing buildings to 20% of roof area, while a top lit notional building will have 12% roof-lights [14]. ASHRAE used to limit the roof-lights for prescribed compliance to 5% [15, 16] and in the latest edition to only 3% of the roof area [9]. Serbian Rulebook on Energy Efficiency of Buildings [17] does not directly prescribe the roof-light area, only the energy consumption.

Roof-lights come in various forms and shapes (from flat surfaces to pyramids and domes), which influences how light from different parts of the sky gets redirected through the light well. The analysis assumes continuous dual aspect punctures, for a more equal distribution of light, which would allow easier internal planning.

Thermal analyses have been conducted using IES-VE [18] to estimate the thermal effect of roof-lights. Assumed U-values and internal gains have been taken from the Rulebook on Energy Efficiency of Buildings [17]. The analyses show that the introduction of roof-lights (U-value: 1.5 W/m^{2}K, SHGC: 0.4) has a negligible effect on the annual heating loads, but a significant effect on the annual cooling loads. Without roof-lights, top level cooling loads are likely to be 37% smaller than heating loads. However, if the roof-light area is above 15% of the roof, the average annual cooling loads are becoming higher than heating loads (Fig. 8). Therefore, daylight analysis will focus on roof-light area of 5% and 10%.

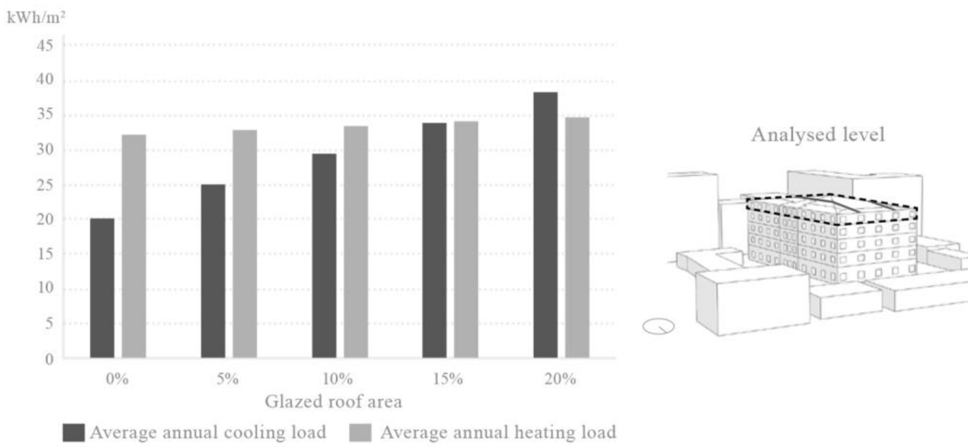

Fig. 8 Average cooling and heating load for different roof-light ratios

If 5% of the roof area is glazed, the average daylight factor could be increased to 3.4%, while with 10% glazed it could be increased to 5.7% (Fig. 7). Therefore if 10% of the roof is glazed, the space might not need artificial lighting during daytime hours. This is confirmed using sDA 300lux [50%]. LEED's 55% threshold could be met with this glazing area. However ASE value without incorporating shading is extremely high. This indicates the importance of careful design and operation of blinds that would limit the glare while maximizing daylight penetration into the space.

9. ADDITIONAL CONSIDERATIONS

Daylight penetration in industrial buildings can be amended in a number of additional ways.

9.1. Introduction of atriums

In a fully daylit atrium, the maximum atrium height is less than 2.5 times its width [19]. This means that an atrium that would serve the upper 4 floors of the analyzed warehouse would need to be at least 6.3 meters wide. This would significantly impact the internal organization and is therefore not analyzed. Smaller atriums could bring some daylight benefit only to the areas directly adjacent to them.

9.2. Glazing properties

Window openings and frames give a building's elevation its character. They should not be altered in their proportions or details, as they are conspicuous elements of the design. The depth to which window frames are recessed within a wall is of historical significance and greatly affects the character of a building, and therefore has to be respected [20]. Replacing traditional single-glazed steel windows with double-glazed PVC or aluminum frame windows can be very damaging to the special character and appearance of a building (thickening the dimensions of glazing bars). In addition, the increased frame factor negatively affects daylight levels in the space. Traditional wooden frames were made of slow-grown, high-quality timber, and should be refurbished and retained whenever possible. Today's timber is of inferior quality, resulting in frames that have a much shorter expected lifespan.

Historic England [20] points out that old glass is of interest as it has a sparkle that today's flat sheets with their uniform reflections do not have (Fig. 9). Therefore, whenever possible, the original glazing should be retained and alternative means of thermal improvement should be considered. If an adaptation project aims to meet and exceed the requirements of the current regulations [17] drought proofing would not be sufficient. In this case, the original window should be kept, and an additional double or triple glazed window should be added on the inside (Fig. 9). External walls are often deep enough to house the second window.

9.3. Light redirection

As previously mentioned external light shelves or prismatic glass are usually not acceptable in adaptation of historical buildings. One possibility is the installation of integrated shading/light redirecting devices in the air gap between the original single glazed and the new double/triple glazed window. Slat blinds could offer both shading and redirection of daylight. However, due to their limited width and internal position, light redirection will be very limited. In addition, slat blinds need a wider gas gap and thicker panes, which are harder to integrate into a slim frame.

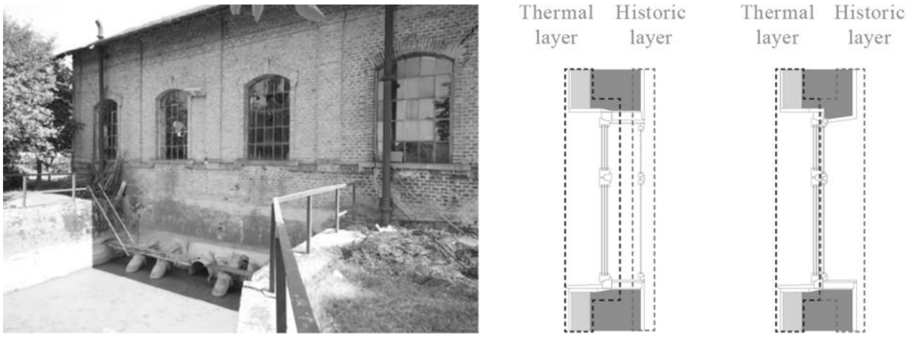

Fig. 9 Original glazing (pump station Boljevci) and energy efficient refurbishment options (Sources: Photo: Kulenović, 2010; Diagram: after Troi and Zeno, 2014 [21])

Light tubes are a strategy that could be applied to the level below the top floor. However the resultant daylight benefits have to be measured against the impact that the tubes would have on the internal arrangement of the top floor.

10. CONCLUSIONS

Environmental design and operation rating systems are constantly evolving, and their daylight criteria are becoming more stringent with every new version. The acceptable illuminance range for LEED 'Daylight' credit changed from 108-5400 lux in LEED 2009 version to 300-3000 lux in version 4 [5]. Belgrade's historical industrial buildings would rarely meet the revised criteria. Analyses have shown that even buildings with a glazing ratio between 20-30% and a width below 15 meters are likely to struggle to comply with this criteria.

In addition, there is a very limited number of strategies that could improve daylight performance, without having a negative impact on building's character. The most effective strategies are increased reflectance of internal surfaces (walls, ceilings, furniture) and introduction of roof-lights, where this is possible. Finally, key to achieving daylight credits is careful internal planning, where regularly occupied areas are distributed in zones with best daylight environment.

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PRIRODNO OSVETLJENJE
U ADAPTIRANIM INDUSTRIJSKIM OBJEKTIMA

U radu je analizirana prenamena industrijskih objekata izgrađenih pre Drugog svetskog rata u poslovne. Industrijsko nasleđe Beograda je klasifikovano prema kriterijuma koji utiču na vizuelni komfor, uključujući veličinu prozora, dubinu osnove i orijentaciju objekata. Količina prirodne svetlosti je analizirana korišćenjem faktora dnevne osvetljenosti (daylight factor), nivoa osvetljenosti (point in time illuminance) i prostorne autonomije dnevne svetlosti (spatial daylight autonomy). Nakon analiza, razmatrane su potencijalne strategije za unapređenje nivoa osvetljenosti koje ne bi imale negativan uticaj na istorijski karakter zgrada. Dalje analize uključuju povećanje vrednosti refleksije površina prostorije i uvođenje krovnih prozora. Uticaj krovnih prozora na godišnju potrebnu energiju za grejanje i hlađenje objekata je takođe razmatrano.

LEED je dominantan program za sertifikaciju poslovnih zgrada u Srbiji. Stoga, rad uključuje preliminarane analize svih opcija za usklađenost sa zahtevima LEED v4 kredita „Prirodno osvetljenje”.

Metodologija i zaključci ovog istraživanja mogu se primeniti na širok spektar industrijskih objekata u sličnim klimatskim uslovima.

Ključne reči: *industrijski objekti, prenamena, poslovne zgrade, prirodno osvetljenje, LEED, Beograd*