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Evaluation of indoor daylighting performance changes in a historical khan building in Istanbul

Asli Agirbas[1*] and Ayse Ozlem Dal[1]

Abstract

The daylighting feature of historical buildings can be accepted as an intangible heritage since it contributes to the unique atmosphere of the buildings. However, with the change of the built environment and the change of the historical building itself, the level of daylight intake of historical buildings changes. This study contributes to the field by revealing the daylighting performance changes of a historical khan building which has a unique architectural characteristics. The changes in the daylighting levels of Buyuk Yeni Khan, one of the largest historical khans in Istanbul, are examined through its modifications. Using 3D Lidar scanning technology, the current state of the khan is scanned. The daylight intake and glare analyzes of the khan for its current and original states are made through simulations, and the values found are compared. DA, cDA, UDI, sDA and DGP metrics are used in the simulations. As a result, due to the changes such as enlargements along the arcades, additional overhangs and the change of window ratios of the facades of the rooms on the ground floor, the rooms of the khan have different daylighting values compared to its original state.

Keywords Daylighting analysis, 3D Lidar scanning, Khans, Historical buildings, Buyuk Yeni Khan

Introduction

Changes in the urban built environment are typically manifested through variations in morphological characteristics, such as alterations in building heights, the shapes of building blocks and the dimensions of plots [1, 2]. Institutional factors such as formal organisations, and natural factors such as natural disasters can lead to change in built environment [3]. As a result of the modifications of the built environment, the indoor environment quality (IEQ) of buildings can change. This situation can greatly affect the IEQ of historical buildings as well. Also, historical buildings may undergo various modifications or restorations [4] that can effect their IEQ. IEQ parameters are accepted as thermal comfort, air quality, lighting and acoustics [5–7]. As Che et al. [8] and Ridolfi et al. [9] have done, there are studies that examine how the indoor environmental quality changes as a result of the modifications in buildings and make inferences for future studies. In addition, as Balocco and Calzolari [10], Zhang et al. [11] and Marzouk et al. [12] have done, studies are also carried out on improving IEQ of heritage buildings.

In addition to the studies on improving the energy efficiency and thermal comfort of historical buildings within the scope of IEQ [13], the studies on daylighting analysis and daylight intake control in historical buildings have also accelerated in recent years. For example, there are studies on the suitability of the daylighting level in the new use of historical buildings originally designed for a different purpose [14, 15]. Studies are also carried out to provide light control in order to protect the light sensitive valuable artifacts in the interiors

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of historical buildings [16–18]. There are also studies on the use of daylighting as a design strategy in historical buildings [19–21]. In addition, analyzes are made on historical buildings whose daylight intake levels have changed due to the change in the built environment around them [22]. This study also focuses on the daylighting performance change of a historical building.

Daylight intake in buildings affects the visual comfort, productivity and well-being of the occupants [23–27]. In addition, the proper intake of daylight into the space reduces electricity consumption and prevents unnecessary energy consumption [28, 29]. Besides, as Al-Maiyah and Elkadi [30] mentions, daylighting performance is rarely considered when renovating historical buildings. Because if the renovated building takes on a new function, the new daylighting performance of the interior is shaped according to the lighting required by the new function. Also, other performance metrics such as thermal performance and energy performance may be shaped according to a new function or energy retrofit regulations. However, daylighting performance of historical buildings is actually a part of the visual character of these buildings. Daylighting parameters of a building can be defined as the combination of sunlight, skylight and the reflected light from the facades and the ground, and these parameters affect visual perception and the identity of the place, so that it forms visual character of the building [31]. Original visual characteristic of a historical building is a part of its identity. Therefore, this feature can be accepted as an intangible cultural heritage and should be preserved. Additionally, with the advances of UNESCO's Safeguarding of Intangible Heritage adoption, digitalisation and documentation of intangible cultural heritage is important [32].

The interior space performance changes of historical buildings that have changed over time can be observed by comparing the old and new states of the buildings. In this study, it is focused on the changes of daylighting performance of khan buildings. This paper aims to examine indoor daylighting performance change of Buyuk Yeni Khan by comparing its current and original states. By detecting the changes in daylighting performance of the khan, actions can be taken to improve IEQ in a possible restoration or renovation work. This paper not only emphasizes and quantifies the atmosphere created by daylighting in the khan buildings which have unique architectural characteristics, but also defines the changes of daylighting performance through the time. This study contributes to the literature by providing an analysis of the changes in daylighting performance of historical khan buildings, a topic that has not been previously explored.

Materials and methods

The function of closed areas of the khan and the height of the surrounding buildings have been examined (Fig. 1). Then, the parts of the khan such as semi-open areas (arcades), courtyard and the rooms have been scanned with Lidar 3D scanning technology. After collecting the data from the site, the 3D modeling and daylighting analysis have been done. The model created with Lidar technology was used as a base for 3D modeling. 3D modeling was done in Rhinoceros [33] programme. Daylighting and glare analysis were performed using Grasshopper [34] and Honeybee + Ladybug tools [35]. Honeybee + Ladybug tool uses Radiance, EnergyPlus/OpenStudio, Therm/Window and OpenFOAM programs in the background. For the sensitivity analysis Colibri [36] add-on for Grasshopper was used. Since this study utilizes Rhinoceros for 3D modeling, Grasshopper, which is compatible with Rhinoceros, was chosen as daylighting analysis platform. Additionally, a script was created with the help of add-ons added to Grasshopper. Another reason for choosing the Grasshopper platform for daylighting analysis is its capability to integrate additional IEQ parameters, such as acoustics and thermal comfort, into the script. However, it is important to note that other programs, such

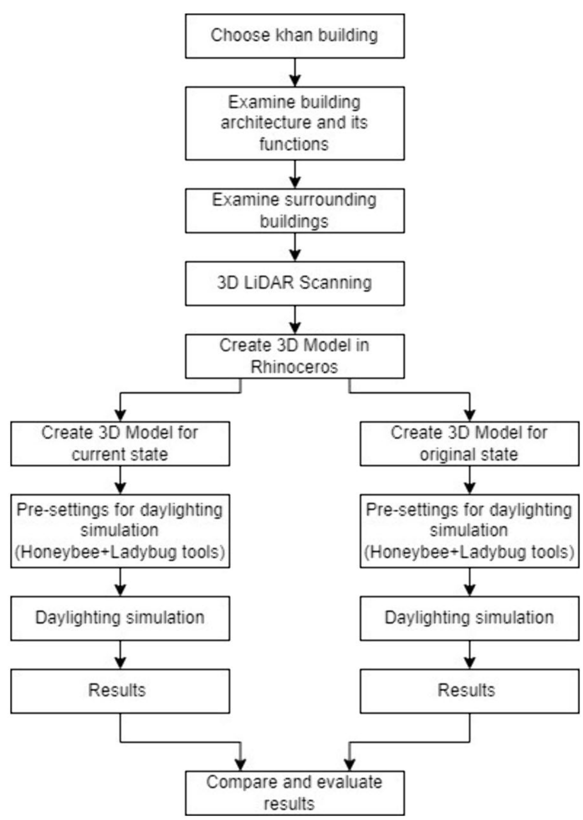

Fig. 1 Framework of the study

Fig. 2 The location of Buyuk Yeni Khan and the neighbourhood area

as VELUX Daylight Visualizer and LightStanza, can also perform daylighting analysis through modeling.

Daylight Autonomy (DA), Continous Daylight Autonomy (cDA), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP) metrics were used in the daylighting and glare analysis. DA measures annual (climate-based) indoor daylighting performance based on the location of the buildings and is defined as the percentage of the time that a particular daylight level is exceeded a specified illuminance [37, 38]. When the illuminance level in the space drops below the required threshold, partial credit is allocated to time intervals based on the cDA metric [39, 40]. sDA reports the percentage of floor area in a building that exceeds a specified illuminance level for a specified amount of annual hours [41, 42]. This metric helps understand the distribution of daylight within a space, ensuring that a substantial portion of the area receives adequate natural light for a significant part of the day. UDI defines the percentage of time that daylight levels fall within a "useful" range for a given space [43, 44]. If daylight illuminance falls below 100 lx at a given time, it is insufficient for proper lighting, resulting in an undersupply UDI bin. If it exceeds 2000 lx, it likely causes visual or thermal discomfort, leading to an oversupply UDI bin. If the illuminance is between 100 and 2000 lx, it offers useful lighting levels, resulting in a useful UDI bin. DGP metric is used to measure daylight comfort level of the spaces. DGP levels are as follows: imperceptible (< 0.35), perceptible (0.35–0.40), disturbing (0.40–0.45), intolerable (> 0.45) [45, 46].

Daylighting simulations are done with grouping the rooms according to their sides. The groups are named as the rooms at the North side, the rooms at the South side, the rooms at the West side, the rooms at the East side and the rooms at the Transition area. Glare simulations are done by selecting a room from each side. Sensitivity analyses are also done by taking account of the selected rooms for glare simulations.

Case study

City khans are the places that have been used as shops, warehouses, offices, manufacturing and trade spaces from the past to the present. There could also be city khans with accommodation functions. City khans that did not provide accommodation were called commercial khans [47]. The historical khans include courtyards which are surrounded by semi-open spaces (arcades/*revak*) and closed rooms. They usually have rectangles or squares in the plans. This building type referred as khans [48–50], han [51] or inns [52] in the literature. However, since the word "khan" is used in the UNESCO's "Bursa and Cumalıkızık: the Birth of the Ottoman Empire" [53] description, the word "khan" used in this study as well.

It is known that in the Ottoman Period, from the fifteenth century to the first quarter of the twentieth century, approximately 300 khans were built and 110 of them are still standing [52, 54]. There are many khans in the

Fig. 3 Buyuk Yeni Khan drawing in Charles Edouard Goad's map (1904) [63] and Jacques Pervititch's map (1942) [64]

historical peninsula of Istanbul, which has been a trade center for many years in the Ottoman period. Since there are many khans located as clusters around the Grand Bazaar in Eminonu, this area is called the khans district [55]. Buyuk Yeni Khan is also located in this region (Fig. 2). Buyuk Yeni Khan is a busier khan compared to other khans in Eminonu district of Istanbul. As Yaşar [56] mentioned, this khan is the one of the largest khan in Istanbul. In this khan, almost all the rooms are in use today. Therefore, Buyuk Yeni Khan has been selected to be examined in this study.

Buyuk Yeni Khan is located in Taya Hatun district of Eminonu. The location is at the intersection of Cakmakcilar Yokusu Street, Sandalyeciler Street and Carkcilar Street. It is known that Buyuk Yeni Khan was constructed during the period of Sultan Mustafa III [57]. According to the date written in a script on the façade of the khan, it is thought that the built date of the building could be around 1763–1764 [58]. It is also thought that the architect of the khan could be Mehmet Tahir Aga [47].

Buyuk Yeni Khan has a rectangular-like plan shape, and it has three floors covering 5180 m^2 [54]. The khan has two courtyards. The main entrance to the khan is from Cakmakcilar Yokusu Street. The first courtyard is 42 m in length, while the second courtyard in the south is 25 m in length. Widths vary between 12–15 m [58]. The building is situated on sloping terrain. According to Goad's map (1904) and Pervititch's map (1942) (Fig. 3), there is one more courtyard at the Southern side. However, this part has lost its original character, so that this part was not taken into consideration in this study. There are also materialistic differences between floors. For example, stone material was used for the ground floor, and mixed technique with the use of stone and brick materials was applied for the other two floors [57, 59]. Unlike the other façades, there are six cantilevers at the north façade. As

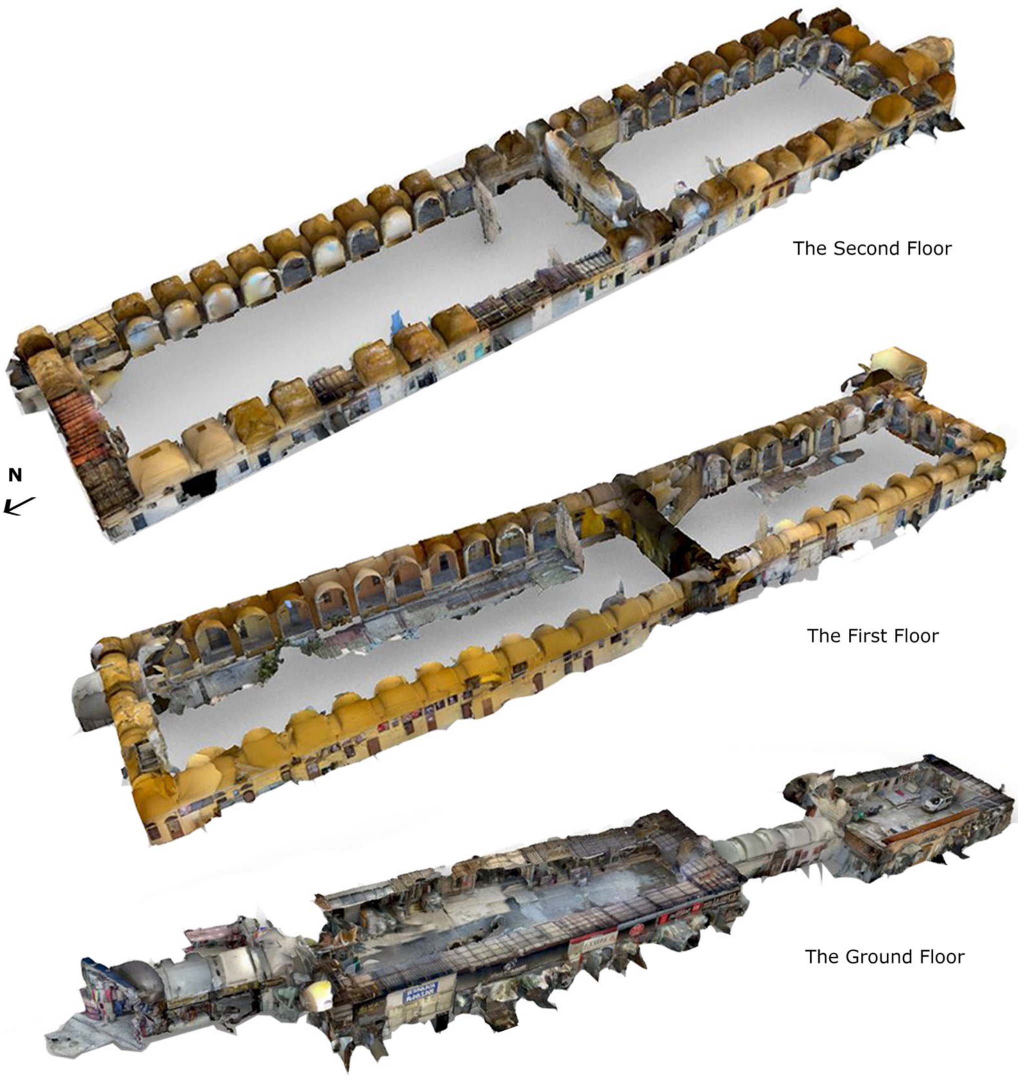

Fig. 4 3D Lidar interior scanning results of the khan's current state

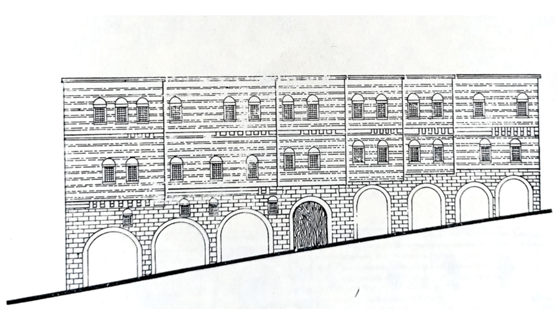

Fig. 5 The North facade of Buyuk Yeni Khan [65]

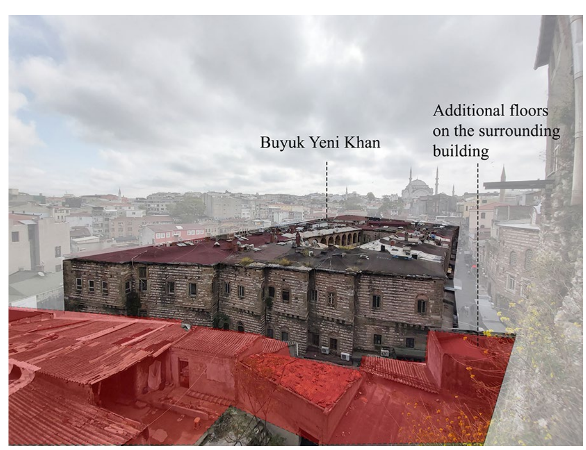

Fig. 6 The additional floors on the surrounding building have been marked with red color

noted by Yasar [58], it is assumed that this façade typology has been designed to receive more daylight to the interior space. Today, the functions of ground floor level

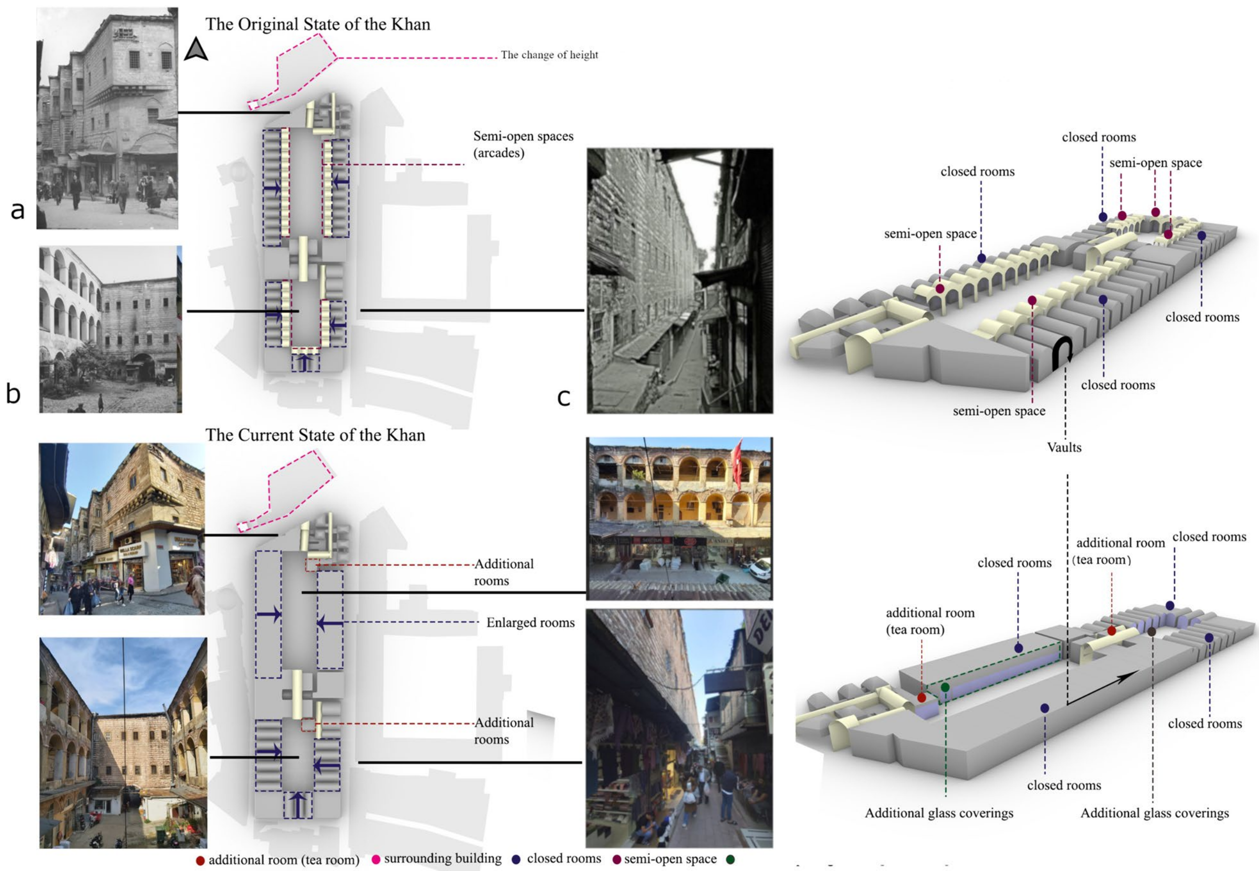

Fig. 7 A comparison of the original state with the current state of Buyuk Yeni Khan. **a** The original state of the North façade of the khan [67]. **b** The original state of the courtyard of the khan [68]. **c** The original state of the East façade of the khan [69]

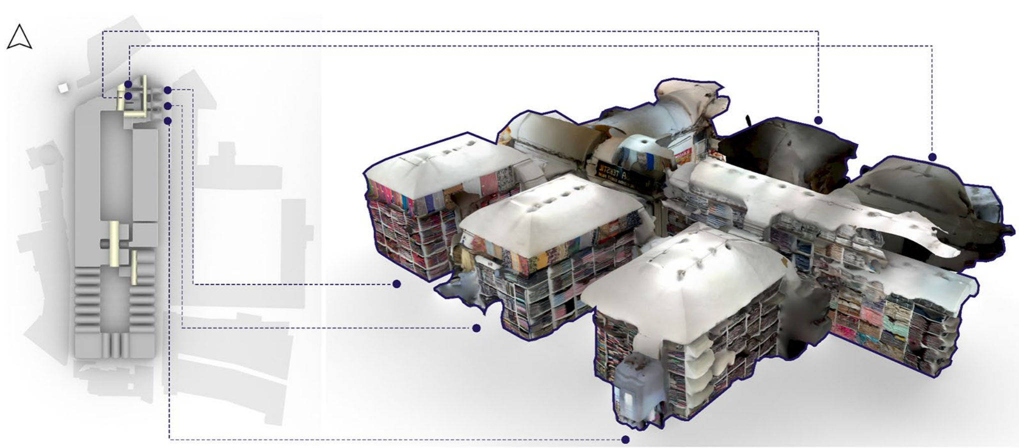

Fig. 8 The vault coverings of the rooms (extracted from 3D scanning)

rooms of Buyuk Yeni Khan are based on textile. Textile-based shops, handicraft shops for silver and copper are common on the first floor. The functions of the rooms on the second floor are mainly related to the handicrafts for silver, copper, and beads. Since some of the rooms were locked, the functional definitions of the rooms could not be made.

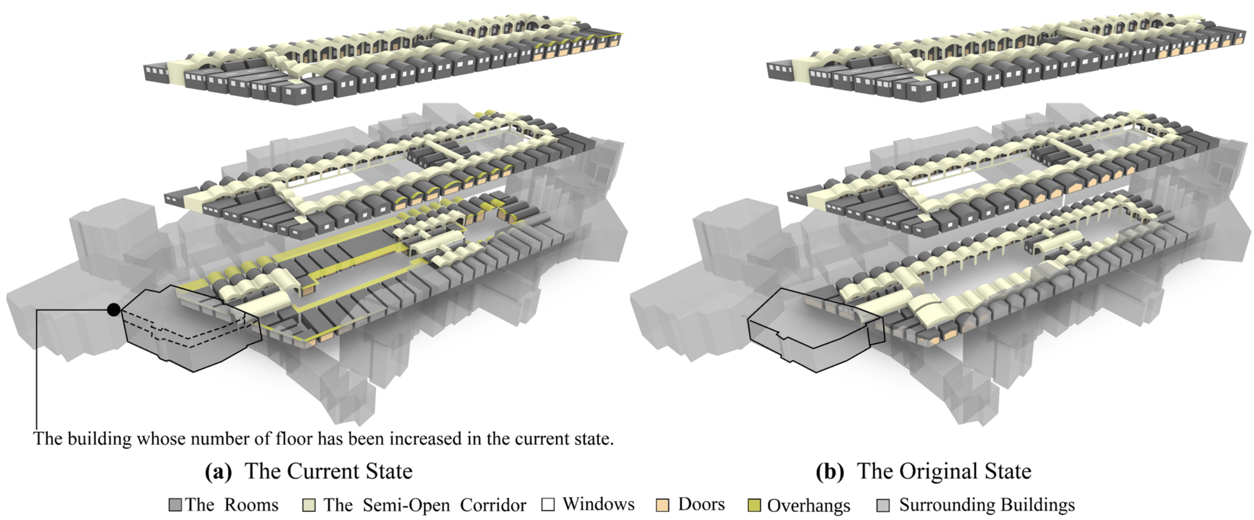

Fig. 9 Exploded perspective of the modeling of Buyuk Yeni Khan (**a**) the current state and (**b**) the original state

Table 1 Modelling details

No	Changes	Current state modelling	Original state modelling
1	The surrounding building at North was increased (3 m higher)	Included	Not included
2	The semi-open spaces (arcades/*revak*) were transformed to the rooms in the ground floor level	Transformed rooms have been included	Semi-open spaces included
3	The vaults in some of the rooms were covered and ceilings were transformed to flat surfaces (mainly in ground floor level)	Flat ceilings observed in the accessible rooms have been included. Others have been left as vaulted ceiling	Vaulted ceiling included
4	Arches at the shop facades were transformed to rectangular frames (by coverings)	Rectangular shop facades have been used in the model	Arches have been included to the model
5	Overhangs were added to the interior and exterior parts of the ground floor level	Included	Not included
6	Additional closed rooms can be seen in courtyards	Included	Not included

Manufacturing businesses, which were once densely located in the khans area, have now begun to be replaced by wholesale and retail businesses [60]. In particular, craftsmanship as manufacturing businesses in the region is covered within the scope of intangible cultural heritage [61]. While manufacturing businesses in khans decrease and wholesale and retailing come to the fore, spaces of the khans also transforming. This transformation also changes daylighting needs. However, in the original state of the khan buildings, there were ateliers (such as spaces for silver and copper handicrafts) where daylighting was important. Today, ateliers are still exist mostly on the upper floors of the khans. Although Buyuk Yeni Khan has lost its importance in the last decade, it is still considered one of the most important centers of silver craftsmanship in Istanbul [62]. In addition to being a necessity in these spaces, daylight also creates the visual characteristics of the spaces. The architectural design of the khan is shaped to receive light from both the facade and the courtyard.

3D scanning and modelling

The scanning of the interior side of the khan was done with 3D Lidar scanning technology (Fig. 4). An iPhone 13 Pro Max device was used for this process. 3D Lidar is a remote sensing scanning method that measures distances by illuminating a target with laser light. Scans made with 3D Lidar technology generate accurate measurements. With the help of the precise measurements of the scanned building, the 3D model created for daylighting analysis also features accurate dimensions. As a result, realistic daylighting simulations results can be found. The scanning has been done part by part. For the scan of the interior rooms, reference rooms from different sides were selected for each floor (because every room was

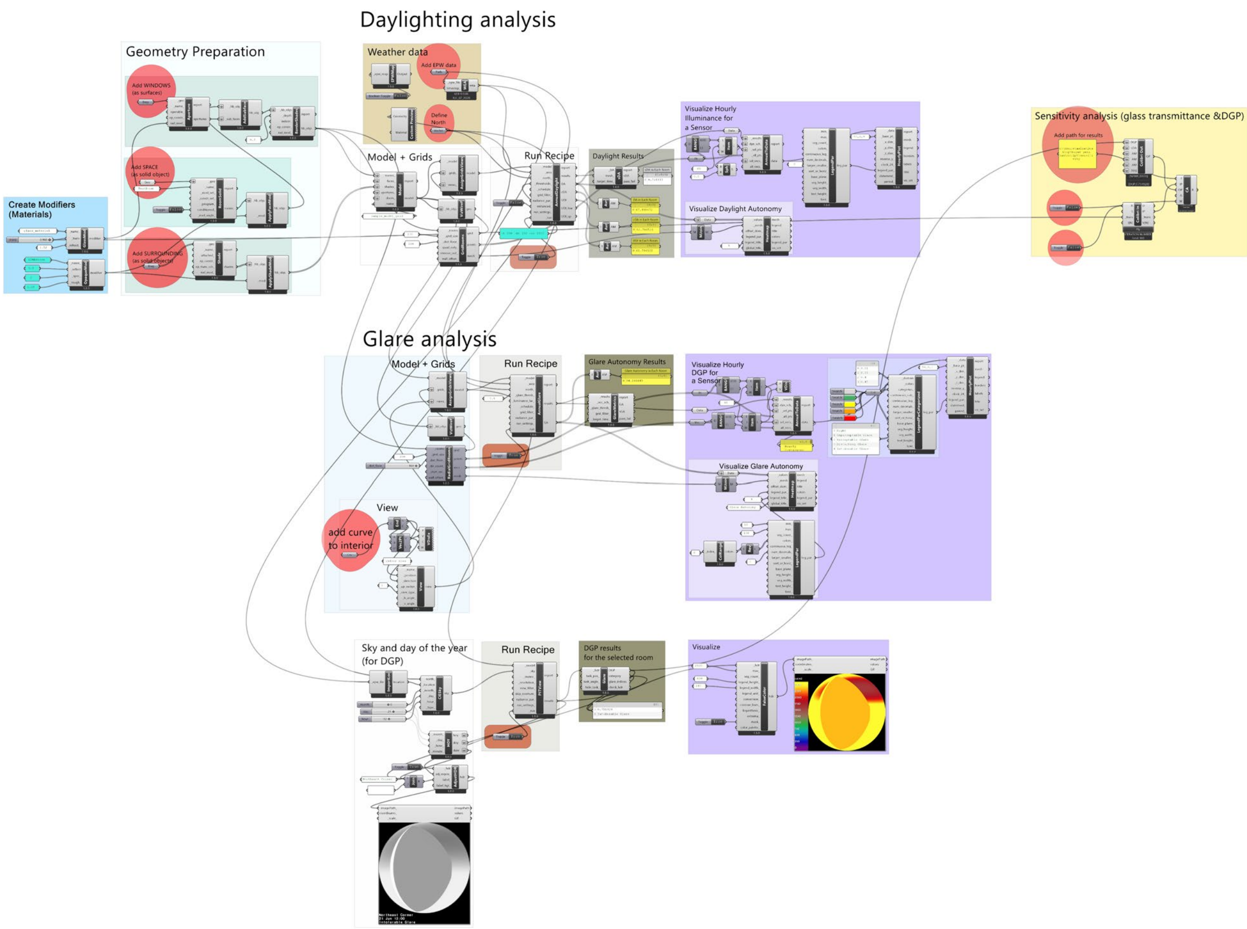

Fig. 10 Daylighting analysis script

not open). After completing the scanning of the parts, the scans were combined and saved as an fbx file. Photos of the site were used for the details of the exterior side. Since the model was computationally intense, the mesh model was simplified. Then, the file was transferred to Rhinoceros 3D modeling programme. The created mesh model from 3D scan has been used as a layout for the creation of a 3D model in Rhinoceros. The plan in Pervititch's map [64] was used as a layout in the 3D model creation process in Rhinoceros (Fig. 3). Güran's drawing of the North façade of Buyuk Yeni Khan was also used for the creation of the North façade (Fig. 5). The form-based changes have been reflected in the current and original state modelling of the khan.

The current state of the khan and the drawing of the khan in Pervititch map [64] were compared. As mentioned by Sabancioglu [66], it has been known that Pervititch maps have been drawn between 1922–1945 by Jacques Pervititch. According to the comparison, the boundaries of the khan have not been changed. The outer boundaries of the surrounding buildings have not been changed. However, it has been obtained from the in-situ site analysis that the surrounding building on the Northern side has an additional floor, which is approximately 3 m in height (Fig. 6). This surrounding building was originally constructed with stone and brick material. But, the additional floor, which has been marked with red color in Fig. 6, has different material and it is obviously not part of the original design.

The historical photos [67–69] were examined and compared with the current state. As it can be seen in Fig. 7, no change was observed in the window openings on the North façade of the first and second floors of the khan, nor in the window openings on the east and west façades. In the courtyard of the khan, no change was observed in the window openings and semi-open space (arcades) on the first and second floors. However, it has been determined that there are various changes on the ground floor of the khan (Fig. 7). Changes on the ground floor are reflected in Fig. 7.

The semi-open spaces (arcades) were transformed to rooms on the ground floor level. Therefore, the size of

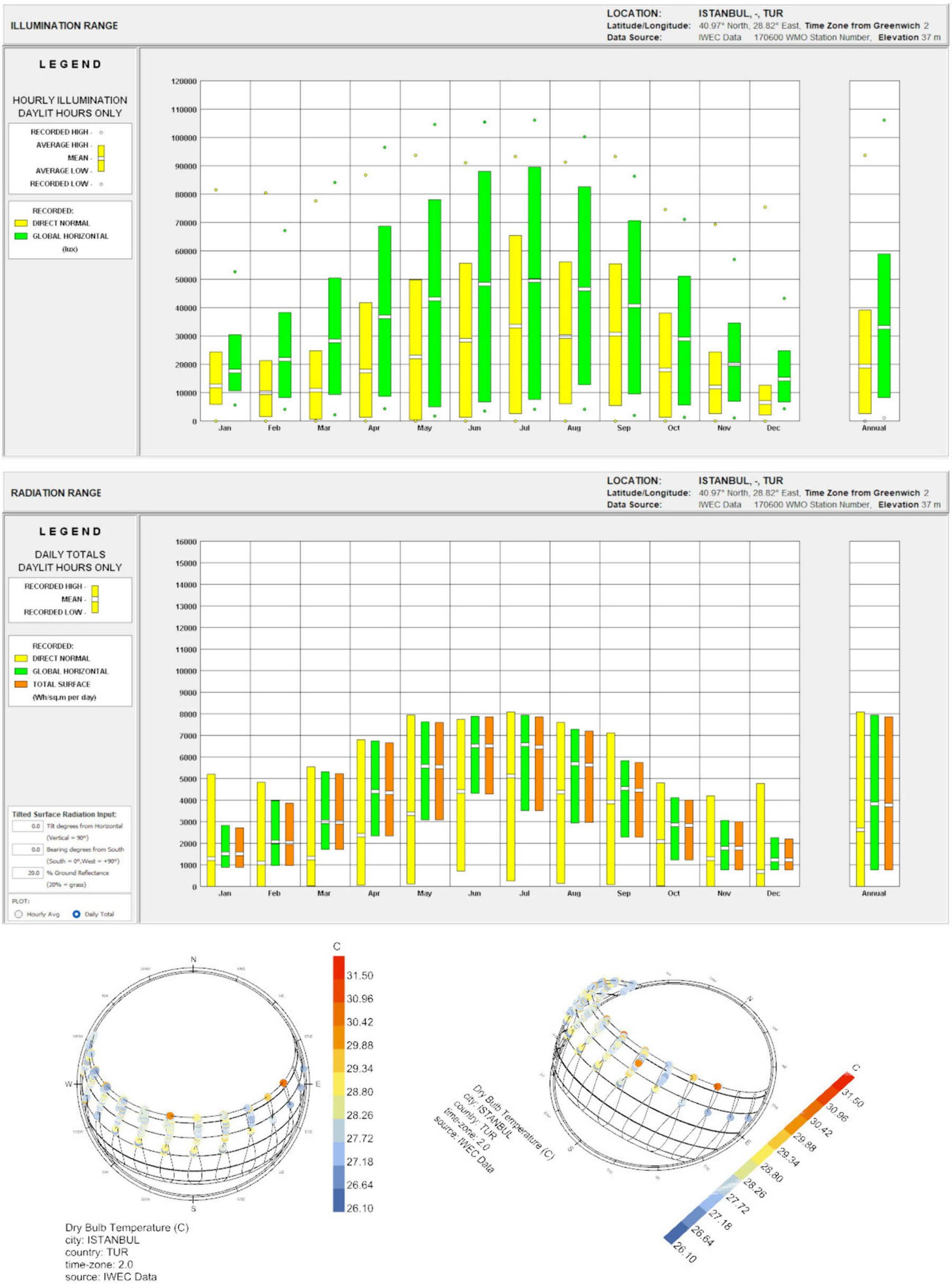

Fig. 11 The illumination and radiation ranges of the location

Table 2 Daylighting simulation presets

Parameter	Value
The surrounding buildings	The surrounding buildings are included
The weather file	Istanbul epw file
The height of the sensors	1 m
The threshold for DA	500 lx
The threshold for DGP	0.4
Occupancy	All year (between 8 a.m. to 5 p.m.) weekdays
Grid density	1 m
Sensor heights	1 m
Sky model for daylighting simulation	Tregenza
Sky model for point-in-time glare simulation	CIE standard sky
Materials	**Material properties**
Opaque materials (for wall, ceiling and floor)	Limestone (reflectance: 0.5, absolute specular reflectance: 0, roughness: 0.05)
Glass material (for windows)	Single glass (transmittance: 0.9, refraction: 1.52)

the rooms at the ground floor level has been dramatically changed. These closed semi-open areas have been covered with glass. Therefore, the typology of the room facades in the courtyard has been changed. The rooms are originally covered by vaults (Fig. 8). Vaults are also shown in the plan drawing of the Buyuk Yeni Khan in Gulenaz's book [47]. However, some of the vaults are not visible in the current state of the khan, and the ceilings of the rooms look flat. In each courtyard, there is one additional closed room (tea room), which is not a part of the original design. Accordingly, 3D models have been created (Fig. 9, Table 1).

Daylighting simulations

Figure 10 shows the used daylight analysis script, which has been adopted from Ladybug Tools tutorials [35] and the studies of Agirbas [70, 71] and Roudsari and Pak [72]. For the daylighting analysis simulation, the surrounding buildings, walls, windows, and floors have been defined. The weather file of Istanbul (by epw format) has been imported to the script. The illumination and radiation ranges of the location have been shown in Fig. 11. Figure 9 demonstrates the closed rooms with walls, windows and doors, semi-open spaces, and surrounding buildings in the 3D model. The semi-open area and the building parts rather than the analysed room were defined as the surrounding context, since it has an impact on the daylighting of the rooms. The model was oriented to the North.

In this study, the visual character of Buyuk Yeni Khan is defined as intangible heritage and the principle of preservation of this visual character is adopted. It is known that Buyuk Yeni Khan in its original state included mostly metalworking ateliers. Although not as much as before, it still maintains this feature today. According to EN 12464–1:2011 (The Indoor Lighting Standard), the minimum illumination value for handicrafts related to metal processing varies between 300–750 lx and illuminance requirement for "offices and writing" is 500 lx. It is envisaged that not very fine metal processing work was carried out in this khan. Therefore, in this study, the threshold for DA was set at 500 lx. Taking into account the various workshop equipment, the height of the sensors in the analysis grid was set to 1 m from the ground. Various sensor heights for daylighting analysis may be preferable for different building functions. For example Noraini [73] used 1.5 m high sensors for performing museum daylighting analysis, Balocco and Volante [74] used various luxmeter heights for different spaces (such as 0.72 m for working surfaces) of a library transformed from a historical church for performing daylighting analysis. The occupancy of the spaces has been set to all year (between 9 a.m. to 5 p.m.) (Table 2).

In this study, the material properties are kept constant in the daylighting analyzes for the current state and original state of Buyuk Yeni Khan. The material properties of the original state of the khan is preserved as accurately as possible. Limestone is used for wall, ceiling and flooring material, and single glass material for windows. Reflectance value for limestone is determined as 0.5 [75]. Transmittance value of single glass is adopted from Gündoğdu and Kunduraci's [76] study. Thus, solely the effect of the change in the architectural form of the khan building and its surrounding built environment on daylighting can be measured. It should also be noted that in the current state of the khan, it is not possible to identify

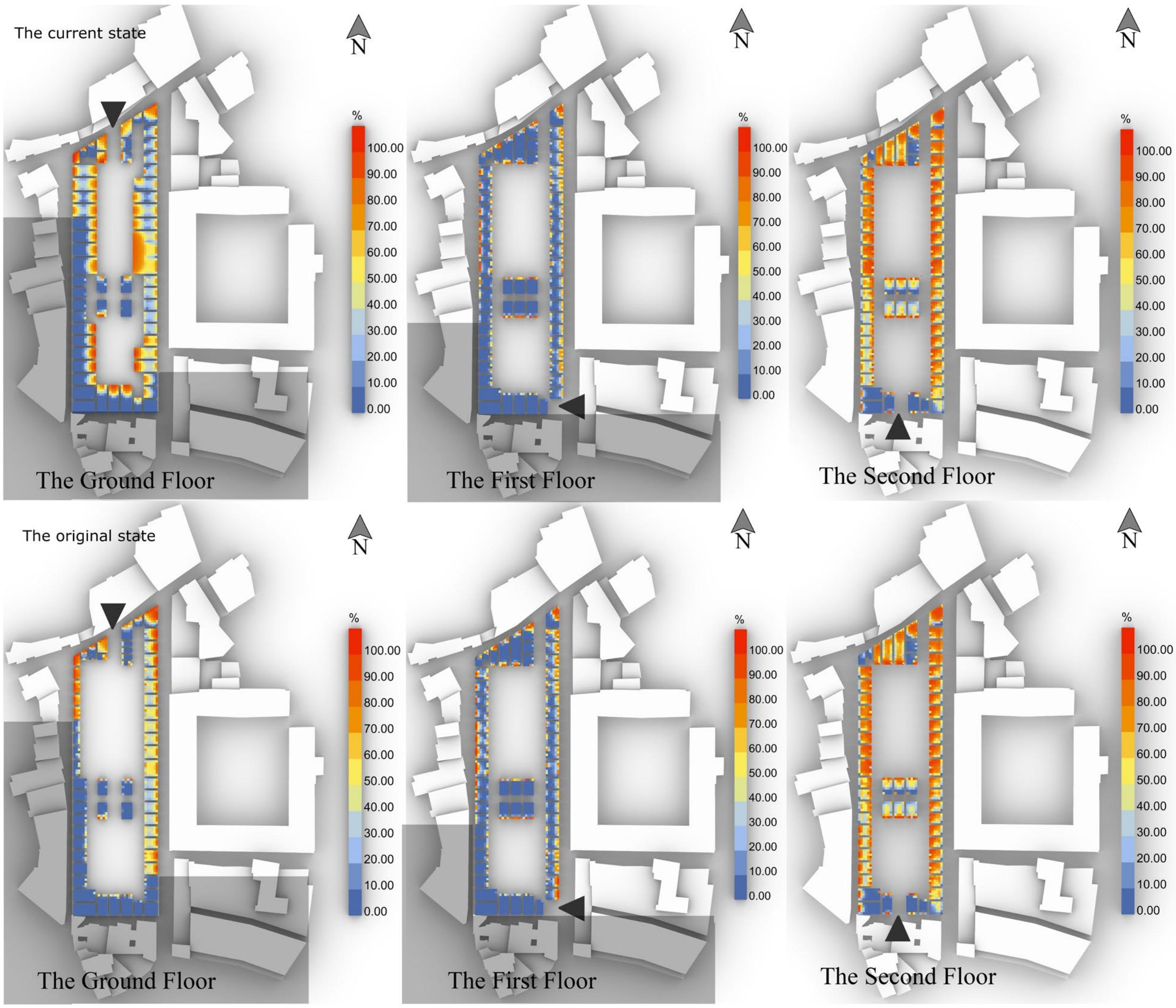

Fig. 12 Results of the annual DA daylighting analysis for the current state and the original state

the materials in all its rooms, as many rooms are private property and may be closed.

Results

Daylighting analysis results for the current state of Buyuk Yeni Khan

The results of annual DA daylight analysis for the current state of Buyuk Yeni Khan can be found in Fig. 12. The DA, cDA, UDI and sDA results have been calculated for each room. The rooms have been grouped as the rooms at the North side, the rooms at the South side, the rooms at the West side, the rooms at the East side and the rooms at the Transition area (the rooms at the courtyard). Figure 13 demonstrates the schematic grouping of the rooms. Accordingly, Table 3 shows daylighting value of the related group.

On the ground floor, the DA result is 45.04% for the rooms at North side; 22.46% for the rooms at the South side; 24.00% for the room at the West side; 41.16% for the rooms at the East side and 10.56% for the rooms at the Transition area (Table 3). On the first floor, the DA result is 16.80% for the rooms on the North side; 2.39% for the rooms at the South side; 11.95% for the room at the West side; 22.15% for the rooms at the East side and 9.71% for the rooms at the Transition area. The DA results of the second-floor level are higher than the ground floor level and the first-floor level. On the second floor, the DA result is 51.35% for the rooms at North side; 12.14% for the rooms at the South side; 50.02% for the room at the West side; 62.02% for the rooms at the East side and 38.46% for the rooms at the Transition area. Since the rooms at the Transition area have roof window openings, the DA result values are more than the rooms at

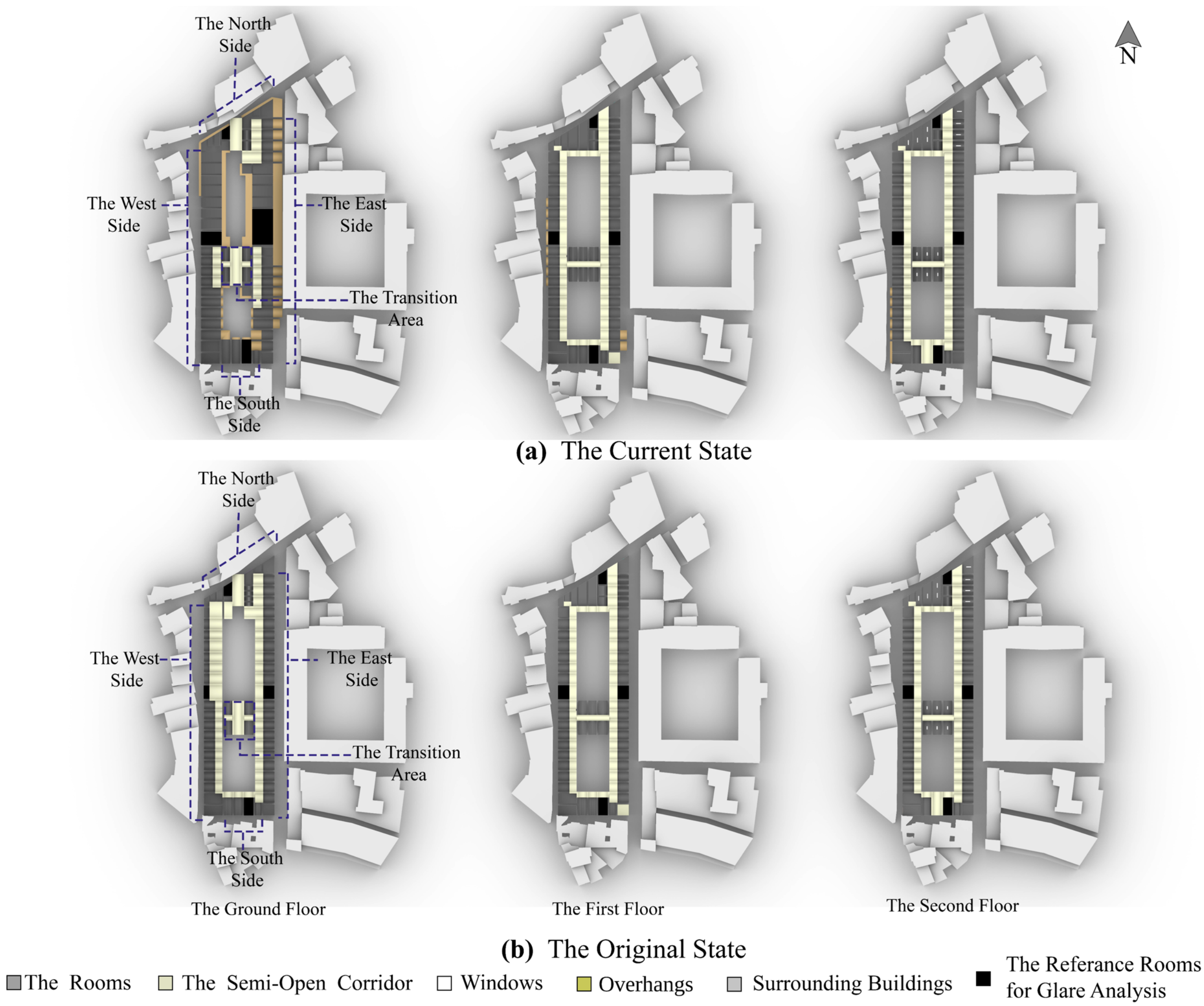

Fig. 13 Schematic demonstration of grouping the rooms

the Transition area in the first-floor level. The results for cDA, UDI, sDA and season based daylighting simulations are consistent with these findings (Tables 3, 4).

Glare analysis have been conducted for selected rooms from the each side. The simulations have been done for the longest day of the year (21 June, Summer) and the shortest day of the year (21 December, Winter). 12 a.m. has been selected for the time period. At the end of the simulations it has been found that DGP values do not show a great difference (Table 5).

Daylighting analysis results for the original state of the Buyuk Yeni Khan

The results of annual daylight analysis for the original state of Buyuk Yeni Khan can be found in Fig. 12. As it has been done for the current state of the khan, the DA, cDA, UDI and sDA results have been calculated for each room. The rooms have been grouped as the rooms at the North side, the rooms at the South side, the rooms at the West side, the rooms at the East side and the rooms at the Transition area (the rooms at the courtyard). Accordingly, Table 6 shows daylighting value of the related group.

On the ground floor, the DA result is 42.38% for the rooms at the North side; 4.09% for the rooms at the South side; 12.98% for the room at the West side; 40.90% for the rooms at the East side and 8.36% for the rooms at the Transition area. On the first floor, the DA result is 18.08% for the rooms at the North side; 2.50% for the rooms at the South side; 15.60% for the room at the West side; 25.00% for the rooms at the East side and 9.76% for the rooms at the Transition area. On the second floor, the DA result is 50.21% for the rooms at the North side; 11.85% for the rooms at the South side; 54.06% for the

Table 3 Daylighting analysis results of the current state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DA_{500} (%)	cDA (%)	$UDI_{100\text{-}2000}$ (%)	$sDA_{500,\ 50\%}$ (%)
Ground floor	The rooms at the North side	45.04	68.48	77.65	0.50
	The rooms at the East side	41.16	67.16	80.81	0.35
	The rooms at the South side	22.46	45.12	60.55	0.23
	The rooms at the West side	24.00	45.64	59.18	0.23
	The rooms at the Transition area	10.56	35.17	51.69	0.09
First floor	The rooms at the North side	16.80	40.11	57.23	0.18
	The rooms at the East side	22.15	57.45	78.38	0.20
	The rooms at the South side	2.39	20.27	31.45	0
	The rooms at the West side	11.95	36.84	55.73	0.10
	The rooms at the Transition area	9.71	30.35	48.43	0.10
Second floor	The rooms at the North side	51.35	74.80	76.21	0.57
	The rooms at the East side	62.02	83.25	80.63	0.69
	The rooms at the South side	12.14	36.66	57.86	0.10
	The rooms at the West side	50.02	71.26	72.99	0.53
	The rooms at the Transition area	38.46	69.29	81.60	0.30

Table 4 Season based daylighting analysis results of the current state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DA_{500} (%)		cDA (%)		$UDI_{100\text{-}2000}$ (%)		$sDA_{500,\ 50\%}$ (%)	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Ground floor	North	32.81	29.80	52.96	49.83	62.49	60.05	0.32	0.23
	East	32.19	28.58	53.60	50.13	65.19	62.68	0.19	0.13
	South	17.47	16.10	36.00	33.82	48.50	45.76	0.15	0.12
	West	18.93	16.98	36.47	34.03	47.38	44.81	0.14	0.11
	Transition	8.18	7.37	27.91	25.75	40.90	38.09	0.05	0.04
First floor	North	13.49	12.55	32.65	30.67	46.49	42.30	0.13	0.12
	East	17.79	16.24	45.31	42.46	62.54	59.55	0.08	0.05
	South	1.98	1.64	16.16	14.76	25.42	23.10	0	0
	West	9.84	8.90	29.71	27.63	44.04	41.17	0.07	0.05
	Transition	7.45	7.12	23.97	22.40	38.25	34.82	0.08	0.07
Second floor	North	40.58	38.04	60.89	58.34	63.55	61.97	0.42	0.38
	East	50.98	48.10	68.41	65.86	65.65	65.04	0.60	0.54
	South	9.41	8.77	29.53	27.84	46.56	43.44	0.09	0.08
	West	41.05	38.36	58.32	55.91	59.11	58.00	0.43	0.40
	Transition	29.53	27.57	55.21	52.50	66.46	64.30	0.12	0.12

room at the West side; 62.03% for the rooms at the East side and 38.45% for the rooms at the Transition area. The results for cDA, UDI, sDA and season based daylighting simulations are consistent with these findings (Tables 6, 7).

Glare analysis have been conducted for selected rooms from the each side. The simulations have been done for the longest day of the year (21 June, Summer) and the shortest day of the year (21 December, Winter). 12 a.m. has been selected for the time period. At the end of the simulations it has been found that DGP values values do not show a great difference (Table 8).

Discussion

According to the comparison of the current state of the khan with the original state, it seems that the daylighting values of the rooms at the ground floor level have been changed. The sizes of the rooms and the window ratios of their interior and exterior facades (together with the enlargement) on the South side, West side and East side have been dramatically changed. Since these rooms have

Table 5 Glare analysis results of the selected rooms of the current state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DGP* 21 June—12.00 a.m The longest day of a year	DGP* 21 December—12.00 a.m The shortest day of a year
Ground floor	The reference room at the North side	0.28	0.21
	The reference room at the East side	0.23	0.20
	The reference room at the South side	0.27	0.29
	The reference room at the West side	0.20	0.15
First floor	The reference room at the North side	0.23	0.22
	The reference room at the East side	0.17	0.07
	The reference room at the South side	0.18	0.17
	The reference room at the West side	0.20	0.16
Second floor	The reference room at the North side	0.23	0.25
	The reference room at the East side	0.20	0.14
	The reference room at the South side	0.27	0.28
	The reference room at the West side	0.22	0.26

* Imperceptible (< 0.35), perceptible (0.35–0.40), disturbing (0.40–0.45), intolerable (> 0.45)

Table 6 Daylighting analysis results of the original state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DA_{500} (%)	cDA (%)	$UDI_{100\text{-}2000}$ (%)	$sDA_{500,\ 50\%}$ (%)
Ground floor	The rooms at the North side	42.38	63.88	67.54	0.45
	The rooms at the East side	40.90	65.17	75.94	0.32
	The rooms at the South side	4.09	23.77	37.57	0.03
	The rooms at the West side	12.98	32.03	45.94	0.13
	The rooms at the Transition area	8.36	33.23	53.14	0.05
First floor	The rooms at the North side	18.08	43.07	62.29	0.20
	The rooms at the East side	25.00	59.02	78.92	0.23
	The rooms at the South side	2.50	20.28	32.29	0.01
	The rooms at the West side	15.60	40.20	56.41	0.13
	The rooms at the Transition area	9.76	30.57	49.03	0.10
Second floor	The rooms at the North side	50.21	73.26	75.75	0.56
	The rooms at the East side	62.03	83.21	80.58	0.68
	The rooms at the South side	11.85	36.43	57.61	0.11
	The rooms at the West side	54.06	74.01	72.57	0.59
	The rooms at the Transition area	38.45	69.34	81.71	0.31

been enlarged in line with arcades towards the courtyard, and the window ratios of their facades have been enlarged, the daylight intake values in those spaces are higher than the original state of the khan. In the current state, despite the addition of many extra overhangs towards the exterior side and towards the courtyard, there is still an increase in daylighting values (Table 9).

On the first floor, the rooms at the North side, East side and West side have more daylight intake in the original state of the khan. This may be because of the change of the level heights of the surrounding buildings at North (Table 9). According to glare simulation results, the glare values at the selected rooms have not greatly changed (Tables 5, 8).

Criteria were determined to measure the sensitivity of the DGP results in the simulation. Accordingly, it was aimed to measure the sensitivity of the DGP value according to glass transmittance. June 21 at 12 a.m. for the selected room at the ground floor level at Western side (current state) was chosen for the sensitivity analysis.

Table 7 Season based daylighting analysis results of the original state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DA_{500} (%)		cDA (%)		$UDI_{100\text{-}2000}$ (%)		$sDA_{500,\ 50\%}$ (%)	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Ground floor	North	33.61	31.34	51.51	48.93	55.23	53.28	0.36	0.33
	East	32.06	28.57	51.97	48.65	61.30	58.92	0.16	0.14
	South	3.26	2.89	18.97	17.41	29.73	26.94	0	0
	West	10.19	9.32	25.55	23.79	36.35	33.81	0.09	0.08
	Transition	6.60	6.01	26.37	24.42	41.78	38.48	0.05	0.05
First floor	North	14.67	13.68	35.11	33.16	50.33	47.27	0.15	0.13
	East	27.21	24.90	53.00	49.92	64.86	62.45	0.21	0.17
	South	1.87	1.70	16.17	14.89	25.64	23.14	0	0
	West	12.47	11.33	32.23	30.05	44.92	42.27	0.09	0
	Transition	7.50	7.21	24.03	22.61	38.43	35.01	0.08	0.07
Second floor	North	40.77	38.25	60.88	58.40	63.57	62.06	0.44	0.38
	East	51.18	47.91	68.46	65.77	65.61	65.02	0.60	0.55
	South	9.50	8.83	29.41	27.90	46.26	43.40	0.09	0.08
	West	44.03	41.28	60.48	58.08	58.87	58.12	0.49	0.46
	Transition	29.65	27.77	55.19	52.79	66.33	64.39	0.14	0.12

Table 8 Glare analysis results of the selected rooms of the original state of Buyuk Yeni Khan

Name of the floor	The location of the rooms	DGP* 21 June—12.00 a.m. The longest day of a year	DGP* 21 December—12.00 a.m. The shortest day of a year
Ground floor	The reference room at the North side	0.28	0.21
	The reference room at the East side	0.24	0.19
	The reference room at the South side	0.24	0.21
	The reference room at the West side	0.20	0.19
First floor	The reference room at the North side	0.18	0.22
	The reference room at the East side	0.17	0.07
	The reference room at the South side	0.24	0.17
	The reference room at the West side	0.22	0.20
Second floor	The reference room at the North side	0.23	0.25
	The reference room at the East side	0.20	0.14
	The reference room at the South side	0.27	0.27
	The reference room at the West side	0.22	0.26

* Imperceptible (< 0.35), perceptible (0.35–0.40), disturbing (0.40–0.45), intolerable (> 0.45)

Glass transmittance value range was set between 0 and 1. According to this result, it was seen that glass transmittance affected the glare results to a certain extent (Table 10).

Individual simulation of the selected Eastern side room at the ground floor level was also carried out. Accordingly, an increase was observed in DA, cDA and sDA values in the current state of the khan (Table 11, Figs. 14, 15). In addition to the horizontal sensor grids, vertical sensor grids were also used for the daylighting simulation. Vertical sensor grids were located at 2 m behind the exterior facade. According to the results, a decrease was observed in DA, cDA, sDA and UDI values in the current state of the khan (Table 11, Fig. 14). Similar results were obtained in the seasonal simulations (Table 11). The change of the facade from arch to rectangular frame and the additional overhangs mainly caused these results.

Table 9 A comparison of the daylighting simulation results of the current state of Buyuk Yeni Khan with the daylighting simulation results of the original state of it

	O DA_{500} (%)	C DA_{500} (%)	O cDA (%)	C cDA (%)	O $UDI_{100\text{-}2000}$ (%)	C $UDI_{100\text{-}2000}$ (%)	O $sDA_{500,\,50\%}$ (%)	C $sDA_{500,\,50\%}$ (%)
Ground floor								
North	42.38	45.04	63.88	68.48	67.54	77.65	0.45	0.50
East	40.90	41.16	65.17	67.16	75.94	80.81	0.32	0.35
South	4.09	22.46	23.77	45.12	37.57	60.55	0.03	0.23
West	12.98	24.00	32.03	45.64	45.94	59.18	0.13	0.23
Transition	8.36	10.56	33.23	35.17	53.14	51.69	0.05	0.09
First floor								
North	18.08	16.80	43.07	40.11	62.29	57.23	0.20	0.18
East	25.00	22.15	59.02	57.45	78.92	78.38	0.23	0.20
South	2.50	2.39	20.28	20.27	32.29	31.45	0.01	0.00
West	15.60	11.95	40.20	36.84	56.41	55.73	0.13	0.10
Transition	9.76	9.71	30.57	30.35	49.03	48.43	0.10	0.10
Second floor								
North	50.21	51.35	73.26	74.80	75.75	76.21	0.56	0.57
East	62.03	62.02	83.21	83.25	80.58	80.63	0.68	0.69
South	11.85	12.14	36.43	36.66	57.61	57.86	0.11	0.10
West	54.06	50.02	74.01	71.26	72.57	72.99	0.59	0.53
Transition	38.45	38.46	69.34	69.29	81.71	81.60	0.31	0.30

O Original state, *C* current state

Table 10 Sensitivity analysis according to glass transmittance value

Glass transmittance	DGP
0.16	0.01
0.24	0.03
0.28	0.05
0.32	0.08
0.37	0.11
0.44	0.14
0.47	0.15
0.51	0.16
0.58	0.17
0.62	0.18
0.69	0.18
0.75	0.19
0.79	0.19
0.83	0.19
0.90	0.20

The study has limitations as listed below:

- Measurements were obtained through simulation rather than in-situ methods. Conducting in-situ measurements could yield more accurate results. Also, as Saraiva et al. [77] did, comparing simulation results with in-situ measurements could lead to determine the accuracy of the simulation method.
- The materials for both the current and original states were kept constant. More accurate simulation results for the current state could be achieved by specifying materials separately for each room. It was found that different materials were used in the current state (e.g., corridors covered with ceramics). Therefore, in a daylighting comparison based on material changes, the impact on daylighting would likely be more significant.
- Since the Lidar scanning has 5 m limitation, the model was created part by part. Other 3D scanning techniques that capable of long distance scanning would create more precise models.
- This study was conducted on the basis of observable changes in the building. There may be other various changes (e.g. material properties of the rooms, physical changes in the rooms) in the building.
- Other metrics such as Characteristic Daylight Illuminance (CDI) [20] can also be used for daylighting performance measurements.

As Ünlü [1] mentioned, the urban environment may change over time. This change may affect special

Table 11 A comparison of the daylighting simulation results of the current state of the selected room (the Eastern side room at the ground floor level) with the daylighting simulation results of the original state of it

	Annual		Summer (June–August)		Winter (January–March)	
	Original state	Current state	Original state	Current state	Original state	Current state
Horizontal sensor grid (1 m above ground level)						
DA_{500} (%)	46.46	52.73	36.83	41.56	32.82	37.69
cDA (%)	71.47	74.61	56.55	58.88	53.43	55.91
$UDI_{100\text{-}2000}$ (%)	84.20	83.02	66.13	65.28	64.32	63.96
$sDA_{500,\ 50\%}$ (%)	0.28	0.52	0.11	0.30	0.11	0.23
Vertical sensor grid (2 m from the exterior façade)						
DA_{500} (%)	50.29	38.97	39.66	30.77	35.40	26.70
cDA (%)	73.99	67.11	58.28	53.01	55.19	49.63
$UDI_{100\text{-}2000}$ (%)	88.20	85.83	69.24	67.04	67.17	64.79
$sDA_{500,\ 50\%}$ (%)	0.52	0.12	0	0	0	0

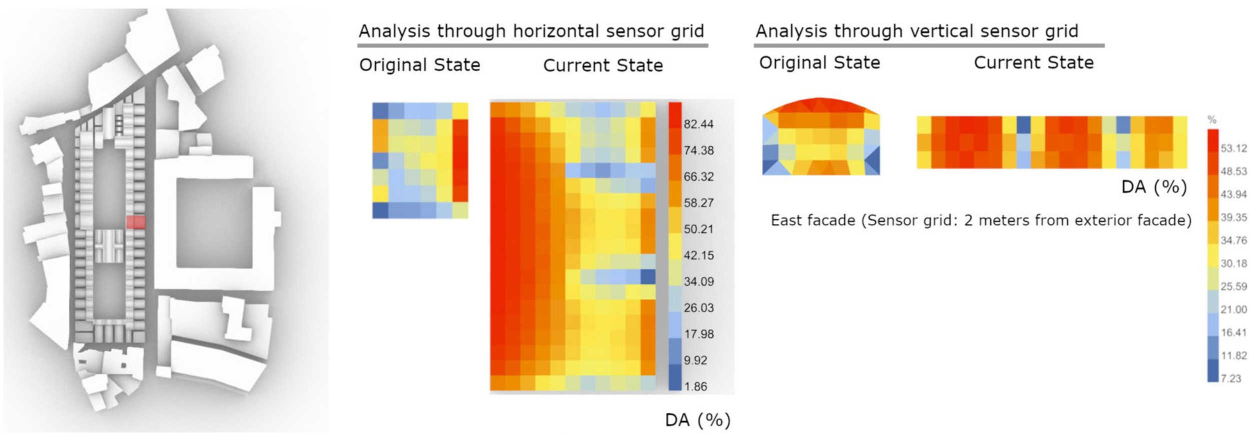

Fig. 14 The daylighting simulation results of the selected Eastern side room at the ground floor level with the use of horizontal and vertical sensor grids

buildings that are considered as one of the constant elements of urban morphology [78]. In the study of Carlos and Martins [22], it was observed that the daylight condition of a historical building changed due to the new urban environment. Similarly, present study found that alterations in surrounding building height affected the daylighting of the khan building. Additionally, Giorgi and Matracchi [4] state that various modifications might be made to historical buildings. Present study revealed that this situation also affected the daylighting of the historical khan building.

Buyuk Yeni Khan is located in-between "Sultanahmet Urban Archaeological Component Area of World Heritage Site" and "Suleymaniye Mosque and its Associated Component Area of World Heritage Site" [79], both are in Historical Peninsula of Istanbul. In line with the conservation strategic plans, Istanbul Historical Areas Directorate prepared "Istanbul Historic Peninsula Site Management Plan Boundaries" [80] which includes khans area. To preserve intangible daylighting feature of the khans, related actions can also be added to the strategic plan. For example, restrictions can be imposed to maintain the height of the surrounding buildings. Additionally, legal constraints should be established to prevent additions to the rooms of the khan and to ensure the preservation of their original form. Furthermore, maintaining the IEQ of the khan would ensure a healthy working environment for the craftsmen.

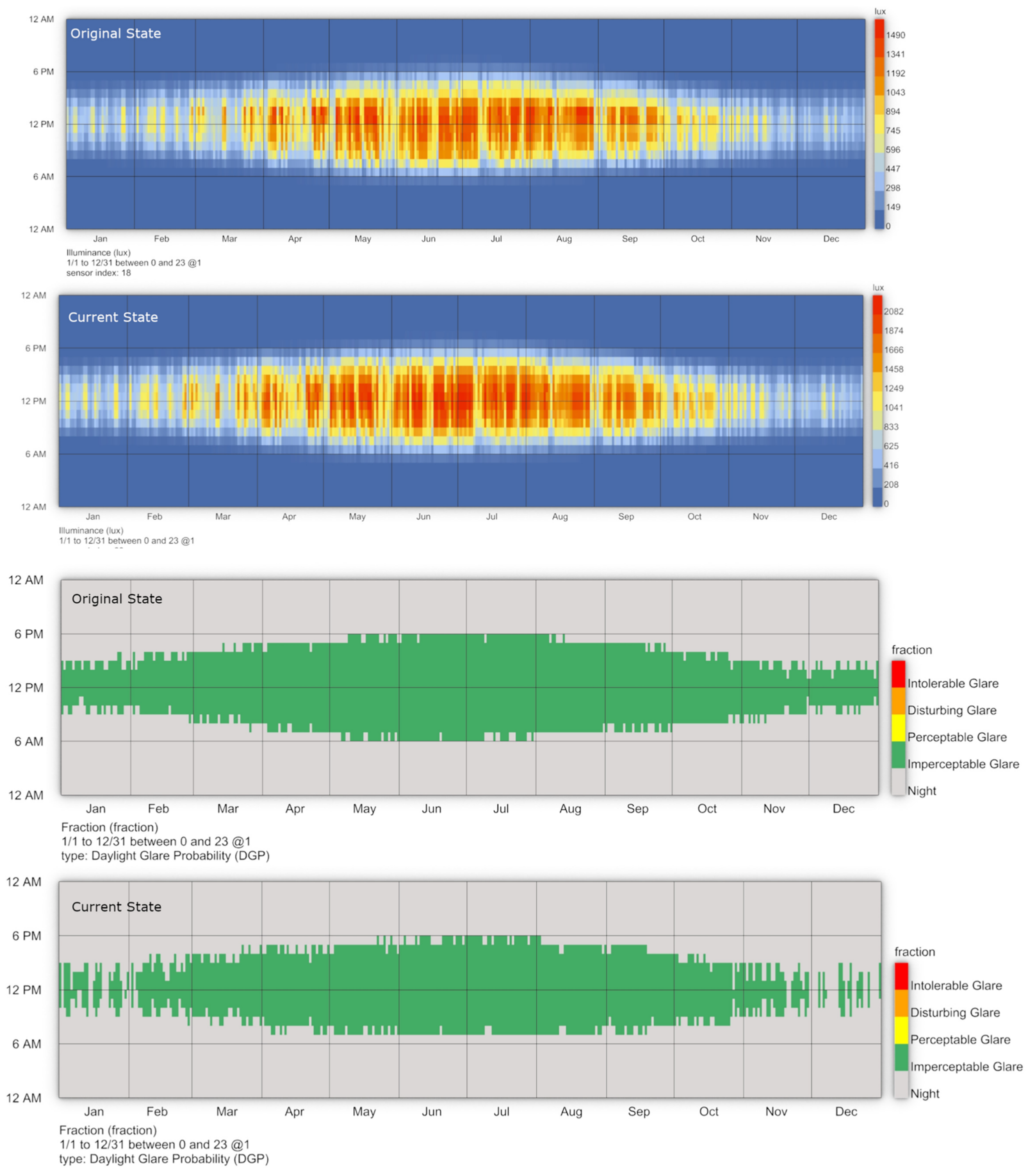

Fig. 15 A graphical comparison of the DA and DGP simulation results of the current state of the selected room (the Eastern side room at the ground floor level) with the daylighting and glare simulation results of the original state of it

Conclusion

The daylighting of Buyuk Yeni Khan, which is still in active use, has been examined within the scope of this study. The study revealed that modifications in the historical khan building and the changes in the built environment caused the daylighting performance changes, which affects the visual characteristics of the khan and visual comfort of the occupants. The North, South, East and West rooms of the khan were grouped and the daylighting levels were examined for their original and current states. The data and evaluations obtained in this study can be used in the possible restoration or renovation works of the khan.

The contributions of the study have been listed below.

- The current state of the khan has been scanned with 3D Lidar technology. The 3D model of the current state of the khan and the 3D model of the original state of the khan have been prepared according to the 3D scanning data and observations.
- At the end of the 3D laser scanning and observations, it was determined that the rooms on the ground floor

in the current state of the khan were enlarged in line with the arcades, the vaults of ceilings were covered, additional rooms were added to the courtyard, façade typology of the khan has been changed and overhangs to the exterior and interior facades have been added.
- After performing daylighting simulations of the current state of the khan and the original state of the khan, it has been found that the changes in the khan building caused the daylighting value changes.

Historical khan buildings, which have their own unique architecture, are special buildings in terms of both their function and their atmosphere. Daylighting analysis studies on historical khan buildings have not been conducted before. This paper is the first study in which the atmosphere of historical khan buildings created by daylighting is emphasized and expressed in numerical data. Although Buyuk Yeni Khan is determined as a case study within the scope of this study, similar daylighting analyzes, and comparisons between the results can be made for many other existing khan buildings. Also, in-situ daylighting analysis can be made in order to validate the simulation results.

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Author contributions
AA: conceptualization, methodology, investigation, formal analysis, writing, editing, supervision, visualization; AOD: investigation, in situ analysis, experimental tests and analysis, writing, visualization.

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Declarations

Competing interests
The authors declare no competing interests.

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