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Optimizing Sustainable Tourism Routes through GIS to Enhance Tourist Length of Stay in Bukhara

Mukhriddin Kilichov[1], Frantisek Olsavsky[2], Ruslan Baiburiev[3], Nilufarbegim Khayrullaeva[4], Lóránt Dénes Dávid[5]

[1] *Department of Tourism and Hotel Management, Bukhara State University, 11, 200114, M.Ikbol street, Bukhara city, Uzbekistan; email: m.h.qilichov@buxdu.uz ; mkilichov.bsu@gmail.com; ORCID ID: 0000-0001-5107-4876*
[2] *Comenius University Bratislava, Faculty of Management, Department of Marketing, Odbojárov 10, 820 05 Bratislava 25, Slovak Republic, e-mail: olsavsky1@uniba.sk; ORCID ID: 0000-0001-7225-8359*
[3] *Recreational Geography and Tourism Department, Al-Farabi Kazakh National University, Kazakstan, Ruslan.Baiburiev@kaznu.edu.kz, ORCID ID: 0000-0001-8752-9190*
[4] *Department of Tourism and Hotel Management, Bukhara State University, 11, 200114, M.Ikbol street, Bukhara city, Uzbekistan; email: n.n.xayrullayeva@buxdu.uz; ORCID ID: 0000-0003-4161-6496*
[5] *Department of Tourism and Hospitality, Faculty of Economics and Business, John von Neumann University, Kecskemét, Hungary; email: david.lorant.denes@nje.hu*
[5] *Department of Tourism and Hospitality, Institute of Rural Development and Sustainable Economy, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, Hungary; email: david.lorant.denes@uni-mate.hu*
[5] *Savaria Department of Business Economics, Savaria University Center, Faculty of Social Sciences, Eötvös Loránd University; Szombathely, Hungary; email: david.lorant.denes@sek.elte.hu*
[5] *Department of Tourism and Hospitality, Kautz Gyula Faculty of Business and Economics, Széchenyi István University, HU-9026 Győr, Hungary; e-mail: dr.david.lorant@gmail.com, ORCID ID: 0000-0001-7880-9860*

*__Corresponding Author:__ mkilichov.bsu@gmail.com

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ABSTRACT

Study analyzes the potential for extending the length of stay of tourists by optimizing tourism routes based on architectural heritage sites located in the Historic Center of Bukhara. Using GIS technologies (QGIS 3.40), the spatial distribution of 92 cultural heritage sites was examined and analyses such as K-means clustering, Shortest Path, and Service Area were conducted. For each cluster, optimal one-day walking routes were developed and the total walking distance and duration were calculated. Moreover, based on real statistical data from 2020-2024, the number of foreign tourist arrivals to Bukhara from 2025 to 2030 was forecasted using the ARIMA(0,0,0) model. The model results indicate that over 21.8 million tourists are expected to visit during this period. If the average length of stay is extended from 3 to 4 days, a further USD 83.33 in revenue may be generated per tourist. This could result in approximately USD 1.694 billion in additional income by 2030. The findings of the study serve as a foundation for strategic planning in developing sustainable cultural tourism in Bukhara, optimizing service infrastructure, efficiently managing tourist flows and ensuring the rational use of heritage sites. Outcomes also bring into line with the broader frameworks of circular tourism and the transition toward a circular society, where heritage resources are reused, community benefits are maximized, sustainability principles are reinforced.

Keywords: heritage sites; GIS; tourist stay duration; circular tourism; sustainable tourism

INTRODUCTION

Geographically, Bukhara province is located in the southwestern part of Uzbekistan (Figure 1), approximately 230 meters above sea level (Figure 1). Bukhara has evolved over millennia as one of the oldest and most historic cities (Juraturgunov et al., 2023). The city was a major center of trade, science and culture for centuries along the Silk Road (Kilichov, 2023). Bukhara stands out for its distinctive architectural monuments, ancient madrasahs, mosques and caravanserais and has preserved its historical grandeur. In 1993, the Historic Center of Bukhara was inscribed on the UNESCO World Heritage List (UNESCO, 2025). This contributed to Bukhara's recognition within Uzbekistan and globally as a significant historical and cultural center. This status created opportunities for the protection of Bukhara's historical monuments and architectural structures and for attracting international programs aimed at their preservation and restoration. Moreover, this process led to an increase in the influx of tourists to the city.

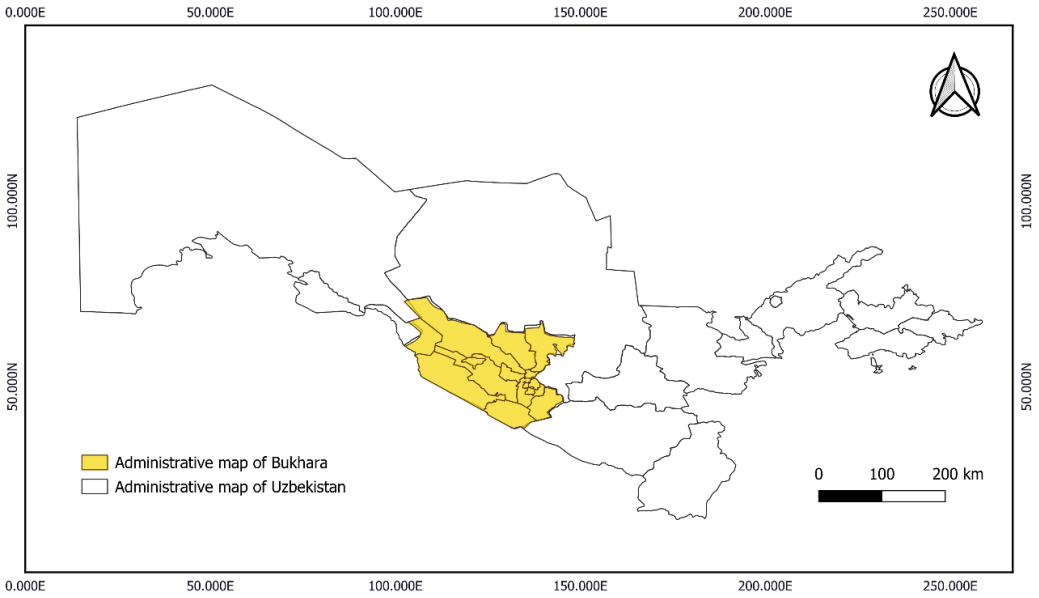

Figure 1. Administrative map of Uzbekistan

Cultural heritage is an integral part of human history and its preservation and widespread promotion play a crucial role in societal development (Song et al., 2020). The employment of cultural heritage in the tourism sector holds social, economic and academic significance, as it enhances a region's touristic appeal and creates opportunities for transmitting cultural assets to future generations (Boc et al., 2022).

According to the research conducted by the World Tourism Organization (UN Tourism) and UNESCO, cultural tourism is considered one of the fastest-growing sectors in global tourism (UNWTO, 2021). Cultural tourism accounts for over 40% of global tourism revenue (UNESCO, 2025) and tourism employment (Zhang & Guo, 2022) with an annual growth rate of around 10–15%. Therefore, cultural heritage is regarded as a key factor in tourism infrastructure and its development plays a significant role in enhancing a country's tourism potential. Contributes to the broader circular economy by linking cultural assets with economic reinvestment (Rodríguez et al., 2020).

Cultural heritage directly influences the following key aspects of tourism:

- Increasing the touristic appeal of a region - historical monuments, architectural landmarks and cultural traditions are considered major attractions for both international and domestic tourists (Herrero & Gómez, 2017; Kadyrbekova, 2024).
- Generating economic benefits - cultural heritage sites serve as tourist centers and have a positive impact on the local economy (Campoy et al., 2017; Adie & Falk, 2021). According to UNESCO, the economic benefit associated with cultural tourism generates 25–30% more income compared to other forms of tourism (UNESCO, 2021). Rudan (2023) stated it reinforces the cycle of reinvestment characteristic of the circular economy.
- Ensuring social and cultural sustainability - through cultural tourism, the historical and cultural values of the local population are preserved. Their active participation in the tourism process is encouraged (Huong et al., 2020; Boulhila et al., 2022), contributing to the emergence of a circular society.
- Contributing to heritage preservation and protection - revenues generated from tourist flows are allocated to the restoration and safeguarding of historical sites (García et al., 2017).

In the tourism sector, the effective management of tourist flows and extending their length of stay is critical. Regardless of the attractiveness of cultural tourism sites, if the duration of tourists' stay within the city is short, tourism's economic efficiency, sustainable development, including pathways toward circular tourism remain limited. Therefore, increasing the length of tourists' stay in the city and organizing the visitation process systematically are considered pressing issues.

The main issues related to tourist flows and length of stay include the following: a) short-term visits by tourists; b) absence of optimized itineraries; c) insufficient development of tourism infrastructure; d) seasonality of tourism and climatic conditions (Gössling et al., 2018; Boto et al., 2019; Estil et al., 2023).

According to empirical studies conducted by scholars, the mean duration of stay for tourists engaged in travel to culturally significant urban centers is estimated to be approximately 5.85 days (Gemar et al., 2022). However, in the case of Uzbekistan's major historical cities, including Bukhara, this figure remains notably lower. Based on data from the official portal of the Government of the Republic of Uzbekistan, the average stay in Bukhara is around 3 days (CRA, 2025), with some instances limited to just 1–2 days. This restricts tourists from fully visiting all significant historical sites, resulting in the loss of potential revenue for the tourism sector.

Considering the above-mentioned challenges, this study's primary objective is to systematically examine the cultural heritage sites in the Historic Center of Bukhara and develop optimal tourist itineraries for visitors. The utilization of GIS technologies has been defined as a key strategic approach for improving tourism infrastructure and increasing the length of stay for tourists. This approach also reinforces the transition toward a circular society through sustainable and equitable resource use.

LITERATURE REVIEW

Cultural heritage sites constitute a vital component of the global tourism industry that considered one of the primary factors for shaping of tourist routes. According to UNESCO (2021) approximately 40% of tourists worldwide travel with the purpose of visiting historical sites. This highpoints the considerable role heritage sites in travel and tourism sphere (Panzera et al., 2021). It is noted that cultural tourism has a positive impact on regional economies with historic cities (Cerisola & Panzera, 2022; Muštra et al., 2023), particularly heritage cities, such as Bukhara being regarded as strategically important in the context of international tourism. In this context, as a heritage destination Bukhara has a pivotal role in developing models of circular tourism, where the use of heritage assets generates continuous cultural, social and economic benefits (Buckley et al., 2019).

Tourism is recognized one of the key drivers in the global promotion, preservation, conservation of cultural heritage (Bujdosó et al., 2015; Lamoria et al., 2024). Historical cities can generate proceeds for the local economy, stimulate the development of traditional crafts and service industries by means of tourism (Yang & Wall, 2021). Therefore, it is essential to modernize tourism infrastructure, enhance service quality to ensure the economic sustainability of cultural heritage.

Inclusion of cultural heritage sites in the UNESCO list serves to elevate their international visibility and contributes to generating additional revenue streams through tourism (Panzera et al., 2021). Gao et al. (2022) and Zhang et al. (2023) have identified positive effects with World Heritage Sites in China increased tourist inflows by 6.7-10% that contributing significantly to the development of regions' tourism. The designation of Historic Center of Bukhara in the UNESCO World Heritage List in 1993 enhanced its competitiveness in the international tourism market and positively influenced the development of its infrastructure. Furthermore, Mariani and Guizzardi (2020) emphasizes that UNESCO designation is not solely associated with increased tourist flows, along with entails a responsibility for heritage preservation. This aspect is central to circular tourism, which seeks to balance increased tourist activity with long-term resource conservation (Bosone & Nocca, 2022).

Studies examining the relationship between tourism flows and UNESCO heritage indicate that: 1st ensuring a balance between the exploitation of heritage sites; 2nd the potential damage to them along with their protection is critical (Orts-Cardador, 2024). These considerations require managing the flow of tourists and developing tourism infrastructure in the Historic Center of Bukhara.

The management of tourist flows is considered most essential factor for conserving cultural heritage sites for ensuring their long-term sustainability. It has been noted that overtourism may result in damage to the heritage sites and effect the circular society concept negatively which relies on equitable use of shared cultural resources. In particular, the lack of effective controling mechanisms for regulating tourist flows in historic centers often leads to excessive pressure on municipal infrastructure (García et al., 2017; Zubiaga et al., 2019). It has been observed that the overdevelopment of cultural tourism can lead to the deterioration of historical sites (Frey & Briviba, 2021; Frey & Briviba, 2021a; Khater et al., 2024). This issue has become particularly evident in historic cities such as Venice, Barcelona and Dubrovnik. Therefore, regulating tourist flows and developing optimal routes is essential to avoid similar encounters in the Historic Center of Bukhara. It is essential to move toward a more balanced circular tourism model.

One of the most effective methods for managing tourist flows is the scientific optimization of tourism routes through the application of Geographic Information Systems (GIS) (Pei et al., 2022; Seidualin et al., 2024). GIS are recognized as a key mechanism for modeling tourist flows and planning tourism infrastructure. This enables the optimization of tourist movement within Bukhara and the regulation of pressure on cultural heritage sites. The use of GIS also supports the planning of sustainable and inclusive systems consistent with circular society principles, where cultural, social, and environmental aspects are interconnected.

GIS have widely been used as an important tool in the planning and management of tourism in recent years. Through GIS technologies precise and visual analyses can be conducted regarding the location of tourist sites, their accessibility, infrastructure networks and service areas. This facilitates the efficient use of resources, the regulation of tourist flows and the optimization of tourism itineraries (Piras et al., 2024; Seidualin et al., 2024).

GIS has been broadly recognized for its effectiveness in mapping cultural heritage sites, tourist resources, identifying spatial relationships and designing optimal travel routes. It is considered particularly valuable for planning service infrastructure around tourist centers. Particularly, in historic cities where managing accessibility, visitor flow and ease of movement is crucial. Through spatial analysis, including the calculation of distances between sites and the assessment of accessibility, the tourist experience can be enhanced significantly. This GIS-based approach is viewed as a key tool for supporting sustainable and circular tourism development while reducing pressure on urban infrastructure simultaneously (Xing, 2024).

Simultaneously, the analysis of existing literature dedicated on cultural heritage sites in the Historic Center of Bukhara focuses on historical-geographical descriptions, general tourism potential or the historical significance of individual monuments. In most studies, there is a lack of systematic and spatial (geographic) analyses related to tourist movement, infrastructure and routing. In particular, there is a notable absence of studies that offer tourism management based on scientific approaches using GIS technologies, such as clustering, route optimization, service area identification and spatial decision-making systems. This demonstrates the necessity of studying the topic through a novel scientific lens. Especially, for a compact city with rich historical heritage like Bukhara, it is essential to regulate tourist flows through spatial analysis, plan service zones and create convenient itineraries for visitors. Therefore, within the framework of this study, an integrated approach was developed and tested in practice, based on GIS tools including K-means clustering, Shortest Path, Service Area, and Quick Time Map analyses, ultimately contributing to the conceptualization of circular tourism within a circular society framework.

METHODOLOGY

Data Collection and Analysis

The data collection process aimed at identifying architectural heritage sites and evaluating their potential utilization in tourism commenced in 2021. Throughout the research, data were compiled based on official registers of tourist sites, academic sources and field surveys conducted on-site. As a result of these analyses, the tourism potential of the identified sites was assessed, and their spatial analysis was carried out using the QGIS 3.40 application.

The primary focus of the study was directed toward the Historic Center of Bukhara. This area encompasses more than 260 historical and cultural heritage sites, all of which are classified in accordance with the National register of tangible cultural heritage immovable properties, approved by the Resolution No. 846 of the Cabinet of Ministers of the Republic of Uzbekistan, dated October 4, 2019. Special attention was devoted to identifying the sites currently integrated into tourism activities and this data was compiled systematically based on field investigations.

According to the fieldwork findings, a total of 92 architectural heritage sites located within the Historic Center of Bukhara that were integrated into tourism operations were selected. The precise coordinates of these sites were determined and entered into the QGIS database. The methodological approach adopted in this stage included the following components (Figure 2.):

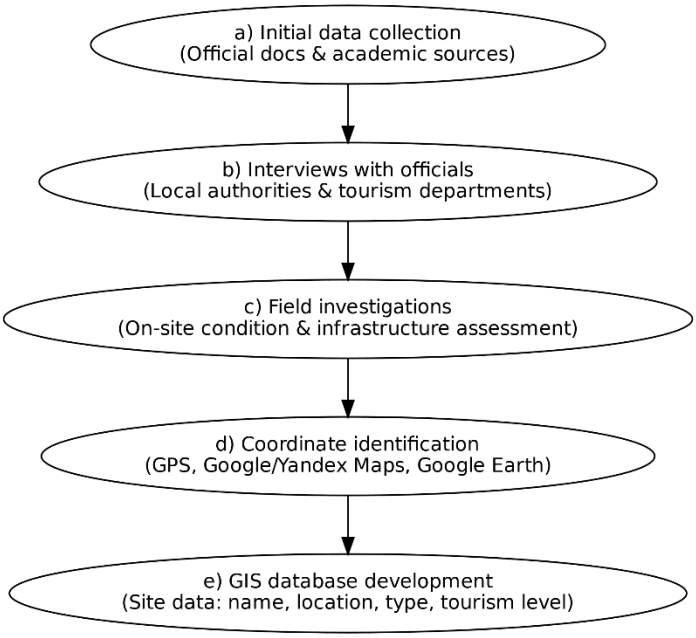

Figure 2. Stages of Cultural Heritage Site Analysis

K-means Clustering Method

The K-means clustering algorithm was employed for the purpose of grouping tourist sites during the progression of the study. K-means is a machine learning algorithm used to partition data into a specified number of k clusters. Allowing for the classification of objects based on their spatial characteristics (Oh & Min, 2022). This approach enabled the systematic identification of the geographical distribution of tourist sites and facilitated the development of efficient travel routes, supporting the creation of balanced and reusable itineraries consistent with the concept of circular tourism.

The K-means clustering algorithm is implemented in several stages. Initially, k random initial cluster centroids are selected from the dataset. Then, each object is assigned to the nearest cluster centroid based on distance calculations. The cluster centroids are subsequently recalculated as new mean values. A process carried out using the following formula:

$$C_j = \frac{1}{|s_j|} \sum_{x \in s_j} x_i$$

here, $C_j - j$ - new centroid of the cluster, $s_j - j$ -set of objects belonging to the cluster, x_i – coordinates of the objects assigned to the cluster. This iteration is repeated until each object is reassigned to its nearest centroid.

The 92 heritage sites were classified into four groups using the K-means algorithm. This method involved analyzing the number of clusters and the value k=4 was identified as the most appropriate.

Network Analysis and Shortest Path Identification (Shortest Path Analysis)

Network Analysis and Shortest Path Analysis (Point to Layer) methods were employed to identify optimal movement routes between heritage sites, determine the most convenient itineraries for tourists (Granja-Martins & Fernandez, 2024). These analyses enabled to reduce the travel time of visitors, facilitated more accessible visits to tourist sites, allowed for the efficient utilization of the urban road network, thereby reinforcing the efficiency-oriented principles of the circular economy within urban tourism infrastructure (Kabil et al., 2024).

The Shortest Path Analysis is an algorithm designed to identify the shortest possible route between two or more points and is applied to optimize tourism itineraries. This analysis was conducted in QGIS 3.40 using the Shortest Path (Point to Layer) tool. Within each cluster, the shortest routes between heritage sites were determined. In the initial phase of the analysis the tourist sites and starting points within each cluster were identified. Subsequently, the route calculations were refined in the GIS environment by specifying the length and connectivity of the road segments. During the route calculation process, the Dijkstra algorithm was applied to analyze the shortest path for each group and to determine the optimal travel routes. The Dijkstra algorithm is computed based on the following formula:

$$d(v) = min\{d(u) + w(u, v)\}$$

Here, $d(v)$ - node v shortest distance to reach the node, $d(u)$ - distance to the previous node, $w(u, v)$ - length of the path between nodes is calculated.

Utilization of the TravelTime Plugin and OpenStreetMap data

The TravelTime plugin was employed within the QGIS 3.40 platform to assess pedestrian mobility within the Historic Center. Through this analysis, 10-, 15- and 20-minute walking zones were identified, allowing for the evaluation of tourists' freedom for movement within the historical core. Based on OpenStreetMap (OSM) data, pedestrian-accessible routes in the historical center were delineated and travel time coverage areas were determined through isochrone mapping.

Forecasting Foreign Tourist Arrivals Based on the ARIMA Model

Time-series-based statistical modelling was conducted to demonstrate the potential for increasing the length of stay of tourists economically and forecast the number of foreign tourists visiting Bukhara up to 2030, with projections interpreted through the lens of the circular economy, emphasizing reinvestment of tourism income into local services and heritage preservation. For this purpose, the widely used and highly accurate ARIMA (AutoRegressive Integrated Moving Average) model was selected. This model accounts for stationarity, random fluctuations and internal dependencies in the time series that enabling reliable prediction of future values (Safarov et al., 2022; Turtureanu et al., 2022).

For the analysis, the number of foreign tourists visiting Bukhara during 2020-2024 was chosen as the primary data source. This selection was made because the variable growth from 2016 to 2019 and the sharp decline during the 2020 pandemic created significant discrepancies within the time series. These factors compromise the time series' stationarity and negatively affect the model outcomes' reliability. Therefore, the post-pandemic period of 2020-2024 was deemed appropriate for forecasting.

Mathematically, the ARIMA model is expressed by the following formula:

$$Y_t = \mu + \varepsilon_t$$

here,

Y_t – the number of foreign tourists at time t;

μ – constant (stable) mean value;

ε_t – random error, i.e., white noise with constant variance and zero mean.

RESULTS AND DISCUSSION

Spatial Profiling and Temporal Characterization of Cultural Heritage Sites in Bukhara

According to the National register of tangible cultural heritage immovable properties, approved by Resolution No. 846 of the Cabinet of Ministers of the Republic of Uzbekistan dated October 4, 2019, a total of 829 heritage sites have been officially registered in Bukhara Region. Based on the data provided by the Cultural Heritage Department and the Bukhara Tourism Department, as well as the outcomes of field investigations, it was determined that 146 of these sites are currently utilized for tourism purposes.

The study analyzed the spatial distribution of these heritage sites. Within the city of Bukhara, 354 sites were identified, of which 262 are located in the Historic Center of Bukhara. Of the 146 heritage sites actively used for tourism, 92 sites (63%) are situated within the boundaries of the UNESCO historical core, including its buffer zone.

As the primary focus of the study, these 92 cultural heritage sites located within the historic center and utilized for tourism were analyzed according to their original functional purpose (Table 1). The majority of the sites consist of madrasahs (29.3%), mosques (26.1%), and caravanserais (12.0%). These findings underscore the historical significance of Bukhara as a religious and commercial-industrial center.

The high proportion of madrasahs and mosques reflects the city's historical development as a center of religious education and worship. Meanwhile, the presence of caravanserais (12.0%) and trading complexes (4.3%) indicates Bukhara's historical prominence as a major commercial hub. In addition, other structures such as mausoleums (4.3%), historic gates (3.3%), minarets (3.3%), and passageways (2.2%) have played an important role in the architectural and cultural evolution of the city.

Table 1. Original functional purposes of architectural heritages utilized for tourism in Historic Center

Construction Purpose	Quantity	Percentage	Cumulative Percentage
Gate	3	3,3	3,3
Hammam	2	2,2	5,4
Statue	1	1,1	6,5
Houz (pool)	2	2,2	8,7
Caravanserai	11	12,0	20,7
Medical facility	1	1,1	21,7

Madrasa	27	29,3	51,1
Educational institution (school)	1	1,1	52,2
Mausoleum	4	4,3	56,5
Mosque	24	26,1	82,6
Square (public space)	1	1,1	83,7
Minaret	3	3,3	87,0
Passage (covered market or arcade)	2	2,2	89,1
Historical residential building	2	2,2	91,3
Fortress (Citadel)	1	1,1	92,4
Trade center (Commercial facility)	4	4,3	96,7
Theatre building	1	1,1	97,8
Khanakah (Sufi lodge)	1	1,1	98,9
Prison	1	1,1	100,0
Total	92	100,0	

Structures that reflect the social and cultural life of the city also hold significant importance. Facilities such as hammams (2.2%), hauz (pools) (2.2%) and traditional residential houses (2.2%) constituted an integral part of everyday life for the population of their respective eras. Establishments, such as hospitals (1.1%), schools (1.1%), theaters (1.1%), khanakahs (1.1%), and prisons (1.1%), indicate the advancement of Bukhara's medical, educational, and social infrastructures. The preservation and effective utilization of these sites for tourism contribute to the sustainable safeguarding of the city's cultural heritage and the development of the tourism sector, reflecting the principles of circular tourism, where heritage resources are reused and regenerated through responsible visitation (Rudan, 2023).

The majority of these heritage sites were constructed during the 16th to 19th centuries, which represents one of the most significant periods of cultural and economic flourishing in the city's history. Specifically, 22 sites (23.9%) date to the 16th century, 11 sites (12.0%) to the 17th century, 17 sites (18.5%) to the 18th century and 23 sites (25.0%) to the 19th century. These figures confirm Bukhara's development as a major scientific, religious and commercial center during that historical epoch.

Moreover, the oldest site in the city (Shahristan square) dates back to the 3rd century BCE (1.1%), demonstrating the deep historical roots of Bukhara. Sites from the 9th to 12th centuries (4.4%) reflect the early Islamic period and the city's role in a significant era of cultural renaissance. In contrast, the 13 heritage sites constructed in the 20th and 21st centuries (14.2%) represent efforts toward modern reconstruction and initiatives aimed at the preservation of cultural heritage (Table 2).

Table 2. Construction periods of architectural heritage sites utilized for tourism purposes

Construction Period	Quantity	Percentage	Cumulative Percentage
3rd century BCE	1	1,1	1,1
9th century	1	1,1	2,2
12th century	3	3,3	5,4
15th century	1	1,1	6,5
16th century	22	23,9	30,4
17th century	11	12,0	42,4
18th century	17	18,5	60,9
19th century	23	25,0	85,9
20th century	11	12,0	97,8
21st century	2	2,2	100,0
Total	92	100,0	

Based on interviews conducted with representatives of the Bukhara Tourism Department, the following data were analyzed. In 2024, a total of 5,755,525 tourists visited the city of Bukhara, of whom 1,745,200 were international tourists and 4,010,325 were domestic visitors (UZA, 2025). The majority of foreign tourists originated from CIS countries (965,924 individuals), followed by Europe (366,492), Asia (359,658), and the Americas (38,624). Revenue generated from services provided to foreign tourists amounted to USD 436.3 million, while domestic tourism accounted for income in total of 802.1 billion Uzbek soums.

Generally, the average length of stay among international tourists ranged primarily between 1 to 3 days, with each foreign visitor spending approximately USD 250 during their trip to Bukhara (calculated based on the ratio of total tourism service exports to the number of international visitors).

To this end, it is essential to develop optimal travel itineraries and tourism plans that respect tourists' time. Given the high concentration of cultural heritage sites in Bukhara, it is necessary to conduct a systematic analysis of existing travel routes and to design the most convenient and efficient itineraries for tourists. Optimal routes will facilitate easier navigation across the city, enrich the tourist experience and create opportunities to extend the length of stay (Granja & Fernandez, 2024).

Cluster-Based Spatial Optimization of Tourist Routes

Based on these considerations, a four-day program was developed for the 92 architectural heritage sites located within the Historic Center of Bukhara. The heritage sites were classified into four groups using the K-means clustering algorithm. This approach, which takes into account the spatial distribution (density of tourist sites), enables the development of optimal travel routes for visitors and the formulation of strategies aimed at increasing the average length of stay (Figure 3).

The first cluster (western area) includes sites located near the historic city walls. Primarily consists of defensive structures and places of religious pilgrimage and worship. The second cluster (eastern area) comprises madrasahs, mausoleums and architectural monuments which are of significant importance for cultural and religious tourism. The third cluster covers the most prominent landmarks of the city that serves as Bukhara's main tourist hub. This area receives the highest volume of tourist visits and is well-equipped with accommodations, infrastructure facilities. The fourth cluster is located in the northern part of the Historic Center that includes lesser-studied cultural heritage sites.

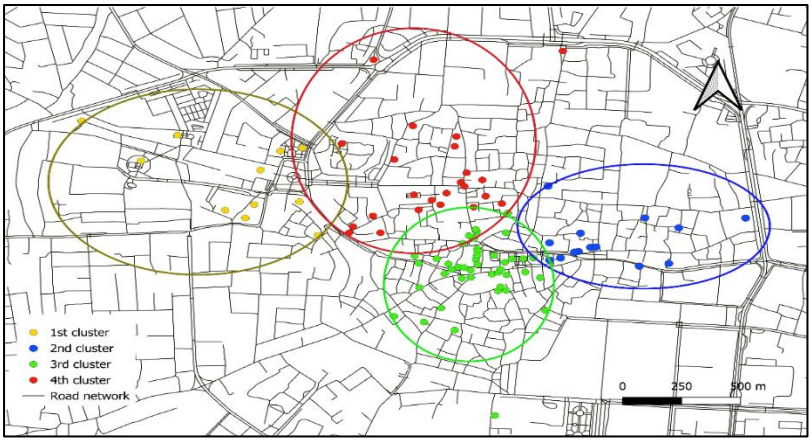

Figure 3. Spatial Outcomes of K-means Clustering within the Historic Center of Bukhara

The clustering results facilitate the development of optimal four-day itineraries for tourists and support the diversification of tourism services. While the central clusters are suitable for short-term visits, the creation of dedicated routes to peripheral clusters enhances the overall tourist experience. The outcomes of the K-means clustering provide a vital scientific foundation for making strategic decisions aimed at improving tourism infrastructure and effectively managing tourism services in the city of Bukhara.

Based on the four clusters identified in Figure 3, the Network Analysis tool was applied to design the most efficient and convenient routes for tourists. In the subsequent stage, the Shortest Path Analysis (Point to Layer) method was utilized to evaluate the feasibility of visiting all sites within each cluster and to determine the optimal navigation paths for tourists. Through this analysis, a starting point was identified within each cluster and the shortest distances were calculated accordingly.

A key aspect emphasized in the analysis is that pedestrian mobility is considered the most appropriate mode of movement within the Historic Center of Bukhara. This form of transportation aligns with the principles of sustainable tourism development, as it produces no CO_2 emissions (Weston & Mota, 2012). Furthermore, due to the narrow streets and the presence of protected cultural heritage sites, many areas within the area are inaccessible to motor vehicles. Consequently, the road networks used in the analysis were limited to routes designated for pedestrian movement only.

Analysis of Cluster 1

Cluster 1 holds significant importance in terms of its tourist landmarks and supporting infrastructure. This cluster comprises a total of 11 historical monuments (Figure 4). During the analysis, the Shortest Path Analysis (Point to Layer) method was employed to generate an optimal route that connects these heritage sites.

According to the results, the total length of the travel route within Cluster 1 is about 2,800 meters. Considering the average walking speed for tourists (3–5 km/h), this distance can be covered in approximately one hour. This enables visitors to thoroughly explore the area within a relatively short period.

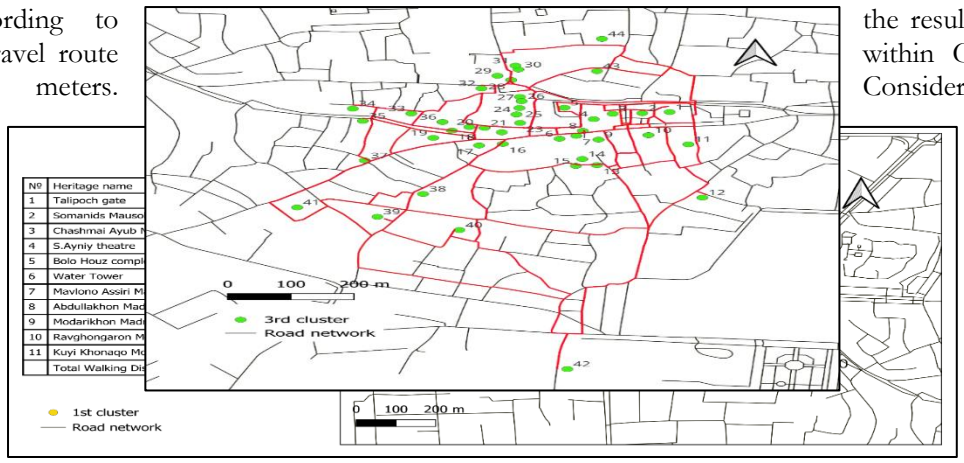

Figure 4: Cluster 1 – Western historical zone: route of madrasahs and places of worship

Analysis of Cluster 2

Cluster 2 comprises culturally and religiously significant heritage sites that are highly relevant for tourists. This cluster includes 14 cultural heritage sites (Figure 5). An optimal route connecting these sites was developed using the Shortest Path Analysis (Point to Layer) method.

The starting point of the route was designated as the Khoja Kurbon Madrasah. Within this cluster, the Ibrohim Okhund and Domla Hasan madrasahs are located adjacent to each other. It is also evident that while some heritage sites are located in close proximity to one another and appear sequentially on the route, the last two destinations are situated at a greater distance, with the segment between them alone amounting to 1,264 meters.

The total length of the travel route across Cluster 2 amounts to 3,335 meters. Considering the average pedestrian walking speed, this distance can be covered in approximately 1 hour and 15 minutes. While navigating this cluster, tourists have the opportunity to visit cultural, religious, and historical significant heritage sites.

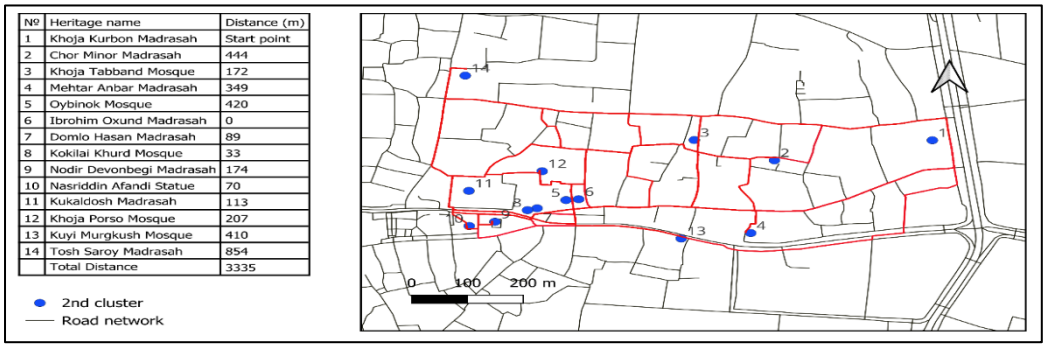

Figure 5. Cluster 2 – Eastern Historical Zone: route of religious and cultural heritage sites

Similar to Cluster 1, visitors can explore 14 points of interest within a relatively short time frame, with the added benefit of gaining detailed information about each individual site.

Analysis of Cluster 3

Cluster 3 encompasses some of the city's most prominent and frequently visited areas (Figure 6). This cluster includes a diverse range of cultural, religious, and commercial heritage sites, such as the Nodir Devonbegi complex, the Magoki Attori Mosque, and the Gaukushon Ensemble, among others - amounting to a total of 44 historical monuments (Table 3). The sites within this cluster are characterized by high geographic density and close proximity to one another, offering visitors the opportunity to explore Bukhara's most significant historical and commercial centers.

The shortest route within this cluster has a total length of 6,026 meters. Taking into account the average pedestrian walking speed, this distance can be covered in approximately 2 hours.

Figure 6. Cluster 3 – Central Bukhara: route of commercial and architectural heritage sites

Table 3. Cluster 3 Heritage sites and their positions along the route

№	Heritage name	Distance (m)
1	Nodir Devonbegi Hauz (Pool)	Starting point
2	Nodir Devonbegi Khanakah	42
3	Badriddin Caravanserai	50
4	1st Passage Building	117
5	Magoki Attori Mosque	62
6	Nugay Caravanserai	149
7	Toki Sarrafon Mosque	28
8	Toki Sarrafon	21
9	Sarrafon Hammam	65
10	Sayfiddin Caravanserai	96
11	Kokilai Kalon Mosque	131
12	Eshoni Pir Madrasah	212
13	Jurabek Caravanserai	282
14	Rashid Caravanserai	22
15	Kori Izro Merchant House	10
16	Old School Building	272
17	Olimjon Caravanserai	57
18	Gaukushon Minaret	63
19	Gaukushon Madrasah	3
20	Gaukushon Hauz (Pool)	3
21	Abdurahmon A'lam Madrasah	3
22	2nd Passage Building	28
23	Siyogaron Mosque	26
24	Fatxullojon Caravanserai	57
25	Ayozjon Caravanserai	27
26	Ahmadjon Caravanserai	17
27	Mirzo Ulugbek Caravanserai	70
28	Toki Telpakfurushon	73
29	Kulita Caravanserai	12
30	Bozori Kord Hammam	15
31	Bozori Kord Mosque	19
32	Magoki Kurpa Mosque	102
33	Hotam Hindu	181
34	Rashid Madrasa	96
35	Pochchokul Khoja Mosque	12
36	Khoja Kalon Mosque	133
37	Chor Xarroz Mosque	262
38	Turki Jandi Mausoleum	153
39	Khusaini Madrasah	124
40	Ancient Residential Yard	218
41	Gozion Madrasa	401
42	Boboi Poraduz Mausoleum	932
43	Turkmen Madrasa	1248
44	Chuqur Madrasa	133
	Total Distance	6026

Analysis of Cluster 4

Cluster 4 (Figure 7) comprises the primary architectural monuments and religious landmarks situated within the central zone of the city. This cluster includes such significant heritage assets as the Rahmonkul Madrasah, Dustim-Chorgosi Mosque, Khoja Zayniddin Mosque, Mir Arab Madrasah, Kalon Minaret, Toki Zargaron Complex, the Ark Citadel, Hazrati Imam Gate and Samarkand Gate.

№	Heritage name	Distance (m)
1	Rahmonkul Madrasah	Starting point
2	Dustim-Chorgosi Mosque	28
3	Xoja Zayniddin Mosque	132
4	Domlo Tursunjon Madrasah	118
5	Siddiqiyon Mosque	263
6	Kalon Minaret	104
7	Amir Olimxon Madrasah	6
8	Mir Arab Madrasah	51
9	Kalon Mosque	118
10	Zargaron Mosque	280
11	Toki Zargaron Complex	40
12	Said Kamol Madrasah	96
13	Ulugbek Madrasah	195
14	Abdulazizxon Madrasah	68
15	Timi Abdullaxon	260
16	Mavlono Sharif Complex	112
17	Shahriston Square	546
18	Emergency Hospital	141
19	Prison (Zindon)	387
20	Mirzo Usmon Mosque	218
21	Ark Fortress	663
22	Hazrati Imom Gate	760
23	Samarkand Gate	916
	Total distance	5502

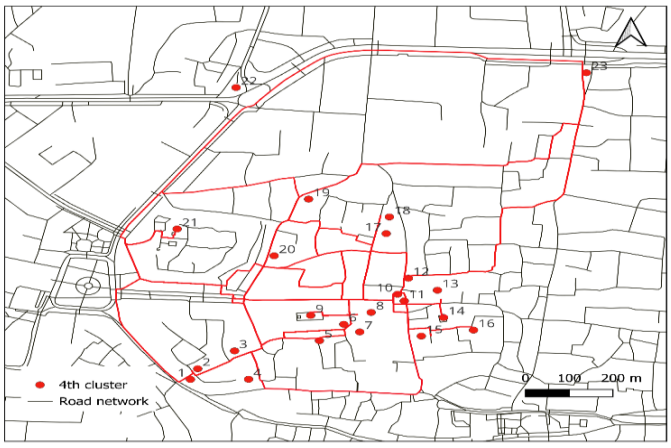

Figure 7. Cluster 4. Northern Historical Zone: route of religious and architectural complexes

The total length of the shortest route within Cluster 4 is 5,502 meters. Taking into account the average pedestrian walking speed, this distance can be traversed in approximately 1 hour and 50 minutes.

An advantage of this itineraries is that tourists can not only visit all the heritage sites but also efficiently allocate their time to acquire detailed information about each monument. During movement along this cluster, the majority of tourists' time is dedicated to exploring the sites and engaging with historical content, while only a minimal portion of time needs to be allocated to dining and auxiliary services. This model allows visitors to comprehensively experience the historical heritage and gain a meaningful tourism experience within a limited timeframe.

Infrastructure Optimization for Sustainable Heritage Tourism

Another critical aspect of the analysis involved delineating 300-meter service areas from each heritage site within the existing road network using the Network Analysis Service Area method (Figure 8). This approach was employed to enhance the effective promotion of each cluster and to facilitate improved service delivery for tourists. These service areas contribute to optimizing visitor mobility, refining the wayfinding system and providing structured informational support across clusters, thereby improving the overall spatial experience of tourists within the historic center.

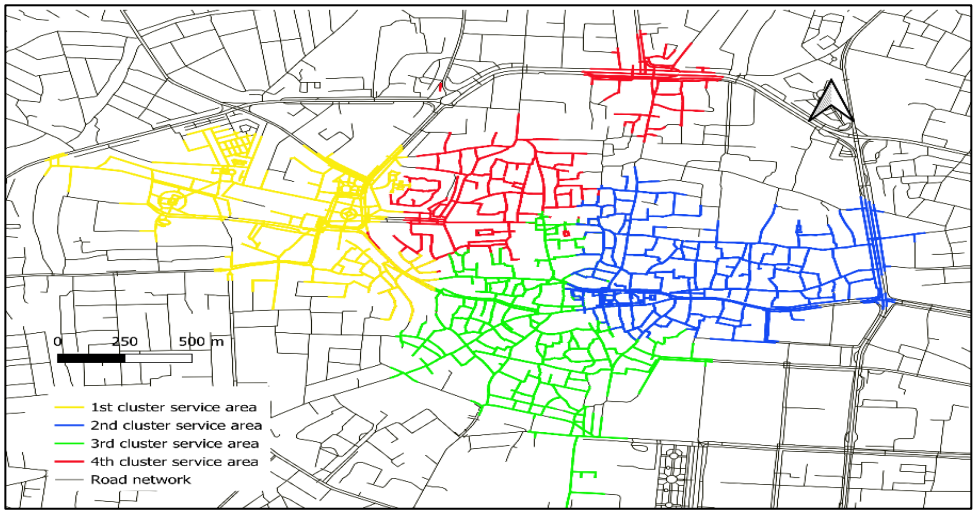

Figure 8. Service area of 4 clusters

In each cluster, it is imperative to enhance the provision of accurate navigational information, integrate interpretive signage for historical and cultural monuments, develop interactive guides, expand opportunities for cultural immersion. Besides, the implementation of informative panels, directional indicators and improved audio guide services across heritage sites can enrich the overall tourist experience to a large extent (Jiang et al., 2022).

Strategic planning of service areas facilitates the enhancement of visitor mobility and contributes to the optimization of tourism infrastructure (Sugimoto et al., 2019). The development of cluster-specific services and the efficient allocation of tourism resources provide a foundation for advancing sustainable and visitor-friendly tourism in Bukhara.

A Quick Time Map analysis was conducted for Historic Center of Bukhara to evaluate pedestrian accessibility from the city center to various heritage points. The findings reveal that the farthest heritage site can be reached within 20 minutes on foot, while the majority of sites are situated within a 15 minutes walking radius (Figure 9). Analysis demonstrates the potential for optimizing pedestrian-based tourism itineraries and strengthening urban tourism infrastructure. Consequently, enriching the tourist experience within short distances in central areas and formulating well-planned routes are of strategic importance. The development of efficient routes, the expansion of tourism services are essential for improving visitor mobility and overall cultural tourism experience in Bukhara. The spatial contiguity of cultural heritage assets within the urban core facilitates the efficient structuring of tourism itineraries within condensed temporal frameworks.

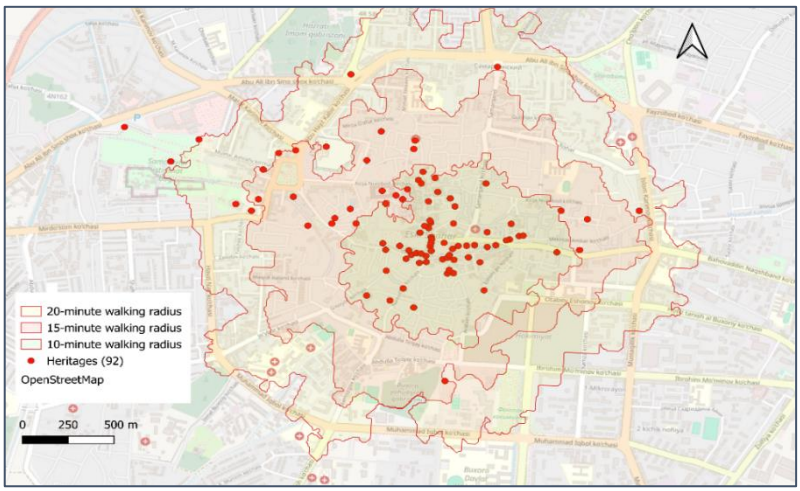

Figure 9. Walking distance-based coverage zones

Furthermore, the geographic proximity of heritage attractions enhances their functional integration, enabling the development of cohesive and contextually enriched touristic narratives (Rantala et al., 2020). In this regard, the expansion of visitor-support infrastructure surrounding heritage clusters, the refinement of interpretive signage systems and the establishment of pedestrian-oriented mobility networks represent key imperatives for advancing sustainable and accessible cultural tourism development, ultimatily contributing to a resilient circular society.

Forecast Results and Economic Evaluation

Extending the length of tourist stay increases expenditures and positively impacts the local economy. Therefore, this study assumes as a primary hypothesis that if the average stay of foreign tourists in Bukhara is extended from 3 to 4 days, an additional USD 83.33 in foreign currency revenue may be generated per tourist.

The annual variation in foreign tourists was thoroughly examined to substantiate the economic analysis. The following table presents the number of foreign tourists who visited Bukhara during the period from 2016 to 2024 (Table 4):

Table 4. Number of foreign tourists visiting Bukhara in 2016–2024 (actual figures)

Year	Total Number of Tourists	Domestic Tourists	Foreign Tourists
2016	827 700	726 400	101 300
2017	1 179 900	1 010 300	169 600
2018	2 512 000	2 210 500	301 500
2019	3 640 900	3 037 800	603 100
2020	249 900	236 600	13 300
2021	2 265 300	2 216 400	48 900
2022	3 514 200	2 961 600	552 600
2023	4 877 000	3 490 000	1 387 000
2024	5 755 525	4 010 325	1 745 200

As Table 4 indicates, the number of foreign tourists gradually increased between 2016 and 2019. However, due to the pandemic it sharply declined in 2020. Because of this significant discrepancy, the data from 2016-2019

were excluded from the ARIMA model. The reason is that such abnormal variations which disrupt the stationarity of the time series, reduce the reliability of forecast results.

Therefore, the forecasting model was constructed solely based on the real data from 2020-2024 which exhibits a stable recovery trend. This decision contributed to improving the statistical quality and predictive accuracy of the model. Notably, tourists grew significantly during this period-from 13,300 in 2020 to over 1.7 million in 2024. This provides a reasonable basis for projecting a steady growth trajectory through 2030. Based on these real trends, the number of foreign tourists for 2025-2030 was forecasted using the ARIMA(0,0,0) model. The model demonstrated high accuracy with a Stationary R-squared of 0.934 and a Normalized BIC of 25.365. The randomness of the model residuals was confirmed by the Ljung-Box test supporting the reliability of the forecast results.

The following Table 5 presents the forecasted number of tourists for the years 2025–2030 based on the ARIMA model:

Table 5. Projected number of tourist arrivals for 2025–2030

Year	2025 (6)	2026 (7)	2027 (8)	2028 (9)	2029 (10)	2030 (11)
Number of tourists	2 190 262	2 670 193	3 150 136	3 631 386	4 111 323	4 591 259

As shown in the table above, the number of foreign tourists is expected to increase yearly during the forecast period. Specifically, while 2.19 million tourists are projected for 2025, this figure is anticipated to reach 4.59 million by 2030. The growth trajectory is not linear but is characterized by a stable upward dynamic.

In Figure 9, the forecast results are presented graphically, where the red line represents the actual figures for 2020–2024, while the blue line indicates the projected values for 2025–2030 based on the ARIMA model.

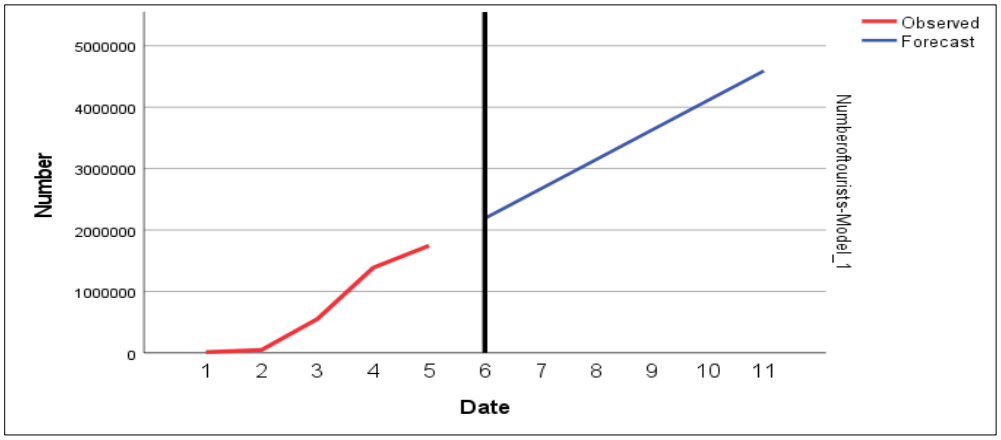

Figure 9. Graphical representation of forecast results for 2025–2030

Assuming that the average tourist stay is extended to 4 days and the daily expenditure is estimated at USD 83.33, each tourist would generate an additional income of USD 83.33. Based on this indicator, the expected annual foreign currency revenues for 2025–2030 are calculated as follows (Table 6):

As observed in table 6, if the number of foreign tourists continues to grow as forecasted and each tourist extends their stay by one additional day, Bukhara City could generate approximately USD 1.694 billion in additional foreign currency revenue by 2030.

Table 6. Projected additional foreign currency revenue from extended stay of foreign tourists by one day (2025–2030)

Year	**Number of Foreign Tourists**	**Additional revenue per tourist (USD)**	**Total additional revenue (USD)**
2025	2 190 262	83.33	182 518 508
2026	2 670 193	83.33	222 478 592
2027	3 150 136	83.33	262 437 344
2028	3 631 386	83.33	302 395 546
2029	4 111 323	83.33	342 353 328
2030	4 591 259	83.33	382 311 272
Total			**1 694 494 590**

The projected growth in foreign tourists is based on statistical dynamics solely (Table 6). Several external and internal factors may influence these trends, include: political stability, transport infrastructure development, visa policies liberalization, international promotional campaigns, global economic crises, public health emergencies and security-related conditions. Furthermore, the average daily expenditure of tourists in Bukhara may increase over time due to inflation, improvements in service quality and pricing and the emergence of new tourist attractions

and experiential offerings (Gedecho et al., 2022). Current analysis relies on the present-day estimated value of USD 83.33 for one additional day, it is likely that this figure will rise annually due to inflationary adjustments between 2025 and 2030, thereby further reinforcing the adaptive mechanisms of a circular society where tourism, economy and cultural heritage are interlinked through sustainable feedback loops (Rudan, 2023; Yu et al., 2023). In such a scenario, increased tourist inflow and higher expenditures may result in even greater foreign currency earnings for Bukhara.

CONCLUSION

According to the findings of the study, the cultural heritage sites located within the Historic Center of Bukhara can be effectively categorized and used as a basis for developing optimal travel itineraries. The heritage objects were systematically grouped into four distinct clusters by applying the K-means clustering method. Tailored recommendations were developed for enhancing tourism infrastructure and optimizing travel routes for each cluster. This methodological approach facilitates efficient spatial movement for tourists and allows for more rational allocation of their time.

The Shortest Path Analysis (Point to layer) technique was employed to determine the most efficient routes within each cluster. The results demonstrated that tourists can access the cultural heritage objects located within the city center in the shortest amount of time possible. In particular, the fact that the majority of these sites are located within a 15-minute walking distance presents a significant opportunity to enhance the organization of tourist experiences.

The aggregate walking distances, the number of sites and the estimated time required for exploration within each cluster are summarized in the following table (Table 7):

Table 7. Walking distance and duration by cluster

Cluster	Number of Sites	Distance (meters)	Average Walking Time
Cluster 1	11 sites	2,800 m	1 hour
Cluster 2	14 sites	3,335 m	1 hour 15 minutes
Cluster 3	44 sites	6,026 m	2 hours
Cluster 4	23 sites	5,502 m	1 hour 50 minutes

Using the Quick Time Map analysis, pedestrian mobility opportunities within the city were examined within 10, 15, and 20-minute walking intervals. Based on these results, it was determined that there is strong potential to develop four-day tourism programs and to encourage extended stays of visitors within the urban area.

Additionally, through the application of the Network Analysis Service Area method, a 300-meter service zone was delineated for each cluster. This approach facilitates the development of tourism infrastructure by improving signage systems, information centers, and interactive guide services associated with each cluster. The findings of the study also reflect the principles of sustainable utilization of cultural heritage assets (Table 8).

Table 8. Analytical assessment of the sustainable use of cultural heritage sites

Sustainability Dimension	Analytical Content
Economic	• Attaining a minimum four-day stay by tourists within the Bukhara region generates positive economic externalities for local tourism services and the regional economy; • Tourist expenditures contribute additional financial inflows to the region and enhance the potential for investment in the tourism sector.
Social	• Visitor satisfaction levels increase; reduced walking distances enable tourists to access a wider range of actively promoted heritage assets; • A broader and more comprehensive perception of the Historic Center Bukhara is formed; • Public awareness and local community engagement in heritage preservation are strengthened.
Environmental	• Expansion of pedestrian tourism opportunities contributes to the reduction of CO_2 emissions, thereby reinforcing environmental sustainability; • Limited reliance on motorized transport supports ecological equilibrium and heritage conservation efforts.

In addition, a forecast analysis of the number of foreign tourists for 2025–2030 was conducted based on the ARIMA model. According to the model results, the number of foreign visitors to Bukhara is expected to grow steadily, reaching 4.59 million by 2030. Over the period from 2025 to 2030, a total of more than 21.8 million

foreign tourist arrivals is projected. If, during this period, the average length of stay per tourist in Bukhara is extended to 4 days, an additional USD 1.69 billion in foreign currency revenue could be generated, based on the estimated USD 83.33 per person for one extra day.

This confirms the economic effectiveness of approaches such as developing four-day tourist programs, as proposed in the analytical framework. Furthermore, based on the forecasted increase in foreign tourist inflows, extending the length of stay would create opportunities to expand tourism services in Bukhara, promote the sustainable use of cultural heritage sites, enhance local economic activity and develop targeted strategic directions for broader promotion of cultural heritage.

The research findings align with the principles of circular tourism. It emphasize the continuous reinvestment of cultural and economic value into local systems. The spatial optimization of tourist routes extends length of stay of visitors, enhances pedestrian-oriented infrastructure, reduces resource and time consumption, contributes to the circular economy by maximizing local benefits. In unison, it conditionally requires the preservation of heritage, community participation and sustainable mobility. Thus, the study presents a conceptual model illustrating how the integration of cultural heritage management and GIS-based tourism planning in Bukhara can facilitate the transition toward a more circular and sustainable urban tourism system.

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