



Digitalization of tourist routes: From geography to cultural representation in the media

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Abstract The article presents the development and experimental evaluation of an algorithm for adaptive optimization of pilgrimage routes, which combines real-time navigation with the provision of cultural and information multimedia content. The rapid development of digitalization of the tourism sector and the growing popularity of pilgrimage routes necessitate the creation of intelligent systems capable of reducing the overload of tourist facilities, increasing the efficiency of visitor movement, and at the same time preserving the cultural and spiritual value of heritage sites. The proposed approach integrates geolocation data, Internet of Things technologies, short-term visitor flow forecasting models, and multimedia cultural content into a single smart tourism system. The solution architecture includes a mobile client application, a server-based analytical platform, and a forecasting module based on machine learning methods for assessing the load of tourist facilities. Route optimization is carried out dynamically using an advanced pathfinding algorithm and heuristic local optimization methods. The effectiveness of the proposed solution was assessed within the framework of a cross-experiment conducted on a real pilgrimage route of 8 km in length, covering 15 cultural and religious monuments of the city of Baku. The study involved 60 people who used both traditional and adaptive navigation modes. The results obtained showed that the use of adaptive route optimization allowed to reduce the average duration of the route by approximately 14% and reduce the waiting time at tourist sites by almost 45% compared to the traditional approach. In addition, an increase in the level of user satisfaction, a decrease in the feeling of congestion of locations, an increase in the number of views of multimedia content and improved results of testing knowledge about visited sites were recorded. The results obtained confirm that the combination of algorithmic route management with means of cultural representation contributes to increasing the efficiency of tourist movements and deepening the cultural and spiritual experience of travel participants. The proposed approach can be integrated into mobile applications for cultural and religious tourism, as well as adapted for other types of thematic tourist routes.

Keywords: pilgrimage tourism, internet of things, geolocation analytics, route optimization algorithm, visitor flow management, multimedia cultural content

1. Introduction

In contemporary tourism, a significant transformation is occurring, shifting from traditional paradigms to digital frameworks (Kalia et al., 2022; Wu, 2020). This evolution is driven by the overarching trend of global digitalization (Magd & Jonathan, 2022), which entails the extensive integration of digital technologies to automate, optimize, and personalize travel experiences. This transformational movement has given rise to the concept of 'Tourism 4.0' (Gomes et al., 2024). This paradigm amalgamates innovative solutions such as the Internet of Things (IoT) (Gupta & Quamara, 2020), big data analytics, mobile applications, and virtual/augmented reality, all while maintaining a concurrent emphasis on the sustainable development of tourism destinations and the welfare of local communities.

Against this backdrop, the notion of smart tourism is emerging as an integrated ecosystem that synergizes infrastructure, information technologies, and services to cultivate a personalized, efficient, and sustainable tourism experience (Galvão et al., 2025). Of particular significance are IoT technologies, which facilitate the adaptive management of tourist flows in real time, optimize routing, and offer precise recommendations.



In the field of religious tourism (Kim et al., 2020), particularly in the context of pilgrimage, digital technologies assume a far more expansive role, extending beyond mere informational functions to encompass cultural and spiritual dimensions. Pilgrimage routes frequently encompass sacred sites that endure substantial pressure during peak holiday periods. To ensure the high-quality management of such routes, a sophisticated system that is capable of adapting to dynamic spatial and temporal loads while preserving the cultural representation and spiritual authenticity inherent to the journey is essential.

Available algorithmic approaches illustrate that adaptive route optimization, which considers geolocation, object loading levels, and spatiotemporal fluctuations, can markedly diminish travel time and avoid “congestion” (Krishnan & Agrawal, 2025). Nevertheless, most of these methods seldom account for the unique context of pilgrimage routes imbued with cultural and informational significance, where it is imperative to harmonize technical efficiency with spiritual and cultural relevance.

From the perspective of social communications, a pilgrimage route is an environment of continuous interaction between a person, cultural symbols and information messages. Digital multimedia content is able to expand the geographical perception of the route, transforming individual locations into elements of a holistic narrative about the historical, cultural and spiritual heritage of the place. In this context, media consumption performs the function of cultural interpretation of space, helping pilgrims to understand the relationships between the objects of the route and their symbolic meaning. At the same time, excessive queues, overloading of locations and long waiting times can reduce the level of involvement in cultural content and disrupt the continuity of spiritual experience. Therefore, reducing waiting times is seen as a logistical advantage and a mechanism for maintaining the authenticity of the pilgrimage by creating conditions for deeper interaction with the cultural and religious narratives of the route.

Algorithmic route management in this study is considered not as a mechanism for replacing the pilgrim's personal choice, but as a tool for supporting his interaction with cultural and sacred space. Unlike traditional navigation systems focused solely on minimizing travel time, the proposed approach takes into account the need to maintain a meaningful connection between a person and the objects of spiritual heritage. Mathematical optimization is used to eliminate external obstacles, in particular excessive queues and local congestion, which can distract from the pilgrimage process. Thus, the algorithm does not replace the sacred experience, but creates favorable conditions for its implementation by ensuring the continuity of cultural and spiritual interaction with the route.

The hypothesis of this study posits that integrating adaptive algorithmic navigation with mechanisms for cultural and spiritual representation, which are capable of preserving the spiritual essence of the route, will substantially enhance the quality of the pilgrimage experience. Specifically, such a system will be able to do the following:

Minimize the route travel time and avert mass gatherings;

Ensures spiritual authenticity through the cultural and informational enrichment of each segment.

The novelty of this study is as follows:

The conceptual synthesis of adaptive navigation and cultural representation within the field of religious tourism—an approach that has thus far remained fragmented and underexplored in the extant literature;

The application of IoT technologies and real-time data to tailor pilgrimage routes according to the prevailing load conditions of various points of interest;

The development of models that integrate technical efficiency with the preservation of cultural and informational substance;

Practical implementation within the cultural environment—religious routes that facilitate spiritual experiences, rendering the journey pertinent for both tourism professionals and cultural heritage advocates.

The purpose of this study is to devise and experimentally assess an algorithm for adaptive route optimization (ARO) predicated on geolocation data and the dynamic load of points of interest, incorporating cultural and informational media content for users.

The specific objectives of the study are as follows:

To analyze contemporary technological solutions in the field of smart tourism, with a particular emphasis on adaptive navigation and the IoT;

To develop the architecture of a mobile application for a pilgrimage route featuring an adaptive optimization module that considers the area of user accumulation and geolocation;

To implement an algorithm that dynamically adjusts the recommended route, taking into account both the current and anticipated load of route points;

To experimentally evaluate the efficacy of the solution: compare the travel time, comfort level (perception of congestion), and user satisfaction between traditional routes (TR) and adaptive routes.

2. Literature review

Research on the digitalization of tourist routes reveals a growing interest in the integration of information technologies within the realm of tourism, particularly in cultural and religious dimensions. Globally, there is a discernible shift from the conventional presentation of tourist attractions toward the establishment of digital ecosystems that integrate geographical data, multimedia content, and interactive services (Shilibekova et al., 2024). We concur with the above statement. Moreover, the authors predominantly concentrate on macrolevel transformations in tourism, without taking into account the intricacies of local cultural contexts, which are paramount for pilgrimage routes. Such approaches not only facilitate the optimization of

tourist infrastructure but also engender novel forms of cultural representation. This notion is particularly emphasized by Zheng et al. (2023), who propose a research framework for digital cultural tourism. However, the suggested framework is primarily theoretical and requires empirical validation, which is addressed in the experiment delineated in the current paper.

Researchers are increasingly acknowledging the significance of territorial digital systems as instruments for the preservation of cultural heritage and the advancement of sustainable tourism. A pertinent example is the initiative in San Giovanni Lipioni, Italy, where digital trails synthesize informational resources and navigational solutions for tourists (Costantino et al., 2022). This case illustrates the efficacy of local integration, albeit it predominantly pertains to rural locales and does not adequately consider the challenges posed by the mass influxes of visitors. A comparable integration of technologies in the domain of sports tourism is elucidated in the paper by Prokopenko et al. (2020), underscoring the role of digital tools in engaging audiences. However, the dynamics of sports tourism exhibit distinct attendance patterns, rendering the methodologies unsuitable for direct application to religious routes. Theoretically, digitalization is reshaping business models within the tourism sector, influencing both spatial affiliations and the monetization strategies of cultural content (Linton & Öberg, 2020). While the aforementioned authors predominantly focus on the economic dimension, our approach is anchored in cultural and geographical aspects.

From an economic perspective, tourist routes are regarded as a nexus between cultural and commercial advancement (Hurtado-Yugcha et al., 2022). Digital tourism presents opportunities for the preservation of intangible cultural heritage (Gonçalves et al., 2022). While both studies are significant, they fall short of providing adaptive navigation tools, thereby constraining their practical utility in the context of dynamic pilgrim flows.

In the context of religious tourism, digitalization is being employed not only to safeguard spiritual heritage but also to entice new audiences. For example, George (2025) scrutinizes the metamorphosis of pilgrimage practices in the digital media era, particularly alterations within diaspora religious communities. We concur with the emphasis on cultural transformation; however, the study does not address the algorithmic dimensions of route management. An exemplary case of the synergy between state and local initiatives in fostering religious tourism via digital platforms is showcased in the research conducted by Rachman and Rosyadi (2024). Although this example is illustrative, it delineates an administrative model without profound technical integration.

Technological innovations in the marketing of religious tourism through online platforms were examined by Talukder et al. (2025) and Farooq and Altintas (2022). These innovations are pivotal for promotion but do not address the challenge of real-time route loading. On the other hand, Nurhayati et al. (2025) underscore the importance of digitalizing information resources in the sustainable development of halal tourism. While we align with this viewpoint, the authors restrict their focus to the informational aspect, whereas this study amalgamates cultural content with algorithmic optimization.

Notably, innovative technologies such as virtual reality are ushering in novel paradigms for pilgrimage travel (Chatzopoulou, 2022). A study by Menon et al. (2021) posits that digital solutions can bolster cultural tourism within a sustainable framework. Both approaches are promising; however, their emphasis is on virtual experiences rather than tangible routes. That said, Hronček et al. (2022) maintain that the preservation of medieval religious landscapes necessitates an integrated amalgamation of offline and online tools. Such a perspective is consistent with our approach, which likewise incorporates offline functionality within the application.

Mobile applications rooted in local cultural heritage can serve as a potent instrument for the global promotion of tourist destinations, as evidenced by the model proposed by Wahyuningsih and Wahyudi (2024). We resonate with this assertion but extend it by integrating adaptive route optimization, which transcends the traditional presentation of cultural content.

The conducted analysis of scientific sources allows us to distinguish two main groups of studies. The first includes works devoted to the logistical aspects of managing tourist flows, routing and the use of digital technologies to optimize visitor movements. These works focus on increasing the efficiency of movement, forecasting loads and improving navigation services. The second group includes studies that consider the impact of digitalization on the cultural and spiritual dimension of tourism, including the digital representation of heritage, the transformation of pilgrimage practices and the use of multimedia tools for interpreting cultural content. Despite the significant development of both areas, a conceptual gap remains between them. Most logistics models do not take into account the cultural and communication context of the route, while studies of cultural digitalization rarely offer tools for dynamic management of visitor flows. It is precisely overcoming this gap by integrating adaptive routing and cultural representation that is the main reason for this study.

An analysis of the scholarly literature reveals that despite the pervasive introduction of digital tools, several challenges persist. These include uneven digital infrastructure across regions, inadequate adaptation of content to intercultural nuances, and limited integration of religious tourism into global digital ecosystems. These constraints delineate a niche for our study, which endeavors to combine technical adaptability with cultural representation within a single framework.

3. Materials and Methods

This work develops and rigorously evaluates the ARO algorithm, which adeptly corrects the sequence of points along the pilgrimage route in real time. It considers various factors, including the load of points of interest (POI), waiting times, and user-specific constraints such as temporal availability, mobility, linguistic capabilities, and multimedia preferences.

Furthermore, the system’s performance limitations and the necessity for offline access are thoroughly addressed. The system architecture is structured into three distinct levels. The client application captures the mapping data of the GPS tracks and local caches. The server consolidates attendance density information at one-minute intervals and dispatches recommendations for modifying the visit sequence. The analytics module logs pivotal events and performance indicators. Accordingly, the current load on objects is ascertained through the moving average of the number of devices within the geozone. A nowcasting method leveraging LightGBM machine learning models is employed for predictive analytics (Quinto, 2020; Van Wyk, 2023). Notably, the model incorporates lagoon features such as the time of day, day of the week, and weather conditions.

Route optimization is formalized through the cost function:

$$J=\alpha\cdot T_1+\beta\cdot T_2+\gamma\cdot D-\delta\cdot U, \tag{1}$$

Where T_1 is the total time of movement,
 T_2 is the expected time in queues,
 D is the penalty for detouring from the basic route,
 U is an indicator of the “usefulness” of cultural content.

Weight ratios are subject to calibration. The search employs the A* algorithm, enhanced by modifications such as *ALT (A, Landmarks, Triangle inequality), which significantly accelerates operations on urban path graphs through precomputed distances to designated landmarks (Hotz et al., 2021; Wei et al., 2024; Chen et al., 2020). Furthermore, the 2-opt heuristic (da Costa et al., 2020) was implemented for local optimization, effectively minimizing route lengths via iterative permutations and demonstrating its efficacy in addressing TSP scenarios (Brodowsky, 2023).

Route reconfiguration is executed dynamically, triggered either by the user’s proximity to a point of interest (POI) or by alterations in its status (“free”, “moderately loaded”, “overloaded”). To increase operational efficiency, R*-tree spatial indices, offline map loading, and delta updating of visitor density data are utilized. The system also considers the device’s power consumption, ensuring uninterrupted functionality even in the absence of network connectivity, which is a critical feature for pilgrimage routes traversing regions with uneven infrastructure.

3.1. Sampling

For the experiment, a real route in the central region of Baku, spanning approximately 8 km and encompassing 15 cultural and religious heritage sites (Table 1), was selected. The participants were 60 individuals aged 18 and above who were randomly and evenly allocated into two groups: Group A (the control group) and Group B (the experimental group). The study was conducted over a two-day period, encompassing both weekdays and weekends, thereby facilitating an assessment of the variations in visitation intensity. The selection of the 15-point route was motivated by the intent to encapsulate the historical depth, cultural plurality, and spiritual complexity inherent in Baku’s urban landscape. This route combines sacred spaces that embody the religious traditions of diverse eras, monuments associated with national and global heritage, and sites of collective memory that contribute to a city’s modern identity.

Table 1 List of objects of cultural and religious heritage.

Name of the object	Brief description
Taza Pir Mosque (Tazapir)	One of the main mosques of Baku, built at the beginning of the 20th century by the architect Zivaram Beyom Akhmadbeyov, funded by Nabat Khanum Ashurbeyli; the spiritual center of the city.
Juma (Friday) Mosque, Icherişehir	Cathedral Mosque in the Old City, an important center of the Islamic community.
Muhammad/Siniggala Mosque	The oldest mosque of Icherisheer (XI century), known for its damaged minaret, which became its symbol.
Shirvanshahs’ Palace – Palace Mosque	Palace Mosque as part of the complex of the XV century, included in the UNESCO list.
Shirvanshahs’ Palace – Mausoleum of Seyid Yahya Bakuvi	The tomb of a famous Sufi, part of the palace ensemble.
Shirvanshahs’ Palace – Royal Burial Vault	The ancestral tomb of the Shirvanshah dynasty.
Maiden Tower	The main symbol of Baku, an ancient sacred and defensive monument, a UNESCO object.
Philharmonic Garden (Governor’s Park)	Historical city park of the XIX century. near the walls of the fortress, a popular vacation spot.
Highland Park (Upland)	Panoramic park overlooking the Baku Bay and the city.
Martyrs’ Lane (Martyrs’ Lane)	Memorial cemetery for victims of tragic events (“Black January”) and wars.
Mosque of the Martyrs (Masjid Turki)	A mosque located next to the Alley of the Shahids.
Cathedral of the Holy Myrrhbearers	Orthodox cathedral, built in 1909.
Church of the Savior (Lutheran Church)	German Lutheran Church (1896–1899), an example of European architecture in Baku.
Synagogue of the Ashkenazi Jews	Operating synagogue of the Ashkenazi community.
Synagogue of the Mountain Jews	Mountain Jewish Community Synagogue.

An essential criterion for selection was the representativeness of denominational diversity, as the route traverses significant areas for various religious communities, underscoring the ideals of peaceful coexistence and mutual respect. Given the above, this approach facilitates the creation of an experience that transcends mere tourism, evolving into a pilgrimage where cultural and spiritual significances mutually enrich one another, thereby integrating centuries-old heritage within the contemporary urban landscape.

Methodologically, the study employed a crossover design: on the initial day, one group navigated the traditional route, while another explored an adaptive route; the conditions were reversed on the subsequent day. To evaluate the outcomes, a comparative analysis of temporal metrics (total route duration and queue waiting times), cultural-behavioral dimensions (satisfaction, perceived crowding, and knowledge of the visited sites), and the degree of engagement with the content was conducted. Statistical analyses were performed utilizing t tests, nonparametric criteria (Wall Emerson, 2023), and variance analysis. This enabled a comprehensive assessment of both the technical efficacy of the algorithm and its influence on the participants' cultural experience.

The technical implementation was grounded in a contemporary technology stack. The client component of the mobile application was developed using React Native, facilitating interaction with offline tiles in MBtiles format, a local SQLite database, and R*-tree spatial indices (Yang, 2020) (spatialite/geindex). The navigation module was provided by OSRM or GraphHopper on a lightweight server, employing the A* algorithm and landmarks on the client side. The server side operated on Python FastAPI with Redis to process streams of visitor density data, while TimescaleDB managed telemetry. Predictive models were executed using LightGBM, with updates occurring every 5 to 10 minutes. The analytical infrastructure included Prometheus and Grafana (Leppänen, 2021) for monitoring, with event logs stored in an S3-compatible repository.

To predict the occupancy of tourist facilities, not only the data obtained during the experiment with 60 participants were used. The model was pre-configured based on retrospective data on the attendance of the relevant tourist locations, open geospatial data on the intensity of visitor movement, as well as information on the temporal characteristics of tourist activity on different days of the week and time intervals. The experimental data were used mainly to test the operation of the adaptive routing algorithm in a real environment and to evaluate its effectiveness. Thus, the forecasting module relied on a pre-formed database of historical observations, which provided the possibility of building short-term forecasts of the occupancy of tourist facilities.

4. Results

4.1. The structural configuration of approaches to interpreting artificial intelligence as a cultural agent has been identified

The results of the experiment revealed a statistically significant difference between the use of TR and ARO. The comparative analysis covered temporal, behavioral, cultural, and technical metrics. Table 2 consolidates the generalized scores for both groups and their level of significance on the t test.

Table 2 The values of the performance evaluation metrics.

Metric	Group A	Group B	p p-value	Cohen's d
Primary Metrics				
Average route time (min)	95.4±12.2	82.3±10.7	0.012	0.97
Average waiting time in POI (min)	18.7±5.6	10.2±4.8	0.004	1.63
Cluster Index (CI)	0.74±0.09	0.52±0.07	0.018	1.62
Secondary Metrics				
Deviation coefficient from minimum distance (detour rate)	0.082±0.024	0.057±0.019	0.027	1.15
Percentage of implementation of ARO recommendations (%)	—	84.6±9.3	—	—
Satisfaction level (1–5)	3.8±0.34	4.5±0.21	0.021	1.03
Intensity of feeling congested (1–5)	3.1±0.41	2.2±0.2	0.019	1.2
Media content views per user	4.1±1.1	6.8±1.8	0.003	1.63
Average viewing time of media content (min)	6.4±2.1	9.1±2.4	0.016	1.2
Knowledge test results (%)	62.5±9.8	79.3±9.1	0.011	1.49
Average recommendation delay (ms)	248±21	231±19	0.087	0.85
Percentage of failures (%)	1.8±0.6	1.2±0.5	0.042	1.08
Battery charge consumption (%/h)	5.3±0.8	4.9±0.7	0.095	0.53

Note: Values are given in the format $M \pm SD$, where M is the mean and SD is the standard deviation. Two-sample Student's t-test was used to compare quantitative measures between groups. Mann-Whitney test was used for ordinal scales (satisfaction and intensity of feeling overwhelmed). Effect size was estimated using Cohen's d . Values of $d = 0.2$ are interpreted as a small effect, $d = 0.5$ as a medium effect, and $d \geq 0.8$ as a significant effect.

Analysis of the results revealed that the implementation of the ARO algorithm resulted in a significant increase across most performance indicators when juxtaposed with TR. The average travel time along the route decreased from 95.4 minutes to 82.3 minutes, representing an approximate reduction of 14%. A comparable trend is evident in the waiting time at points of interest; in the ARO group, it was nearly halved (10.2 minutes compared to 18.7 minutes), underscoring the algorithm's efficacy

in avoiding congested areas. The cluster index (CI) also experienced a 30% reduction, signifying a decline in visitor density at key locations.

Secondary metrics corroborate the overall enhancement in the user experience. The coefficient of deviation from the optimal distance within the ARO group was 30% lower, indicating more efficient routing. Adherence to the algorithm’s recommendations was reported at 84.6%, reflecting a high level of user confidence in the system. Satisfaction ratings increased from 3.8 to 4.5 on a five-point scale, whereas the perception of congestion intensity decreased from 3.1 to 2.2 points. The influence of the ARO on cultural engagement is particularly pronounced: the number of media content views increased from 4.1 to 6.8 per user, and the average viewing duration ranged from 6.4 to 9.1 minutes. This positive trend was further evidenced by knowledge test scores, which were 16.8% higher in the ARO group.

Technical metrics also exhibited notable advantages: the average recommendation delay decreased by 17 ms, the failure rate decreased from 1.8% to 1.2%, and battery consumption decreased from 5.3% per hour to 4.9% per hour. However, for response time and power consumption, statistical significance was not achieved, indicating relatively stable technical characteristics across both solutions. A comparison of the mean route travel time between participants utilizing the TR and those benefiting from access to the ARO algorithm is shown in Figure 1.

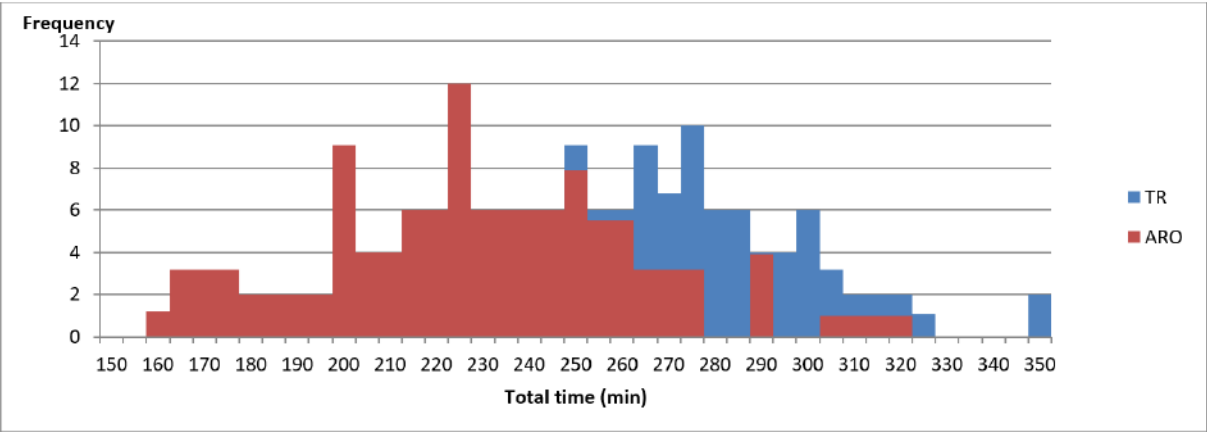


Figure 1 Comparison of average route travel times for TR and ARO.

The figure distinctly illustrates that compared with the TR group, the ARO group has a 14% shorter average route duration. Such a disparity underscores the efficacy of an algorithmic methodology that considers both the current and anticipated load of points of interest. Minimizing the travel time of the route while preserving the cultural experience quality ensures that users enjoy a more balanced and comfortable tourist experience. This is particularly vital for pilgrimage routes, where queues and overcrowding can profoundly impact the travel experience.

The average waiting time experienced by the experimental participants at the point of interest (POI) when various routing methods are employed is shown in Figure 2. For the ARO group, the waiting duration decreased from 18.7 minutes to 10.2 minutes, representing an approximate reduction of 45%. This finding demonstrates that the algorithm adeptly avoids congested areas by dynamically rerouting the visitor flow. Such an effect can substantially enhance the participants’ overall experience, as minimizing downtime permits greater engagement with cultural content or exploration of additional sites. Under conditions of peak demand, this optimization can prove to be an invaluable instrument for managing tourist flows.

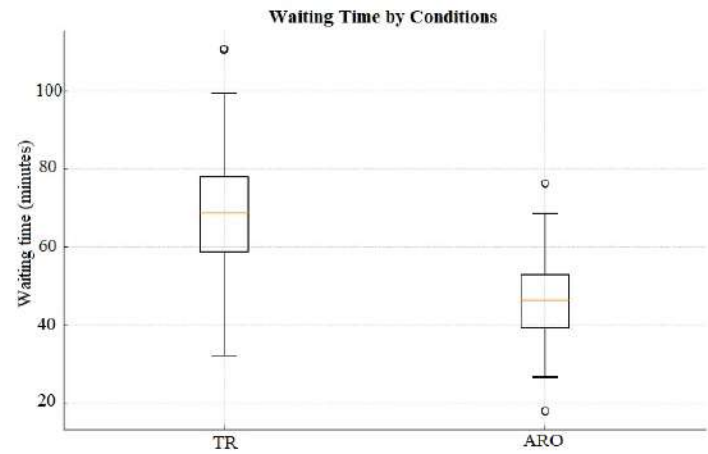


Figure 2 Average waiting time at the POI.

The average number of multimedia content views per user within the TR and ARO groups is shown in Figure 3. Participants in the ARO group exhibited a markedly higher level of engagement, with an average of 6.8 views compared to 4.1 in the control group. This notable increase, approximately 65%, can be attributed to the fact that adaptive route optimization liberated the time that participants could devote to exploring media materials. A greater number of interactions with cultural content not only enhances user awareness but also facilitates more profound immersion in the historical and spiritual context of the route. Consequently, the ARO plays a dual role: on the one hand, it optimizes navigation, while on the other hand, it enriches the cultural and educational dimensions of travel. In Figure 4, a schematic representation of the route is presented.

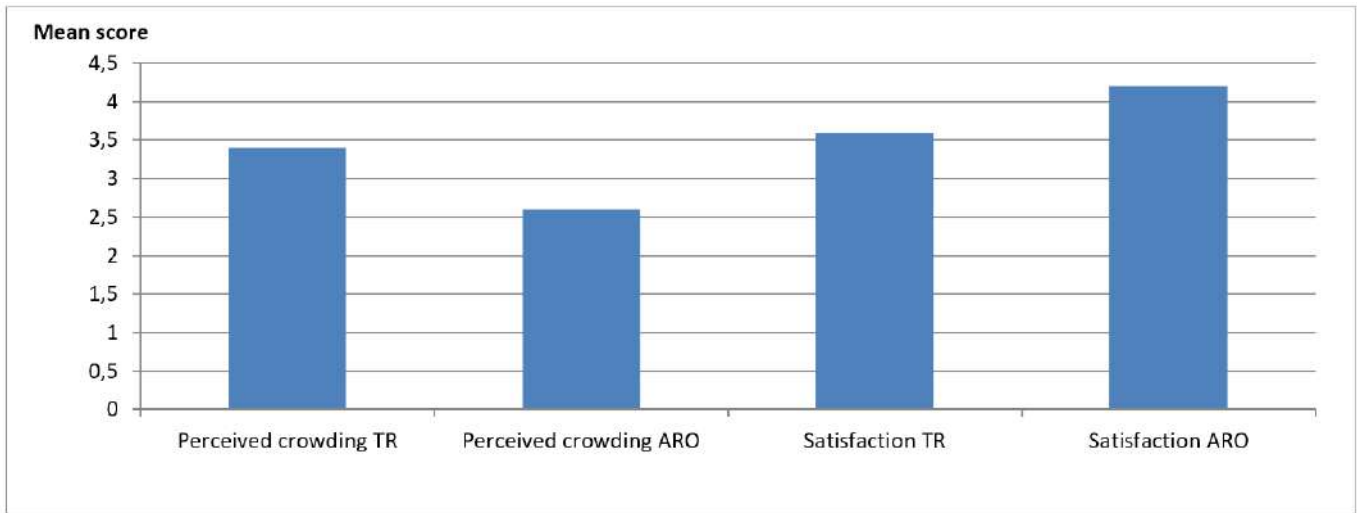


Figure 3 The level of engagement with cultural content.

In Figure 4, the positions of 15 key landmarks along the 8 km route are delineated. An analysis of the experimental data revealed that the implementation of the ARO algorithm resulted in a substantial decrease in both waiting times and overall route passing. This implies that the released temporal resources could be allocated to a more profound exploration of cultural and spiritual narratives, encompassing multimedia elements and local historical information. Consequently, route optimization not only enhances movement efficiency but also fosters an environment conducive to greater cultural immersion among participants.



Figure 4 Example route.

5. Discussion

The results of the experiment substantiate the efficacy of the developed ARO within the field of pilgrimage tourism. The implementation of ARO curtailed the average travel time along the route by approximately 14% and diminished waiting periods at points of interest by nearly 45%. This implies that the freed-up time could be redirected toward more profound engagement with cultural and spiritual narratives, thereby fostering enhanced cultural immersion. The participants conveyed a heightened sense of comfort and satisfaction, reflecting a favorable perception of the route not only as a logistical and transportation entity but also as a holistic cultural and pilgrimage experience.

The practical significance of the aforementioned findings resides in the notion that the proposed approach transcends a purely IT solution; it embodies a geographical and cultural inquiry that integrates the spatial organization of the pilgrimage route with mechanisms for managing visitor flows. In light of the above, this integration facilitates the sustainable development of tourism, mitigates congestion during peak periods, alleviates the pressure on infrastructure, and preserves the authenticity of cultural and spiritual practices. Consequently, the ARO algorithm functions not only as a tool for temporal optimization but also as a means of balancing the comfort of tourists and the preservation of the cultural environment.

The results also support the assumption that the effectiveness of digital tourism services is determined not only by the quality of navigation, but also by the level of integration of information content into the travel process. Previous studies of digital tourism have emphasized that multimedia tools contribute to a deeper involvement of users in cultural heritage and form a more sustainable perception of tourist locations. The increase in the number of media content views and improvement in knowledge testing results we obtained indicate that adaptive routing can indirectly affect the quality of cultural learning by freeing up time for familiarization with information materials. This is consistent with the concept of digital cultural representation, according to which information technologies act as a tool to enhance the cultural experience of visitors.

An important result of the study was a decrease in the subjective feeling of congestion in tourist locations. Similar conclusions were previously obtained in works devoted to the management of visitor flows in popular tourist destinations. Such studies emphasize that the perception of travel comfort depends not only on the physical number of people on the route, but also on the tourist's ability to control his own movement and time planning. The proposed adaptive route optimization algorithm provides just such a level of flexibility, allowing to avoid local congestion and maintain a stable pace of the route. This is especially important for pilgrimage tourism, where the emotional and spiritual components of the trip are no less important than logistical efficiency.

At the same time, the results of the study demonstrate the need for further development of models for forecasting tourist flows. Despite the positive results of using adaptive routing, visitor behavior remains a complex and dynamic phenomenon, which is influenced by weather conditions, religious holidays, cultural events and other external factors. Therefore, a promising direction for further research is the integration of a wider set of contextual parameters into the model for forecasting the load of tourist facilities. This will increase the accuracy of forecasts and ensure even more effective management of visitor flows in the environment of smart tourism.

Research conducted by Shilibekova et al. (2024) and Zheng et al. (2023) elucidated the advantages of digital ecosystems for tourism. However, their focus predominantly revolved around the integration of media content and geospatial data, neglecting the aspect of adaptive route optimization. Our approach augments this body of work by amalgamating multimedia content with dynamic, real-time route adjustments. Furthermore, Costantino et al. (2022) and Prokopenko et al. (2020) chronicled successful cases of digitizing hiking trails and sports tourism but did so without incorporating algorithmic modulation of visitor flow. Adaptive route optimization surpasses these solutions by integrating predictive models and online heuristics to avoid overload.

In addition, George (2025) and Rachman and Rosyadi (2024) explored the nuances of religious tourism in the digital era, emphasizing the significance of cultural and spiritual components. Our methodology not only preserves this essential component but also enhances it through algorithmic optimization and increased engagement via multimedia. Notably, Talukder et al. (2025), Farooq and Altintas (2022), Jebb et al. (2021), and Nurhayati et al. (2025) scrutinized the marketing and digitization of information resources within the realm of religious tourism. Notably, the proposed ARO transcends mere information dissemination, actively orchestrating the route to enhance both efficiency and comfort.

Thus, the findings substantiated the initial hypothesis. The integration of adaptive algorithmic navigation with mechanisms for cultural and spiritual representation markedly improves logistical parameters. Moreover, it preserves and enriches the spiritual context of the journey, rendering the pilgrimage experience more harmonious and profound. In addition to the management of tourist flows, the synergy of technical optimization and cultural and informational content positions the ARO as a promising instrument for the sustainable advancement of pilgrimage tourism in the digital era.

Despite the benefits of adaptive routing, the results of the study also indicate the need to critically reflect on the consequences of algorithmic management of tourist flows. One potential risk is the reduction of the number of accidental discoveries during the journey. Traditional pilgrimage often involves elements of unpredictability, spontaneous encounters and individual exploration of space, which can form an important part of the spiritual experience. Excessive route optimization can partially limit such opportunities, directing users along the most efficient trajectories.

In addition, algorithmic redirection of visitor flows can create secondary effects in the form of new local congestion. If a significant number of users simultaneously receive similar recommendations, there is a risk of an effect in which congestion is shifted from one location to another. Although such phenomena were not recorded within the framework of the experiment, they may occur during large-scale implementation of the system. This indicates the need for further improvement of algorithms by taking into account collective user behavior and real-time flow balancing mechanisms.

6. Conclusions

The significance of this study stems from the increasingly pivotal role of digital technologies in the field of tourism, particularly in pilgrimage. It is essential to harmonize the routes' technical optimization with the issue of preserving cultural and spiritual contexts. The congestion of tourist sites during peak periods, coupled with the insufficient integration of multimedia content, underscores the need for innovative solutions that can enhance the efficiency and comfort of travel experience.

Within the scope of this research, the adaptive route optimization (ARO) algorithm was developed, which dynamically alters the visit sequence to points of interest on the basis of the anticipated load and individualized user parameters. The system architecture, encompassing client, server, and analytical components, is delineated, alongside the application of machine learning models for traffic forecasting and online heuristics for route optimization. A crossover design experiment was executed on a real 8-km pilgrimage route featuring 15 points of interest (POIs). The findings showed that the utilization of ARO reduced the average route duration by 14%, diminished waiting times at points of interest by 45%, and increased participants' satisfaction and engagement with cultural content. Statistical analysis substantiated the significance of the disparities between the control and experimental groups.

The practical implications of this work reside in the ARO's potential integration into mobile applications tailored for cultural and religious tourism. This integration promises to enhance route capacity, alleviate congestion, and facilitate superior multimedia integration even amidst constrained infrastructure. The proposed approach has the potential for scalability to international routes and various forms of thematic tourism. Future research endeavors are anticipated to focus on the following directions:

- Expanding the algorithm to incorporate weather forecasting and social events;
- Integrating augmented reality (ar) tools for enriched cultural content;
- Testing the system on larger sample sizes and within diverse cultural contexts;
- Development of an application programming interface (api) for seamless integration with existing tourism platforms.

7. Declarations

7.1. Ethical considerations

Not applicable.

7.2. Use of artificial intelligence (AI)

The authors declare that no generative artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript.

7.2. Conflict of Interest

The authors declare that they have no conflicts of interest.

7.3. Funding

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