

APPLICATION OF A HIERARCHICAL APPROACH FOR OPTIMAL DISTRIBUTION OF TOURIST FLOWS TAKING INTO ACCOUNT REGIONAL CONSTRAINTS

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Abstract

The article examines modern approaches to improving the transport and logistics network of the tourism sector in the southern region of Kazakhstan. Particular attention is paid to the digitalization of transport infrastructure, the use of mathematical modeling and environmental solutions. The use of a hierarchical approach made it possible to demonstrate the possibilities of optimal distribution of tourist flows, taking into account the constraints of the regions under consideration. The results show that the implementation of the proposed measures can increase the tourist attractiveness of the region and stimulate sustainable tourism development.

Keywords: Tourism, transport infrastructure, digitalization, mathematical modeling, hierarchical management.

1. Introduction

The tourism industry in the southern region of Kazakhstan has high potential, but faces a number of challenges related to limited transport infrastructure, uneven distribution of tourist flows and insufficient coordination between regions [1, 2]. In the context of the growth of domestic tourism and the priority importance of the development of non-resource industries in the strategy of the Republic of Kazakhstan for 2023-2029, the task of a systematic and scientifically based approach to the modernization of the transport and logistics network of the tourism sector arises [3, 4].

In the modern world, digitalization of transport infrastructure plays a key role in increasing the tourist attractiveness of regions. The study by Bukhari et al. emphasizes the importance of using Big Data and IoT to optimize routes and manage tourist flows based on behavioral analytics of tourists [5]. This approach demonstrates effectiveness in cities with high tourism density, such as Almaty and Turkestan.

Mathematical models, including simulation and optimization algorithms, are widely used in tourism for flow distribution and routing. Ghaderi and Henderson [6] present methods for applying linear programming to manage limited tourism resources, which is similar to the problems considered in this paper.

Historically, the transport arteries of southern Kazakhstan have developed unevenly, focusing on industrial rather than tourist potential. Given the current trends in digitalization, sustainable development and environmental constraints, new management methods are required.

According to Hall et al. [7], ecologically sensitive areas require specific approaches to managing tourism loads. The integration of environmental indicators into management models is recognized as mandatory practice by UNEP and WTO.

One of such methods is the hierarchical approach proposed by U. Umbetov [8], which has previously demonstrated effectiveness in industrial and chemical-technological systems. This study is aimed at adapting and testing this approach in the context of tourism logistics.

The work of Wang et al. [9] describes the application of hierarchical control in multi-agent transport systems, which echoes the approach of U. Umbetov. The use of such schemes allows for the efficient distribution of flows between regions and the coordination of the actions of individual transport hubs.

The aim of this work is to demonstrate the possibilities of optimal distribution of tourist flows between the main regions of the south of Kazakhstan, taking into account the constraints of infrastructure capacity and local efficiency functions.

2. Research Methods

The work uses a hierarchical control method that allows decomposing the global optimization problem into subtasks solved in local control nodes, with subsequent coordination of solutions to achieve a global efficiency criterion.

One of the key tasks of managing tourism logistics in the southern region of Kazakhstan is the distribution of tourist flow across regions, taking into account the limited resources and infrastructure capacity [10, 11]. To effectively solve this problem, the hierarchical management method proposed by U. Umbetov was used. A universal scheme for managing complex systems - from industrial to logistics complexes - was proposed. It is adapted to the tourism industry and allows decomposing global tasks into local ones with subsequent coordination. The central idea of the method is the decomposition of a global problem (for example, the distribution of limited tourism resources between regions) into a set of local problems, each of which is solved at its own level and agreed upon with the central coordinating body (CB) through an iterative exchange of control information.

Each subsystem (in our case, a tourist zone or tourist site) has its own local objective function (LOF), reflecting the efficiency of resource use and local constraints (e.g., infrastructural or environmental). The central body, in turn, solves the global problem by formulating a global objective function (GOF) of the following form:

$$G(x_1, x_2, \dots, x_n) = \sum_{i=1}^n f_i(x_i)$$

under global constraint, for example:

$$\sum_{i=1}^n x_i = A,$$

where x_i – volume of tourist flow to the i -th region or zone,

$f_i(x_i)$ – local efficiency function,

A – total throughput.

The iterative process is as follows:

1. The CB sets the control parameters (resource cost constraints or shadows) for each subsystem.

2. Subsystems solve local problems by maximizing their LOFs taking into account the transmitted parameters.

3. The CB receives the results, adjusts the parameters, and the process is repeated until the global maximum G is reached.

This management structure allows:

- taking into account resource constraints and local specifics;
- ensuring coordination of decisions between all levels of the system;
- achieving an optimal equilibrium distribution, in which no subsystem can improve its result without worsening the global performance indicator.

In this paper, this approach is tested for the first time in relation to the management of tourist flows in the south of Kazakhstan – both at the regional and inter-zonal levels.

The southern region includes three key tourist zones: Turkestan, Almaty and Shymkent.

There is a limit on the overall throughput (10,000 people per day). For each zone, a local efficiency function is defined. The goal is to maximize the overall efficiency $G(x)$ under the limit.

Approximate efficiency functions:

$$f_1(x_1) = 2x_1 - 0.0002x_1^2 \text{ (Turkestan),}$$

$$f_2(x_2) = 1.8x_2 - 0.0001x_2^2 \text{ (Almaty),}$$

$$f_3(x_3) = 2.2x_3 - 0.0003x_3^2 \text{ (Shymkent).}$$

The global problem is to maximize $G = f_1(x_1) + f_2(x_2) + f_3(x_3)$, subject to the condition: $x_1 + x_2 + x_3 = 10\ 000$.

In order to solve the problem, an iterative scheme with step-by-step refinement of local flows was used, taking into account the marginal efficiency of redistribution.

As part of the digitalization of transport infrastructure, geoinformation data and statistical indicators presented in electronic formats (data from the Bureau of National Statistics, interactive maps of tourist routes and sites) were used to model the distribution of tourist flows. This allowed not only to increase the accuracy of calculations, but also to adapt the model to real transport and geographic conditions.

The use of numerical optimization methods, including those based on mathematical modeling languages (MATLAB), made it possible to provide iterative refinement of the system parameters, reduce the computational load and speed up the search for the optimal solution.

3. Results and discussion

The simulation results showed that with a uniform distribution of tourists (3,333 people per zone), the efficiency of G is 13,996 conventional units. That is, $G(x) = 4443,8+4899,6+4652,6 = 13\ 996$.

However, when using the hierarchical method and redistributing tourist flows, the efficiency is equal to 13,860 conventional units:

$$G(x) = 4032+6075+3753 = 13\ 860.$$

In this case, 2800, 4500 and 2700 people were selected per zone, respectively (see Table 1).

To find the hierarchical optimal value, the algorithm for distributing tourist flows is implemented using the iterative hierarchical control scheme. The result of the redistribution: Turkestan – 2909 people, Almaty – 4818 people, Shymkent – 2273 people. Then the hierarchical optimal value is 13,927.

This solution allows achieving the global maximum taking into account local constraints. Figures 1 and 2 present the efficiency functions and marginal efficiency for three key tourist zones of the southern region.

Table 1. Comparison of the distribution of tourists

Zones of the southern region	Before distribution	After hierarchical redistribution	
		manually	optimal
Turkestan	3333	2800	2909
Almaty	3333	4500	4818
Shymkent	3333	2700	2273

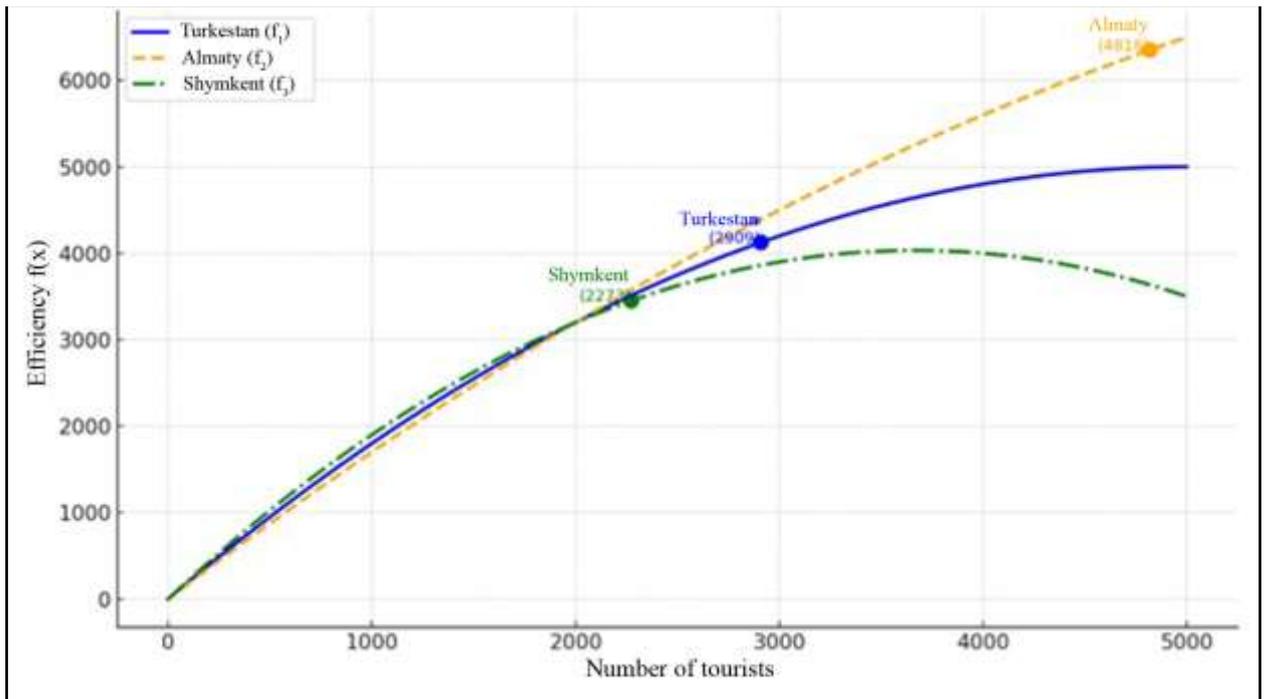


Figure 1. Efficiency functions of tourist zones

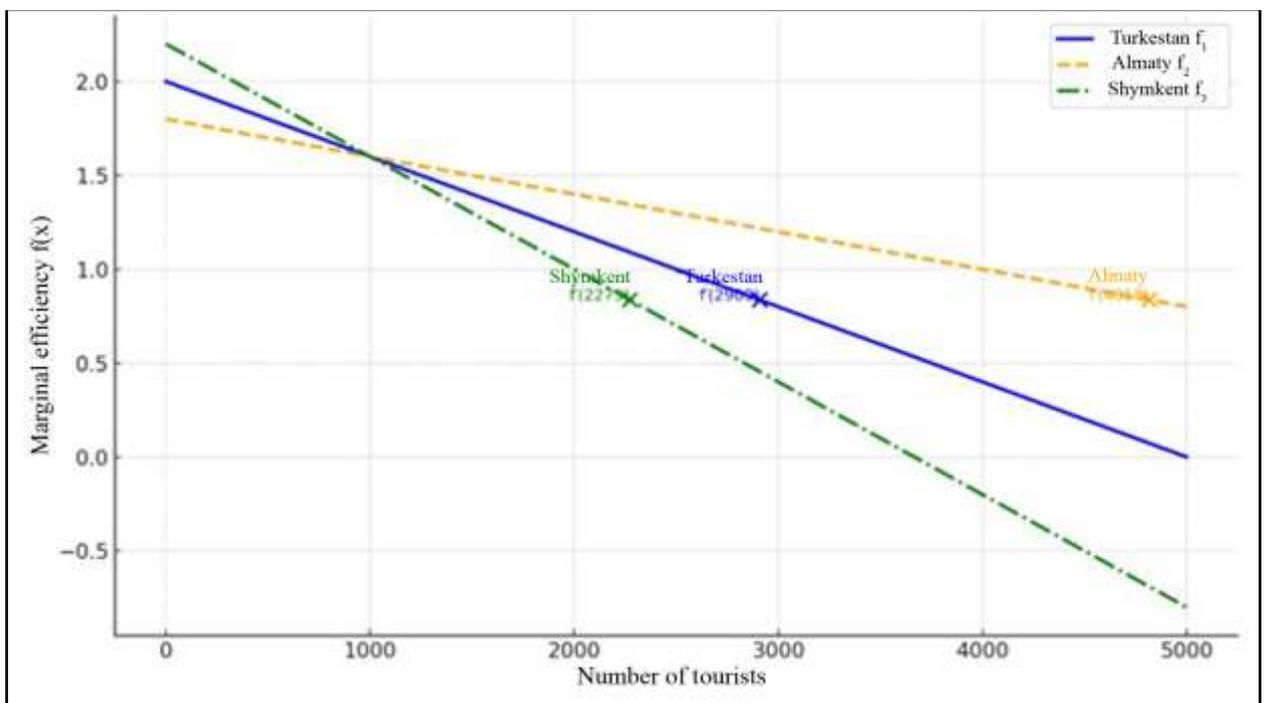


Figure 2. Marginal efficiency of tourist zones

The graph (see Figure 3) shows the dependence of the overall efficiency (x_1, x_2, x_3) on the number of tourists sent to the Almaty region (x_2). At the same time:

- remaining tourists were divided equally between Turkestan and Shymkent,
- the optimum (maximum G) is achieved at $x_2 \approx 4818$ tourists in Almaty.

This confirms that redistribution in favor of Almaty, where the infrastructure is most developed and the efficiency function is higher, provides the best result.

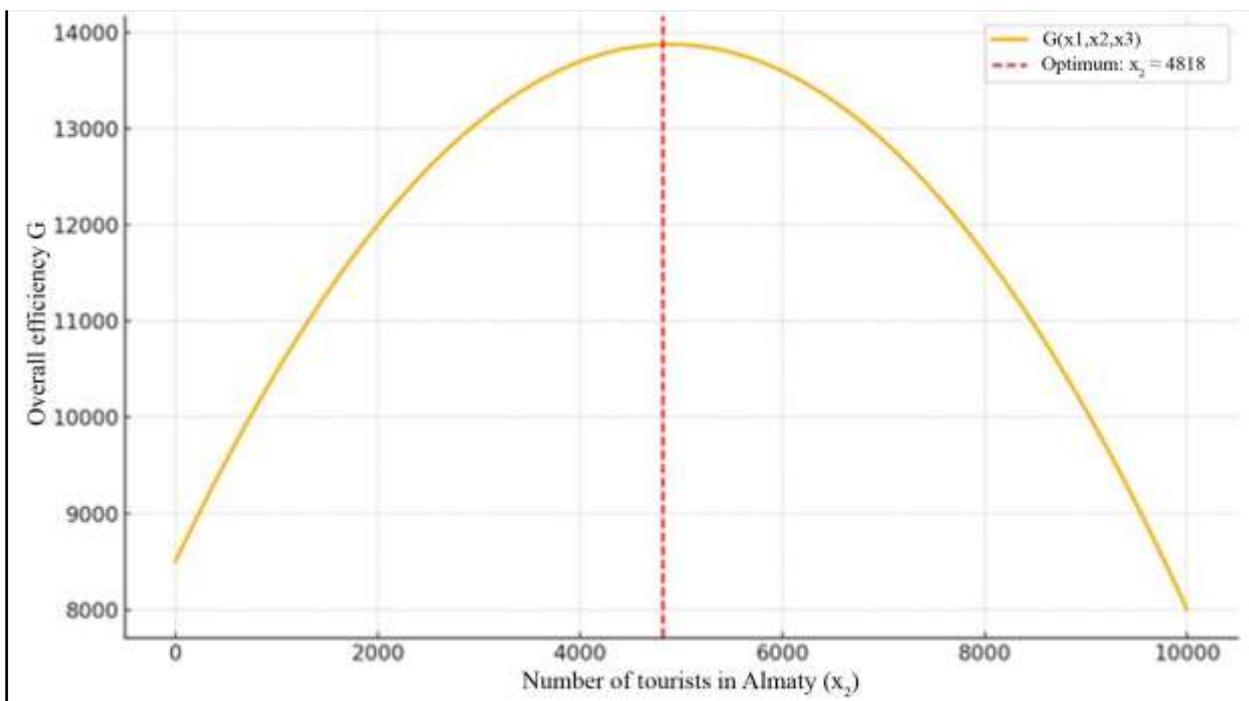


Figure 3. Dependence of the objective function G on the number of tourists in the Almaty region

As a result of numerical optimization, it was found that the highest total efficiency is achieved with the following distribution of tourist flows: Turkestan - 2909 people, Almaty - 4818 people, Shymkent - 2273 people. In this case, the value of the global objective function is $G_1 \approx 13\,927$. This result exceeds the efficiency of $G = 13\,860$ obtained in the previous manual model and demonstrates the potential of rigorous mathematical optimization within the hierarchical approach. This solution takes into account the differences in regional infrastructure and allows for maximum efficiency with limited throughput.

Now, by analogy, using the hierarchical management method, we determine the efficiency functions for three popular tourist sites located in the city of Almaty and the Almaty region [12, 13]:

- Shymbulak ski resort is one of the best ski resorts in Central Asia with developed infrastructure.
- Charyn Canyon is a picturesque natural site with limited ecological carrying capacity.
- State Historical and Cultural Reserve "Tanbaly" - an archaeological site of UNESCO World Heritage with ancient petroglyphs.

Being the most popular among others, the specified sites are visited by tourists most often, i.e. the maximum number can be accepted on average about 60% of all travelers. Thus, if Almaty is visited by 4500 people, then approximately 2700 of them will visit the specified three sites.

To clarify regional planning, additional decomposition was carried out within the Almaty region, one of the key tourist centers of the country. In particular, the tourist flow of 4,500 people distributed to the Almaty region was further optimized between three tourist sites:

The following local efficiency functions were specified:

- $f_{2.1}(x_{2.1}) = 2.1x_{2.1} - 0.0002x_{2.1}^2$ - Shymbulak
- $f_{2.2}(x_{2.2}) = 1.5x_{2.2} - 0.0001x_{2.2}^2$ - Charyn
- $f_{2.3}(x_{2.3}) = 1.8x_{2.3} - 0.0003x_{2.3}^2$ - Tanbaly

General constraint:

$$x_{2.1} + x_{2.2} + x_{2.3} = 4500$$

Objective function for the Almaty region:

$$G_2=f_{2,1}(x_{2,1})+f_{2,2}(x_{2,2})+f_{2,3}(x_{2,3})$$

Optimization showed the following redistribution result (see Table 2):

Table 2. Comparison of the tourists distribution

Site	Distribution	Optimal distribution
Shymbulak	1500	2182
Charyn Canyon	1500	1364
Tanbaly	1500	954

In this case, the maximum efficiency is equal to $G_2 \approx 6\,934,1$.

The graph (see Figure 4) shows the dependence of the total efficiency G_2 when redistributing tourists to Shymbulak, provided that the remaining tourists are divided equally between Charyn and Tanbaly. The optimum is achieved at $x_{2,1} \approx 2182$, it is at this point that the entire system (Shymbulak + Charyn + Tanbaly) operates most efficiently.

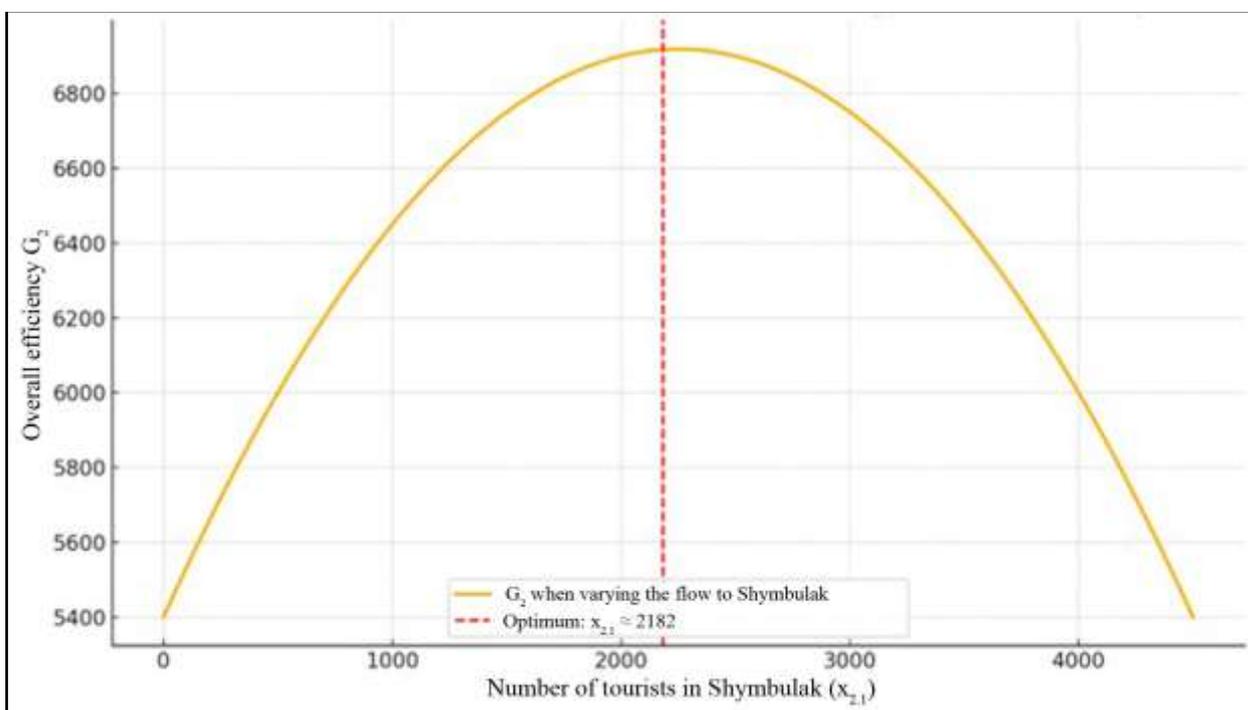


Figure 4. Dependence of G_2 efficiency on the number of tourists in Shymbulak

Taking into account the above, the following conclusion can be made:

The largest number of tourists are sent to Shymbulak, since its efficiency function is higher and it can serve more visitors. Sites with a more fragile ecology and having a higher sensitivity to tourist loads (Charyn, Tanbaly) receive fewer tourists - this corresponds to the principles of sustainable tourism. Optimal distribution reflects both the tourist attractiveness of sites and environmental and capacity constraints.

An important element of the model is the consideration of the ecological carrying capacity of individual sites, especially such as the Charyn Canyon and the Tanbaly Nature Reserve. These zones have high natural and cultural value, but are sensitive to anthropogenic load. Consideration of ecological constraints was implemented through additional coefficients in local efficiency functions, which made it possible to avoid overloading fragile ecosystems and ensure sustainable distribution of tourists.

In addition, all calculations and visualization of results were performed using digital tools

- spreadsheets, graphic modules and online maps, which confirms the possibility of integrating the proposed model into the digital platform for managing regional tourism.

Thus, the hierarchical model has demonstrated high flexibility: first, global distribution by regions is ensured, and then local optimization at the level of tourist facilities. This is especially important in the context of sustainable tourism and ecologically balanced load on infrastructure.

The obtained data indicate that the hierarchical approach allows taking into account differences in regional infrastructure and tourist preferences, optimizing the overall effect. An important advantage of the method is its adaptability and the ability to scale up with an increase in the number of regions or changes in constraints.

4. Conclusion

Testing of the hierarchical management method on the example of tourism logistics in the southern region of Kazakhstan has shown its high efficiency. The application of the model has allowed not only to increase the overall effect of the tourist flow, but also to ensure a more sustainable and balanced development of tourist destinations.

Thus, the proposed model can serve as a basis for further research and practical application in developing regional tourism strategies, digitalization of transport infrastructure and implementation of sustainable development principles. A promising direction for further research is taking into account seasonality, integrating environmental indicators and expanding the model to a wider geographical scale.

The conducted research demonstrates that digitalization of transport infrastructure, including collection, processing and visualization of spatial data, combined with mathematical modeling and consideration of environmental constraints, is an integral part of the modern system of tourist flow management. This opens up prospects for the development of digital solutions and regional platforms that ensure sustainable development of tourism in Kazakhstan.

Acknowledgments and Conflict of Interest.

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Authors' contributions.

Nuralina A.K. made a significant contribution to the work - the concept of the work; collection, analysis and interpretation of the work results; writing the text. Altayeva Zh.Zh, Altynov Zh.L, Turdaliev A. - critical analysis of the work content and approval of the final version of the article for publication.

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