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Designing an Efficient Bike-Sharing System for the University of Bojnord

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ABSTRACT

The rapid growth of urbanization and the increasing use of motor vehicles have intensified transportation challenges, such as congestion and air pollution. In light of this, bicycle-sharing systems have emerged as a sustainable and cost-effective solution. This study presents the design of a bicycle-sharing system for the University of Bojnord, covering an area of approximately 150 hectares with more than 5,000 students. A mixed-integer linear programming model was developed to determine the optimal number and locations of bicycle stations as well as the required bicycles while minimizing total system costs, including installation, purchasing, and maintenance. The model was solved and analyzed using GAMS software. Sensitivity analysis was conducted to evaluate the effects of key parameters, and the most frequent travel routes were identified to enhance system efficiency. The results indicated that implementing the proposed system can significantly improve transportation quality and promote sustainable mobility within the campus. However, successful implementation requires the development of supporting infrastructure, including smart stations and secure parking areas. The proposed framework can also serve as a reference for designing similar systems in other universities and urban areas.

1.Introduction

Rapid urbanization and increased use of motor vehicles have intensified traffic congestion, air pollution, and other transportation challenges, reducing the quality of life in many urban areas. Sustainable, cost-effective, safe, and environmentally friendly transportation solutions are therefore crucial for modern cities (Pucher et al., 1999; Shelat et al., 2018). Bicycles, as a

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sustainable mode of transportation, offer numerous advantages, including improved physical health, ease of parking, reduced fuel consumption, minimized noise and air pollution, and decreased infrastructure costs (Siami & Nodushan, 2018).

Bike-sharing systems (BSS) have gained global popularity as an effective sustainable transportation option, with over 1,900 initiatives and approximately 967 million bicycles implemented worldwide by 2022 (Frade & Ribeiro, 2015; Meddin Bike-sharing World Map Report). These systems provide flexible, low-cost, and environmentally friendly mobility, particularly in densely populated urban and academic environments.

In university campuses, transportation challenges are exacerbated by traffic limitations and environmental concerns, making bicycles a preferred mode for students (Negravi et al., 2016). This study focuses on designing a bike-sharing system for the University of Bojnord, aiming to improve intra-campus mobility, reduce reliance on motorized transport, and promote sustainable transportation practices in an academic setting.

2. Literature Review

In the field of bike-sharing systems, numerous studies have addressed various aspects of the topic. This research focuses on the core aspect of system design, and this analysis contributes to a better understanding of fundamental concepts and the associated challenges in this area.

Lin and Yang (2011) examined a bike-sharing system that allowed unlimited bike storage at each station. The goal of this research was to optimize the number and location of stations, create bike lanes, and select routes between high-demand areas. Due to the complexity of the issue, they avoided precise solutions and, instead, proposed an exploratory method to find nearly optimal solutions on a larger scale. This method initially calculated the total costs of the network and then achieved acceptable results through sensitivity analysis of parameters affecting inventory and routing decision-making.

Thomas et al. (2012) optimized the number of bicycles and stations using GIS optimization analysis while examining the bike-sharing issue in downtown Boise. Their results showed that 140 bicycles and 14 stations were optimal for this area. This method was not only compared with similar projects but was also confirmed as a useful solution for developing the Boise bike-sharing network (Wuerzer et al., 2012).

Martinez et al. (2012) optimized the locations of shared bike stations through an exploratory process using a mixed-integer linear programming approach. The main goal of this research was to maximize revenue from bike stations.

Askari et al. (2017) examined the location-allocation problem in bike-sharing systems, considering station capacity and bike shortages, using a sample mean approximation method to address random shortages. In this study, a hybrid algorithm, particle swarm optimization, and genetic algorithms were used to solve the problem on a large scale.

Yan et al. (2017) presented a novel approach to designing four bike rental networks that considered both deterministic and stochastic demands. Their research focused on station location, fleet size optimization, and route allocation, developing two models: DBLAM (Deterministic Bike Location and Allocation Model) and SBLAM (Stochastic Bike Location and Allocation Model), and introducing a mixed-integer programming model. The results of their computational experiments, using data from the New Taipei City bike program, confirmed the accuracy and efficiency of the proposed model and solution method.

Liu et al. (2019) conducted a study on bike network design, focusing on separating bike paths from main roads. In this research, it was assumed that all roads were suitable for constructing bike paths, demand for bicycles was fixed, and users selected roads based on travel comfort. Additionally, considering budget constraints for building the bike network and using a model to simulate cyclists' route choice behavior, specific dimensions of the topic were examined.

Jahanshahi et al. (2019) assessed the current state of bike-sharing stations in Mashhad and identified potential locations for future stations. This research used seven site selection criteria and employed the AHP method based on GIS to weight the criteria. Utilizing multi-criteria optimization and compromise solutions, the stations were ranked, and locations were classified using the Jenks natural breaks classification method. The results showed that out of 128 stations examined, 51 stations were unsatisfactory, indicating a need for improved distribution of these stations in the city.

Bahadori et al. (2022) proposed an integrated GIS-MCDM decision-making framework that included the AHP process, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and spatial data processing in GIS. This framework was designed to optimize potential locations for bike rental and delivery stations and was successfully implemented in a case study in Lisbon, Portugal.

Bradshaw et al. (2022) designed a floating bike-sharing program at a large university. Using a mixed-methodology, including data collection, quantitative surveys, and focus groups, it was shown that the program was quickly accepted. In the first three months, 19,504 users registered. Among the respondents, 63.3% were primarily first-year students and university residents who used the bicycles. Main concerns included safety, awareness of the program, and costs (Bradshaw & Kitchin, 2022).

Ababneh (2023) conducted research on designing bike-sharing systems for historical sites. The aim of this research was to emphasize the importance of usability, scalability, integration, user experience, and sustainability in designing these systems. To understand visitor needs and reduce negative environmental impacts, intelligent flow analysis and data analysis were employed. The results indicated that implementing an intelligent bike-sharing system using intelligent transportation systems at the historic Gerash site could promote sustainability and safety, enhance the visitor experience, and minimize adverse impacts on the cultural heritage of the site.

Mirosława et al. (2023) aimed to model cyclists' route choice preferences using Strava and OSMnx data. Through a path size logit model, the results indicated that factors such as traffic signals and the presence of cycling infrastructure on bridges significantly influenced route choice. The study provided a better understanding of cyclist behavior and offered insights for urban planning related to cycling infrastructure.

Chalermpong et al. (2023) conducted a meta-analysis of seven studies (2015–2022) to examine the relationship between the built environment (BE) and the use of rail transit and bike-sharing systems (RTBS). The findings revealed that land use, population density, employment density, and proximity to commercial centers significantly affected RTBS usage. The study emphasized the importance of promoting non-residential land uses, developing denser urban areas, and improving transport infrastructure to enhance RTBS adoption.

Ahmadi et al. (2024) focused on optimizing resource allocation and infrastructure planning in bike-sharing systems, considering demand fluctuations during the COVID-19 pandemic. A multi-period stochastic mathematical model was proposed to optimize station allocation and network design. The case study of Vienna's bike-sharing system indicated that increased construction costs of stations and bikes negatively affected meeting demand. The findings highlighted the critical role of cost management and data-driven decision making in designing efficient bike-sharing networks.

3. Research Gaps

Most studies on bike-sharing systems have focused on urban areas, addressing social and environmental issues. However, the specific needs and characteristics of universities—with their unique academic environments and defined populations of students and faculty—have rarely been explored. Existing research primarily aims at improving city-level systems, with limited efforts dedicated to designing bike-sharing systems tailored for academic settings, especially in Iran.

This study addresses this gap by designing a bike-sharing system tailored for the University of Bojnord. The mathematical model is evaluated under various parameter settings, and sensitivity analysis is conducted to identify the most effective scenarios and recommendations for implementation. This approach enables the identification of practical, evidence-based solutions to optimize the system for intra-campus mobility and promote sustainable transportation among students.

4. Case Study

The University of Bojnord, established in 2005, is a public institution located in Bojnord, North Khorasan Province, covering over 150 hectares and hosting approximately 5,000 students. As the main university in the region, it serves as an important hub for education and research. Its campus presents a dynamic environment suitable for implementing a bike-sharing system. The university's spatial layout and student population provide a representative case for analyzing and optimizing intra-campus transportation through a sustainable, bicycle-based mobility solution.

5. Problem Statement

This research develops a mixed-integer linear programming (MILP) model to optimize a bicycle-sharing system at the University of Bojnord. The primary objective is to determine the optimal number and placement of stations and bicycles to minimize costs and maximize system efficiency. The university's location outside the city and the prohibition of private vehicles on campus create the critical need for an effective intra-campus mobility solution. Demand patterns, station capacities, and spatial constraints are formalized within the mathematical model; after solving the model, the results are analyzed to derive recommendations for deploying a sustainable and cost-effective bicycle-sharing system.

5.1. Problem Assumptions

In the following, a set of assumptions that form the basis of the modeling is presented:

- A 12-hour time period during the day, from 8 AM to 8 PM, is divided into six 2-hour intervals.
- A complete graph is considered for all university routes (both paved and unpaved).
- The total cost includes the fixed cost of the location for establishing stations and the cost of purchasing bicycles.
- The gravity model is used to determine the number of trips between locations.
- The bike-sharing network is closed, implying that no bicycles exit the system.
- Each bicycle serves one person at a time, thereby being occupied during the trip.

5.2. Model Symbols

In this modeling, specific symbols are used to represent sets, parameters, and decision variables. Table 1 presents these symbols along with brief explanations.

Table 1. Sets, Parameters, and Variables of the Model

Sets	
i , j = {1,…,41}	Candidate locations for station establishment
t = {t_1,…,t_6}	Time period list
Parameters	
P	Maximum number of required stations
$Maxdis_1$	Maximum distance between stations
$maxdis_2$	Maximum coverage distance for assigning a location to a station
Bicper	Percentage of students using the system
C_1	Cost of establishing a station
C_2	Cost of purchasing a bicycle
C_3	Maintenance and repair cost
Cap	Maximum capacity of each station
d_{ij}	Distance between locations i and j
w_{0it}	Population of candidate location i in each time period t
F_{ij}	Travel time factor between locations i and j
TT_{ijt}	Number of trips produced at location i and attracted to location j in time period t
b	In the gravity model, the exponent is empirically determined and calibrated according to conditions
K	Constant factor for formula correction
Decision Variables	
x_j	Whether or not to establish a station at location *j*
Y_{ij}	If location i is assigned to station j
u_{ij}	Auxiliary variable for linearizing the nonlinear constraint
NB_j	The number of bicycles available at station j

5.3. Mathematical Model

Based on the aforementioned assumptions and the introduced symbols, the problem is modeled as follows:

$$\text{Min } Z = C1(\textstyle\sum_j x_j) + C2(\sum_j NB_j) + C3\,(\sum_j \sum_t NBt_{jt}) \tag{1}$$

Subject to:

$$Y_{ij} \le x_j \qquad \forall i.j \tag{۲}$$

$$\textstyle\sum_j x_j \le p \tag{۳}$$

$$NB_j \ge \sum_i bicper(\max t(\ TTijt\ ))Y_{ij} \qquad \forall j.t \tag{۴}$$

$$NB_j \ge cap \times x_j \qquad \forall j \tag{۵}$$

$$\textstyle\sum_j (d_{ij} \le maxdis_2 \times Y_{ij}) = 1 \tag{۶}$$

$$x_j \times x_i \times d_{ij} \ge maxdis_1 \qquad \forall i.j \tag{۷}$$

$$x_j.\ Y_{ij}.\ U_{ij} \in [0.1] \tag{۸}$$

$$NB_j \ge 0 \ \&\ \text{integer} \tag{۹}$$

Equation (1) represents the cost-based objective function, aiming to minimize the total system setup costs, including station construction, bicycle procurement, and maintenance expenses. Equation (2) defines the relationship between locations and assigned stations, while equation (3) restricts the total number of stations to the predetermined maximum. Equation (4) ensures that the number of bicycles at station j meets the minimum required demand, determined by the maximum number of trips between locations i and j in different time periods. This is then adjusted by the bicycle usage rate (bicper). To estimate this demand, the gravity model is employed, which, based on the physical law of gravity, explains movement and interaction between locations according to their attractiveness and distance. This model considers variables such as population, socioeconomic characteristics, and geographical distance to predict trip volumes. Equations (10) and (11) are used to compute the gravity model and determine the travel time factor necessary for demand estimation (Schaarsberg, 2016).

$$TT_{ijt} = (w0_{it} \times w0_{jt} \times F_{ij} \times K) / \sum^{p} w0_{jpt} \times F_{ijp} \times K \quad \forall i.j.\mathrm{j}.\, i \neq j,\ w0(jp,t)>0 \qquad (١٠)$$

$$F_{ij} = 1 / (d_{ij}^{b}) \quad \forall i.j.\, i \neq j \qquad (١١)$$

Equation (5) impose capacity limits, ensuring that the number of bicycles at each station does not exceed its maximum capacity. Equation (6) restricts the assignment of each location to a single station within a specified coverage distance. Equation (7) enforces a minimum spacing between stations; since it includes the product of two binary variables, it is linearized by introducing an auxiliary variable and three supporting equations.

$$u_{ij} \geq x_j \quad \forall i.j \qquad (١٤)$$

$$u_{ij} \geq x_j \quad \forall i.j \qquad (١٥)$$

$$u_{ij} \leq x_i + x_j - 1 \quad \forall i.j \qquad (١٦)$$

Equations (8) and (9) specify the type of decision variables as binary or integer.

5.4. Solving the Mathematical Model

The proposed mathematical model for optimizing the bicycle-sharing system at the University of Bojnord was implemented and solved using GAMS with the CPLEX solver. The model incorporates 41 demand points, representing building entrances and key student movement locations across the campus. Distances between these points were calculated using campus maps, and trip demands were estimated based on a gravity model.

The system was structured for six two-hour time intervals from 8:00 a.m. to 8:00 p.m., taking into account class schedules and daily student movement patterns. Model parameters include the number and capacity of stations, expected system usage, maximum distances for station placement and coverage, costs associated with station construction, bicycle purchase, and maintenance. Key model parameters and system dimensions are summarized in Table 2, while the corresponding costs are presented in Table 3.

The model was resolved within these constraints to identify the optimal number and placement of stations and bicycles, allocation of demand points to stations, and expected system performance. The results provided an effective configuration that minimized costs while maximizing service efficiency, offering a solid foundation for implementing a sustainable campus bicycle-sharing system.

Table 2. Dimensions of the Mathematical Model

Symbole	Value	Parameter Description
i	۴۱	**Candidate locations for stations**
t	۶	**Number of time periods**
p	5	**Number of stations**
Cap	۲۰	**Station capacity**
Bicper	۵۰	**Expected system usage by students**

$Maxdis_1$	۸۰۰	**Maximum distance between stations**
$maxdis_2$	۷۰۰	**Maximum coverage distance for assigning points to stations**

Table 3. Costs (Million IRR)

Cost of building a station	Cost of purchasing a bicycle	Cost of periodic bicycle maintenance and service
C_1	C_2	C_3
۵۶۰	۱۲۰	۰/۰۱۸

Table 4. Response Values of the Model After Solving in GAMS

Efficiency Ratio (Station)	Efficiency Ratio	Supply	Demand	Objective Function Value	Assigned Points	Required Number of Bicycles (Daily)	Selected Station Points
1.0	1.01	100	99	31070	4, 9, 20, 26, 36, 40	20	L4
1.0					1, 3, 19, 21, 25, 28, 35, 38	20	L25
1.1					7, 8, 14, 17, 22, 32	19	L32
1.0					2, 6, 10, 11, 12, 15, 18, 24, 27, 29, 30, 33, 34	20	L34
1.0					5, 13, 16, 23, 31, 37, 39, 41	20	L41

In Table 4, the selected points for bike stations and the required number of bicycles per day are displayed. Additionally, the allocated points, objective function value, demand and supply, overall efficiency ratio, and efficiency ratio for each station are provided. Efficiency ratios above 1 indicate optimal model performance.

These results demonstrate that the model performed well with the specified parameter values and is consistent with all constraints, making it ready for implementation.

6. Sensitivity Analysis

To assess the sensitivity of the model to key parameters, multiple scenarios were designed. The main parameters considered included the system usage (Bicper), station capacity (Cap), and the number of stations (P), as changes in these parameters significantly affect system performance and associated costs. These parameters were evaluated within the following ranges: system usage of 20% to 80%, station capacity of 20 to 40 bicycles, and the number of stations from 4 to 6.

By combining different values of these parameters, a total of 75 scenarios were analyzed, with 53 scenarios produced feasible solutions. The analysis indicated that increasing the number and capacity of stations enhances system flexibility in response to demand fluctuations while it may also lead to inefficient resource utilization. Higher system usage increases overall costs.

The demand-to-supply ratio, station distribution, and capacity utilization play critical roles in overall system efficiency. Stations located in high-demand areas must have sufficient capacity to meet peak-hour requirements and avoid resource waste. This sensitivity analysis highlights the importance of accurately selecting key parameters in designing an optimized and sustainable bicycle-sharing system.

6.1. The Impact of Key Parameters on the Design of the Bike-Sharing System

Scenario analysis charts illustrate the effect of three key parameters—the number of stations (P), the number of bicycles per station (Bicper), and station capacity (Cap)—on the total system cost. Increasing the number of bicycles and certain system parameters leads to higher total costs, while increasing the number of stations and their capacity can reduce costs. This relationship is not always linear, and an optimal number and capacity of stations can minimize costs and maximize system efficiency.

The analysis indicated that the careful adjustment of these parameters enables the bike-sharing system to efficiently meet user demand while minimizing overall costs.

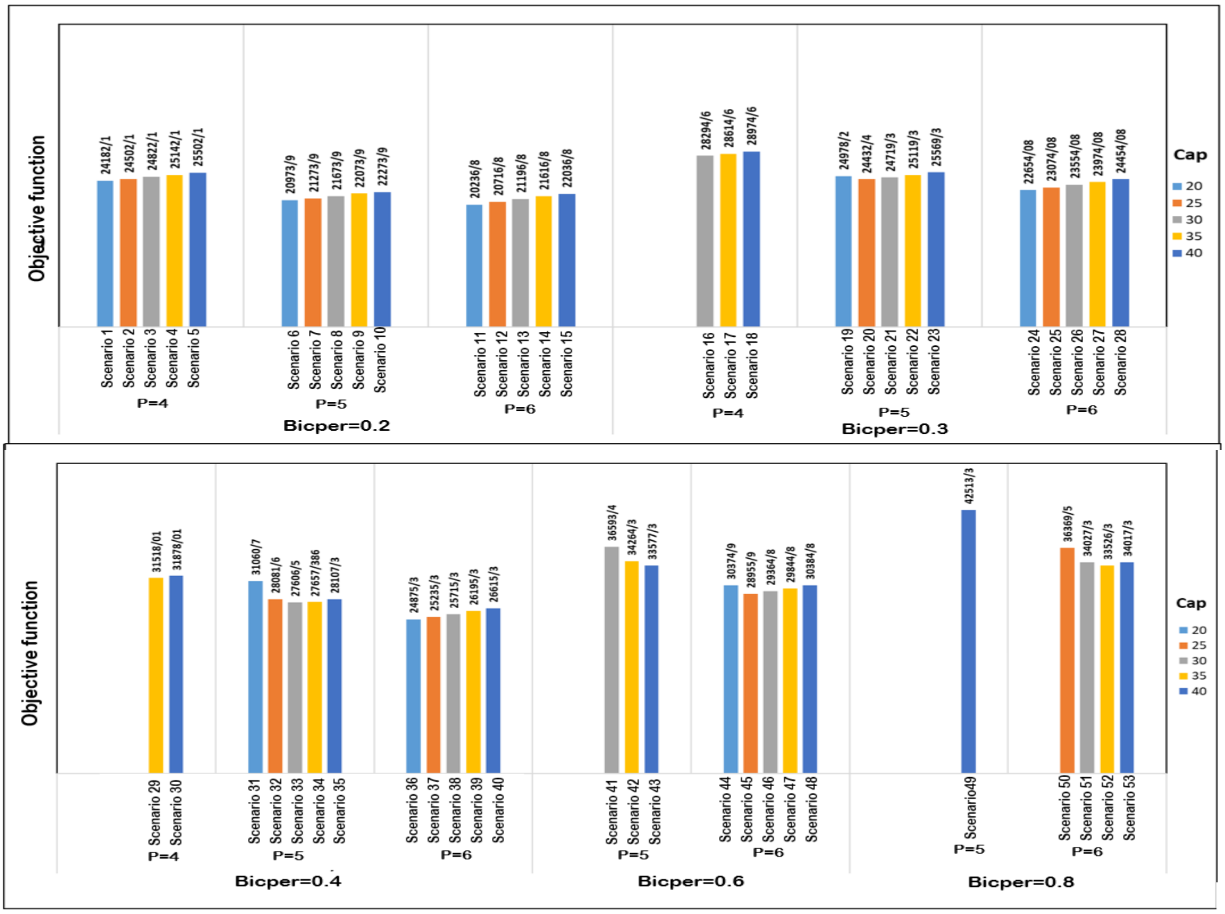

Figure 1. Impact of Key Parameters on the Total Cost of the Bike-Sharing System

6.2. Station Location Results of the Bike-Sharing System

Figure 2 presents the results of station location analysis under different scenarios at the University of Bojnord. The analysis indicated that certain station locations remain consistent across scenarios, reflecting their geographical and functional significance.

However, variations in parameters, such as station capacity, the number of bicycles, and the number of stations, can lead to changes in specific locations, highlighting the sensitivity of the system under specific conditions. Some locations are repeatedly identified as optimal, particularly when the number of stations is limited or user demand is low. This helps decision-makers focus on key points and avoid unnecessary changes in station deployment.

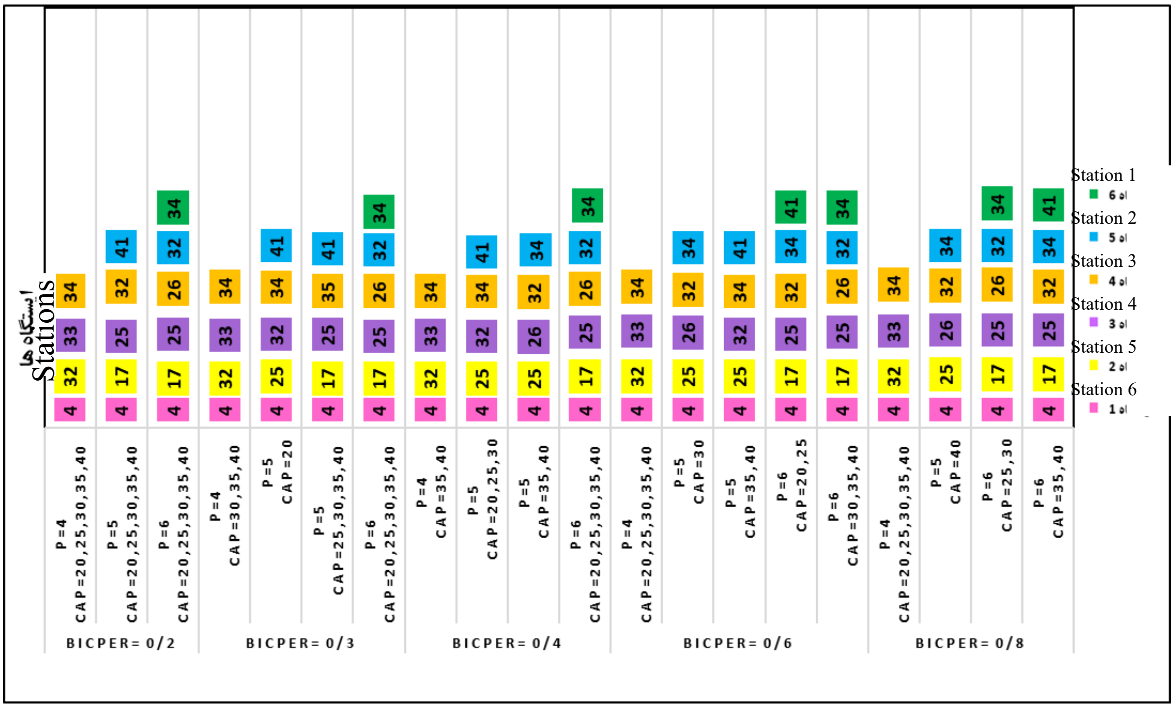

Figure 2. Results of Station Location Analysis for the Bike-Sharing System at the University of Bojnord

6.3. Discussion on Scenario Analysis

The analysis of 53 scenarios for station location in the University of Bojnord bike-sharing system revealed that no single scenario can fully satisfy all objectives. Some scenarios with the lowest objective function values primarily focus on minimizing system costs, while others with the best efficiency ratios aim to maximize system performance and user satisfaction. Another group maintains balanced bicycle distribution, ensuring system stability and preventing shortages or overcrowding at stations.

Overall, selecting the optimal scenario depends on project priorities: cost-sensitive projects may prefer low-cost scenarios, efficiency-focused projects should consider high-performance scenarios, and projects emphasizing operational balance may prioritize scenarios with balanced bicycle allocation.

For practical implementation, the frequently selected network of stations will be further analyzed in the following section and considered as the basis for final optimization and real-world deployment of the system.

6.4. Identification of Frequently Selected Networks

The analysis of 53 scenarios revealed that certain stations and links are consistently selected as optimal across multiple scenarios, establishing the frequently selected networks. These nodes and links are strategically located and serve as the core framework for both practical implementation and future expansion of the system.

By evaluating the selection frequency of each node and link, three representative networks were identified for different numbers of stations:

P = 4: Scenario 16
P = 5: Scenario 34
P = 6: Scenario 36

These frequently selected networks are proposed as final options for system implementation, providing a foundation for enhanced efficiency, reduced costs, and improved user satisfaction.

7. Conclusion

This study focused on the design and analysis of a bike-sharing system for the University of Bojnord, achieving significant results in improving on-campus transportation and promoting sustainable mobility. The proposed mixed-integer programming model determined the optimal station locations and the required number of bicycles across different time periods. The analysis of 53 scenarios revealed that the optimal scenario depends on project priorities, with scenarios 16, 34, and 36 identified as the best options balancing cost and efficiency.

A key contribution of this study is the identification of frequently selected networks, providing a decision-making framework that is adaptable to the specific conditions of the university and can serve as a model for similar implementations in other educational institutions. The model efficiently utilized available resources while addressing constraints such as limited historical data and environmental complexities.

Future research may focus on the long-term influences of the system, enhanced simulation models, and integration of new technologies, such as e-bikes, to further improve the efficiency of bike-sharing systems in university settings.

Overall, this study demonstrates how mathematical modeling and comprehensive analysis can optimize urban mobility solutions in educational environments. The results provide a valuable scientific and practical reference for the planning and implementation of sustainable transport systems in other universities.

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