TOURIST ATTRACTIONS CAPPING VISITOR NUMBERS

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Abstract

Sustainable tourism is essential for preserving natural and cultural heritage while ensuring long-term economic benefits for local communities. This study examines the effects of implementing visitor caps at Manyeleti Nature Reserve, a popular tourist attraction in Mpumalanga, South Africa. We limit visitor numbers at the attraction to mitigate environmental degradation and maintain the quality of the visitor experience. Tourism in Mpumalanga is an important sector that supports the province's economy and promotes environmental conservation and cultural preservation. In this manuscript, we describe a simple mathematical model designed to manage the capacity of Manyeleti Reserve. The presented model is formulated as an optimization problem where the objective is to maximize visitor satisfaction and maximizing revenue collected by the reserve while minimizing costs associated with rendering the service. The model considers visitor numbers, impact on the environment, and community well-being to determine optimal visitor numbers that align

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with sustainability objectives. The developed Mixed-Integer Linear Programming (MILP) problem is solved using the IBM CPLEX Optimization Studio, leveraging the docplex library in Python. The results suggest that capping visitor numbers can reduce ecological strain, support local economies, and enhance visitor satisfaction, thereby contributing to more sustainable tourism management. The Mpumalanga Tourism Parks and Agency may also utilize the obtained results to formulate policy to meet their strategic objective, which is to provide for the sustainable management and promotion of tourism and nature conservation in the province and to ensure the sustainable utilisation of natural resources.

1 Introduction

Tourism plays a crucial role in the economic development of many regions by providing jobs for the locals, providing a market to sell antiques, promoting cultural exchange, and contributing to conservation efforts. The Mpumalanga Province in South Africa is a prime example of a region that relies heavily on tourism. Mainly, Mpumalanga's economy is anchored by tourism and agriculture. Known for its biodiversity and iconic landscapes, such as the Kruger National Park, the Panorama Route, and Blyde River Canyon, the province of Mpumalanga stands out as a prime destination, attracting millions of visitors from across the globe each year. Among these tourist attractions is Manyeleti Game Reserve, a lesser-known gem bordering the Kruger National Park. While the reserve offers a more intimate wildlife experience than its more famous neighbours, the increasing popularity of Manyeleti has raised concerns about sustainable management and the long-term impact of tourism on the environment. With the influx of tourists to the province, there is significant pressure on the environment, infrastructure, and local communities.

As the number of visitors grows, so too does the pressure on a reserve's delicate ecosystems. Unchecked tourism can lead to environmental degradation, disruption of wildlife patterns, and a reduction in the quality of visitor experience. In Manyeleti, there is a need to balance conservation goals with economic benefits. This highlights the importance of sustainable tourism, a model that ensures that tourist activities are managed in a way that protects the environment and local communities while still offering the best experience for visitors. Overcrowding at these key tourist attractions threatens the ecological balance of protected areas and also diminishes the quality of the visitors experience. In Mpumalanga, in recent times, the strain on natural resources, wildlife habitats, and cultural sites has raised concerns among conservationists and policymakers. To address these challenges, limiting the number of visitors at popular tourist spots has become a focal point for sustainable tourism strategies. By restricting the number of tourists allowed at any given time, each tourist attraction can maintain its ecological integrity and ensure that future generations can continue to enjoy the unique beauty and wildlife of the area.

For the MISG study group in 2024, we examined the rationale behind implementing visitor limits in Manyeleti Reserve, especially for the local community from Bushbuckridge, Acornhoek and surrounding areas. We explored the environmental and social imperatives for regulating tourist numbers by developing a mathematical model seeking to find the optimal number of visitors that may be allowed at the attraction to mitigate the adverse effects of overcrowding and over-tourism. By focusing on the Manyeleti Reserve, the study group's aim was to establish the optimal number of tourists allowed to enter the park and to highlight how balancing tourism demand with conservation can protect the province's natural and cultural assets for future generations.

The rest of this report is organized as follows: Section 2 reviews relevant literature on studies addressing similar challenges. Section 3 presents a concise description of the problem tackled in this manuscript. In Section 4, we develop a mathematical optimization model to simulate visitor flow within the nature reserve. Section 5 simulates different crowd scenarios and discusses the results, and finally, Section 6 provides the conclusion of the report.

2 Literature review

In the literature, there are a few studies that were carried out to determine the optimal number of people that may be allowed at any tourist attraction. McCool and Lime [8] discuss how the carrying capacity framework may be used to manage visitor flows in sensitive and protected ecological areas. In the MISG study, understanding the carrying capacity of Manyeleti Reserve is important for limiting visitors to the park without compromising the well-being of wildlife. Coccossis and Mexa [3] carried out a study that offers insights into how carrying capacity assessments can inform decision-making regarding visitor limits. Other studies on visitor management strategies in African protected areas were carried out in [4, 2].

Mathematical models developed for maximizing the revenue collected by tourist attractions and at the same time maximizing visitors experience are built in the framework of capacity management (CM). CM highlights the optimal strategic utilization of a park's resources and services. CM also involves the forecasting possible number of visitors per day, monitoring the flow of visitors, and adjusting and reallocation of resources to meet visitors demands [5, 9]. The need to balance the number of tourists in each cite with available resource to avoid overcrowding is crucial for park management. An efficient management of a park's capacity results in efficiency in a park's operations.

Tourist attractions faces several factors that can influence their capacity and flow. These include the location of the attraction, layout of the attraction, popularity of the attraction, number of attractions, weather conditions, and special events happening in the attraction. These factors, combined, do impact the overall experience of visitors and the ability of management to utilize available resources. CM strategies must be effectively implemented to balance these factors and ensure positive satisfaction of visitors [11]. Existing CM models in the literature include *(i)* the dynamic pricing model which is similar to how airlines adjust ticket prices based on demand, *(ii)* the capacity forecasting model which uses historical data, weather forecast and relevant factors to predict demand, *(iii)* season pass and membership program, and *(iv)* operational flexibility which include strategies such as opening additional attractions during peak times.

Critiques of the existing CM models include that these approaches often lack flexibility and responsiveness to sudden changes in demand [10]. Nature reserves traditionally rely on static capacity planning models that do not account for dynamic changes in the number of guests visiting an attraction cite. This leads to resource under-utilization during off-peak periods as well as long ques and waiting times during peak periods. Also, tourist attractions struggle with forecasting demand accurately which leads to inefficiencies in resource allocation [6]. Finding a CM model that implements real-time data analytics can provide these reserves with the relevant information to adjust staff and operation levels in real-time, thus optimizing operations and improving overall guest experience [7].

3 Problem statement

Several tourist attractions in Mpumalanga are in the process of rejuvenation. It is envisaged that the restored tourist attractions will attract a large number of people, which may lead to overcrowding. Overcrowding has become a significant concern in the context of sustainable tourism. Overcrowding can lead to significant environmental degradation. The excessive footprints wear down the natural landscapes, harm wildlife habitats, increase pollution through littering and increase the use of transportation. In delicate ecosystems such as natural or heritage sites, the damage can be irreversible, leading to loss of biodiversity and natural beauty. It is important for natural attractions to sustain the physical or ecological impact of visitors.

The issue for the tourist attractions managers surrounds the number of visitors that can be accommodated before the experience provided by the attraction is compromised, leading to negative impact on the environment, visitors experience and local communities. This challenge can be resolved through determining the attraction's social carrying capacity (SCC) taking social comfort level (SCL) into account.

The objective of the project is to develop a viable mathematical model to determine the social carrying capacity of a tourist attraction to mitigate the negative impact of over-tourism while providing a high-quality experience for visitors. The model should consider the available infrastructure, activities, natural and cultural resources, and accommodation. The tourist attractions in consideration are Manyeleti Nature Reserve, Mariepskop Nature Reserve, Bushburckrigde Nature Reserve, and Injaka Dam.

4 Mathematical model

4.1 Model development

In this section, we present a mathematical model designed to manage the capacity of tourist attractions, ensuring that resources are not overstretched while maintaining a high-quality visitor experience. Rather than directly answering the question of what the carrying capacity of a tourist attraction is, the model focuses on operational management to prevent overcrowding and optimize resource utilization. It predicts the expected number of visitors at each activity at any given time and suggests the operational levels needed to avoid excessive queues which may ultimately lead to overcrowding. The models developed here is adapted from the work of Ahmadi [1], for capacity and flow management at theme parks. Here were are dealing with nature reserves, which have different characteristics to theme parks.

The model is formulated as an optimization problem where the objective is to maximize overall visitor satisfaction across all activities and time periods, while minimizing the penalties associated with long queues that detract from the visitor experience. Let X_{it} represent the number of visitors served at activity i during time interval t, and let Q_{it} denote the number of visitors in the queue at activity i during time interval t. The objective function is expressed as:

$$\min \left(\sum_{i}^{N} \sum_{t}^{T} q_i Q_{it} - s_i X_{it} \right), \tag{1}$$

where q_i is the penalty associated with queue length for activity i and s_i represents the visitors satisfaction level for activity i. The first term of the objective function aims to minimizes the negative impact of queues, while the second term maximize visitor satisfaction.

The model incorporates several constraints that govern queue management, visitor flow, and resource allocation, ensuring the optimal operation of the attractions. These constraints are defined as follows:

- The following constraint models the dynamics of the queue length Q_{it} for each activity i at time t:

$$Q_{it} = Q_{it-1} - X_{it-1} + P_{0ik} I_{0t} + \sum_{j}^{N} (1 - \mu_{ik}) P_{jik} X_{jt-1} \qquad \forall (i, t), \tag{2}$$

  Here, P_{jik} is the transition probability of moving from activity j to activity i during time segment k, where $k = 0, 1, 2$ represents morning, afternoon, and evening, respectively. P_{0ik} represents the probability of visitors arriving directly at activity i from the entrance, μ_{ik} represents the probability that a visitor leaves the nature reserve after participating in activity i during the time segment k, and I_{0t} is the number of visitors arriving at the nature reserve at time t. This constraint ensures that queue dynamics account for visitors served in the previous period, X_{it-1}, new arrivals, $P_{0ik} I_{0t}$, and transitions from other activities of visitors that remain in the nature reserve, $\sum_{j}^{N} (1 - \mu_{ik}) P_{jik} X_{jt-1}$.

- Let Y_{igk} be a binary variable where 1 indicates that activity i is operating at resource level g during time segment k, and 0 otherwise. The capacity constraint is given by:

$$X_{it} \leq \sum_{g}^{G} C_{ig} Y_{igk} \qquad \forall (i, t), \tag{3}$$

where C_{ig} represents the capacity of activity i when operating at resource level g. This constraint ensures that the number of visitors X_{it} served at activity i during time t does not exceed the total capacity provided by the resources allocated.

Additionally, the resource allocation constraint ensures that each activity operates at exactly one resource level during each time segment:

$$\sum_{g}^{G} Y_{igk} = 1 \qquad \forall (i, k). \tag{4}$$

This constraint prevents overlap and guarantees efficient resource utilization.

- We need to account for the total number of visitors at the nature reserve at time t, which includes both those in queues and those currently participating in activities or have left the nature reserve. We define the following visitors accumulation constraint:

$$\sum_{i}^{N} (Q_{it} + X_{it}) \leq \sum_{\tau}^{t} I_{0\tau} \qquad \forall t. \tag{5}$$

The constraint ensures that the number of visitors at any given time does not exceed the total number of arrivals, preventing unrealistic scenarios where more people are inside the reserve than have entered.

- For completeness, the following constraints ensure that variables are correctly defined:

$$Y_{igk} \in (0, 1) \quad \forall (i, g, k), \qquad \text{and} \qquad Q_{it}, X_{it} \in \{0\} \cup \mathbb{Z}^{+} \quad \forall (i, t). \tag{6}$$

These bounds ensure that resource allocations are binary, and that queue lengths and visitor counts are non-negative integers.

The complete mathematical model is presented as follows:

$$\min \sum_{i}^{N} \sum_{t}^{T} (q_i Q_{it} - s_i X_{it}) \tag{7}$$

$$st \quad Q_{it} = Q_{it-1} - X_{it-1} + P_{0ik} I_{0t} + \sum_{j}^{N} (1 - \mu_{ik}) P_{jik} X_{jt-1} \qquad \forall (i,t), \tag{8}$$

$$X_{it} \leq \sum_{g}^{G} C_{ig} Y_{igk} \qquad \forall (i,t), \tag{9}$$

$$\sum_{g}^{G} Y_{igk} = 1 \qquad \forall (i,k), \tag{10}$$

$$\sum_{i}^{N} (Q_{it} + X_{it}) \leq \sum_{\tau}^{t} I_{0\tau} \qquad \forall t, \tag{11}$$

$$Y_{igk} \in (0,1) \quad \forall (i,g,k), \qquad \text{and} \qquad Q_{it}, X_{it} \in \{0\} \cup \mathbb{Z}^{+} \quad \forall (i,t). \tag{12}$$

This model serves as a simple basic tool for managing the operational capacity of tourist attractions, optimizing visitor satisfaction, and preventing overcrowding through strategic resource allocation and queue management. The objective function is designed to maximize visitor satisfaction at each activity while minimizing the penalties associated with long queues. In practice, visitor satisfaction often depends on the number of people present at an activity, which would make the problem nonlinear and more complex to solve. To simplify the model and ensure tractability, we assume a fixed satisfaction level for each activity, treating it as a constant rather than a dynamic variable influenced by crowd size.

Secondly, minimizing queue length is crucial because long queues can lead to overcrowding, diminishing the overall visitor experience. The model therefore emphasizes serving as many visitors as possible within capacity constraints, ensuring that queues remain manageable. By balancing these elements, the model provides a structured approach to maintain a high-quality experience at the attraction, supporting sustainable tourism management that aligns with both operational goals and visitor satisfaction.

4.2 Optimization techniques

The mathematical model (7) for managing visitors at tourist attractions is formulated as a Mixed-Integer Linear Programming (MILP) problem. Due to the combinatorial nature of the integer and binary decision variables, along with multiple interdependent constraints, the model presents significant computational challenges. To address these challenges, we utilized IBM CPLEX Optimization Studio, leveraging the 'docplex' library in Python for solving the model (7). CPLEX is particularly well-suited for handling MILP problems due to its advanced optimization algorithms, including branch-and-bound and branch-and-cut.

CPLEX employs optimization techniques like branch-and-bound and branch-and-cut to solve MILP problems efficiently. The branch-and-bound method systematically divides the feasible region into smaller subproblems, evaluating bounds to identify optimal solutions while discarding those that cannot improve the objective function. Branch-and-cut further enhances this approach by incorporating cutting planes, which refine the feasible region and eliminate fractional solutions, thereby enhancing computational efficiency. This combined approach allows CPLEX to tackle some difficult MILP models such as the one presented in (7).

Due to the absence of real-world data, synthesized data was used to simulate various parameters, including visitor satisfaction levels, queue penalties, transition probabilities, new arrivals, and operational capacity levels. The model was solved using these parameters for different crowd scenarios, and the results are presented in the next section.

It is important to note that in practice, visitor satisfaction often depends on the number of people present at an activity, introducing nonlinearity into the problem and making it more difficult to solve with standard optimization techniques. In such scenarios, the branch-and-bound and branch-and-cut algorithms employed by CPLEX may not be suitable. Therefore, heuristic methods, which are designed to find good approximate solutions, should be adopted to manage the nonlinearity and provide practical solutions where exact optimization proves computationally infeasible.

5 Results and discussion

This section presents the simulation results for three distinct scenarios: baseline, large and small crowd. The baseline scenario provides a reference for normal operating conditions, while the large and small crowd scenarios highlight how the system will behave under extreme conditions. By comparing these scenarios, we can gain insights into the effectiveness of the resource management, queue dynamics, and operational challenges under varying visitor inflow to the nature reserve.

One of the main challenges in modeling the operational dynamics of nature reserves is the scarcity of real and reliable data. At present, there are no systematic records documenting visitor numbers, behavior, or transitions between activities. This gap highlights the critical need for systems that are capable of capturing and storing relevant data that can inform future model development. To overcome this limitation, we synthesized data for the purpose of simulating potential scenarios at the reserve. The generated data is designed to closely mimic realistic park conditions, allowing us to test the robustness and performance of the proposed model.

Experimental setup

We consider a nature reserve with five distinct activities ($N = 5$) and three operational levels (7) $G = 3$). The operational capacities for each activity, based on the different levels, are shown in Table (1). These operations levels are determined by available resources at a given time. The model simulates 12 time units, which represent the course of a day. The day is divided into three time segments: morning (time periods 14, corresponding to time segment $k = 0$), afternoon (time periods 58, $k = 1$), and evening (time period 912, $k = 2$).

Activity	**Level 1**	**Level 2**	**Level 3**
Activity 1	10	30	50
Activity 2	12	25	40
Activity 3	14	29	45
Activity 4	13	30	45
Activity 5	15	35	50

Table 1: Operational capacities for each activity (C_{ig}).

Visitor arrivals at the park were modeled using a skewed normal distribution to simulate realistic arrival patterns, with the highest inflow of visitors occurring in the early afternoon. This distribution reflects typical visitor behavior, where the bulk of arrivals happens around midday, tapering off toward the evening. The arrival pattern is shown in Figure 1.

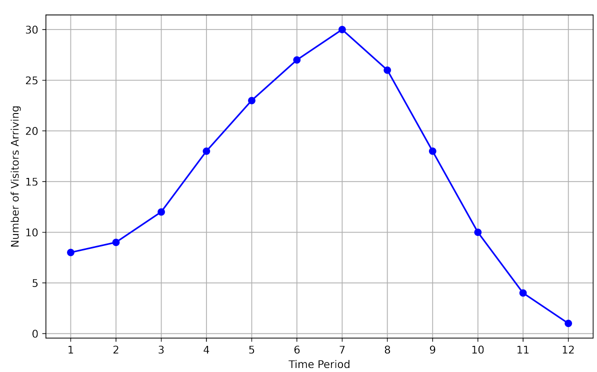
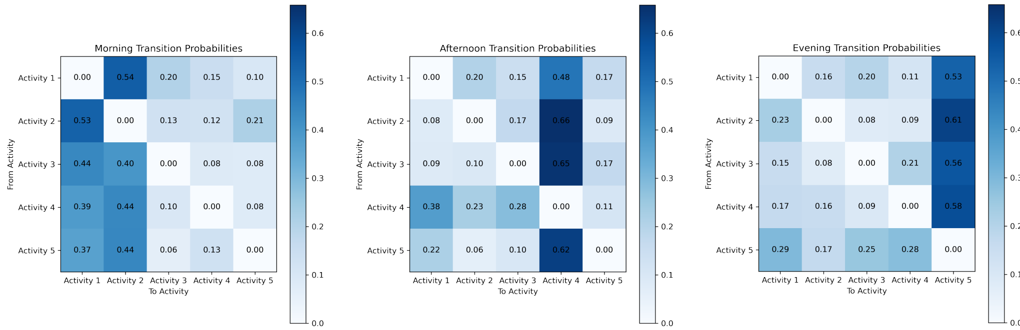


Figure 1: Number of visitors arriving at the nature reserve throughout the day (I_{0t}).

The transition probabilities between activities were calibrated to reflect realistic visitor preferences throughout the day. Specifically: Activities 1 and 2 are preferred in the morning, Activity 4 is favored during the afternoon and Activity 5 is the most popular in the evening. These preferences reflect the nature of the activities, as some may be more suited to specific times of the day due to environmental factors or visitor preferences. The transition probabilities are presented in Figure 2.

The probability of visitors leaving the nature reserve was also modelled to vary throughout the day. In the morning, visitors are less likely to exit, as they are just beginning their experience. The likelihood of exit increases in the afternoon as visitors start to complete



(a) Morning ($k = 0$) (b) Afternoon ($k = 1$) (c) Evening ($k = 2$)

Figure 2: Port of Agulhas wind speed and direction over the period of data (left), and some interpretation as a wind rose showing the magnitude and wind direction over the relevant period at the Port of Agulhas in a convenient format.

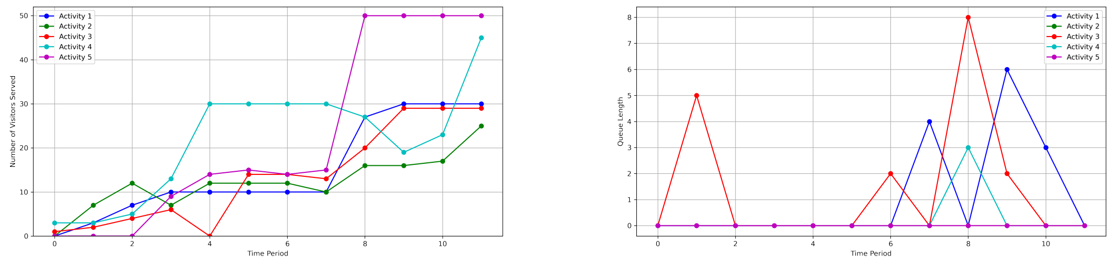
activities and leave the reserve. In the evening, this probability peaks as visitors conclude their day at the park. We take the above experimental description as the baseline scenario.

5.1 Baseline scenario

The baseline scenario represents normal operating conditions with moderate visitor inflow, simulating typical demand levels at the nature reserve. The results, displayed in Figure 3, show the number of visitors served at each activity in Figure 3(a) and the corresponding queue lengths for each activity in Figure 3(b). A primary concern in this scenario is managing queue lengths, as long queues can lead to overcrowding and diminish the visitor experience. The results indicate that queues are well-managed in the baseline scenario. Queue lengths remain moderate and manageable, demonstrating that visitor demand aligns well with the reserve's capacity to serve them effectively. Operational levels are maintained at moderate settings, as shown in Figure 4, ensuring a balanced use of resources that meets visitor needs without incurring excessive costs. This operational balance is beneficial for both visitor satisfaction and operational efficiency, reflecting what could be the optimal state for sustainable tourism management.

5.2 Small crowd scenario

In the small crowd scenario, visitor inflow to the nature reserve is reduced to one-quarter of the baseline, simulating a low-demand period. This scenario allows us to evaluate the system's performance under reduced demand, where resources may be underutilized. The results are presented in Figure 5, where Figure 5(a) shows the number of visitors served at each activity, and Figure 5(b) displays the queue lengths for each activity. Compared to the baseline, there is a significantly smaller crowd, resulting in minimal to no queue lengths. Each activity has ample capacity to serve all visitors without delays,



(a) Visitors (b) Queues

Figure 3: Visitors served and queue length for baseline crowd.

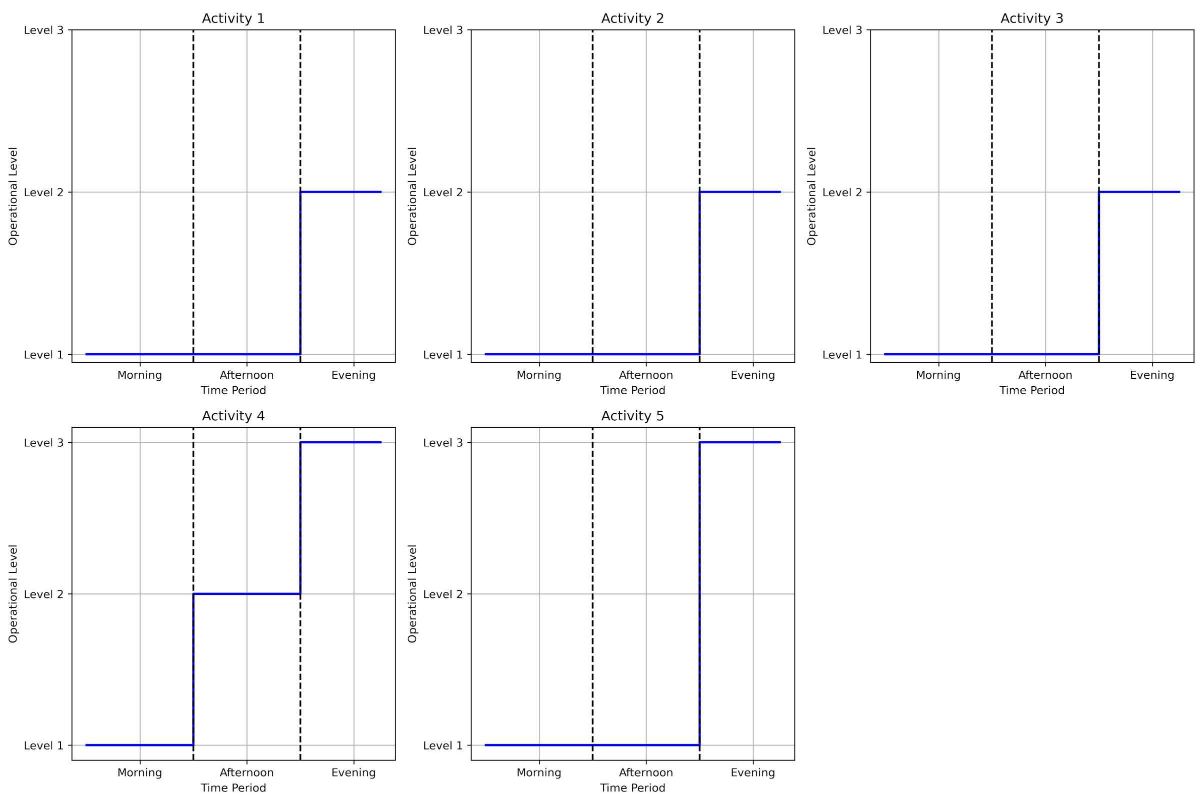
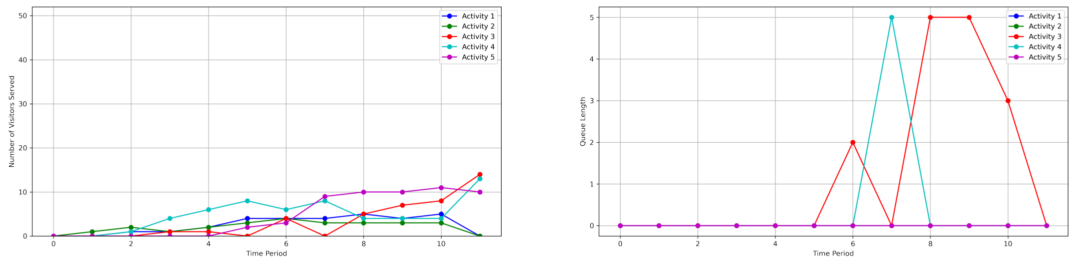


Figure 4: Operational levels for baseline crowd.

leading to an enhanced visitor experience. Operational levels are scaled down to the lowest necessary settings, as shown in Figure 6. This adjustment demonstrates efficient resource allocation, minimizing unnecessary costs while maintaining service quality. The low-demand conditions in this scenario could represent a highly sustainable system with minimal environmental impact due to reduced human activity.



(a) Visitors (b) Queues

Figure 5: Visitors served and queue length for large crowd.

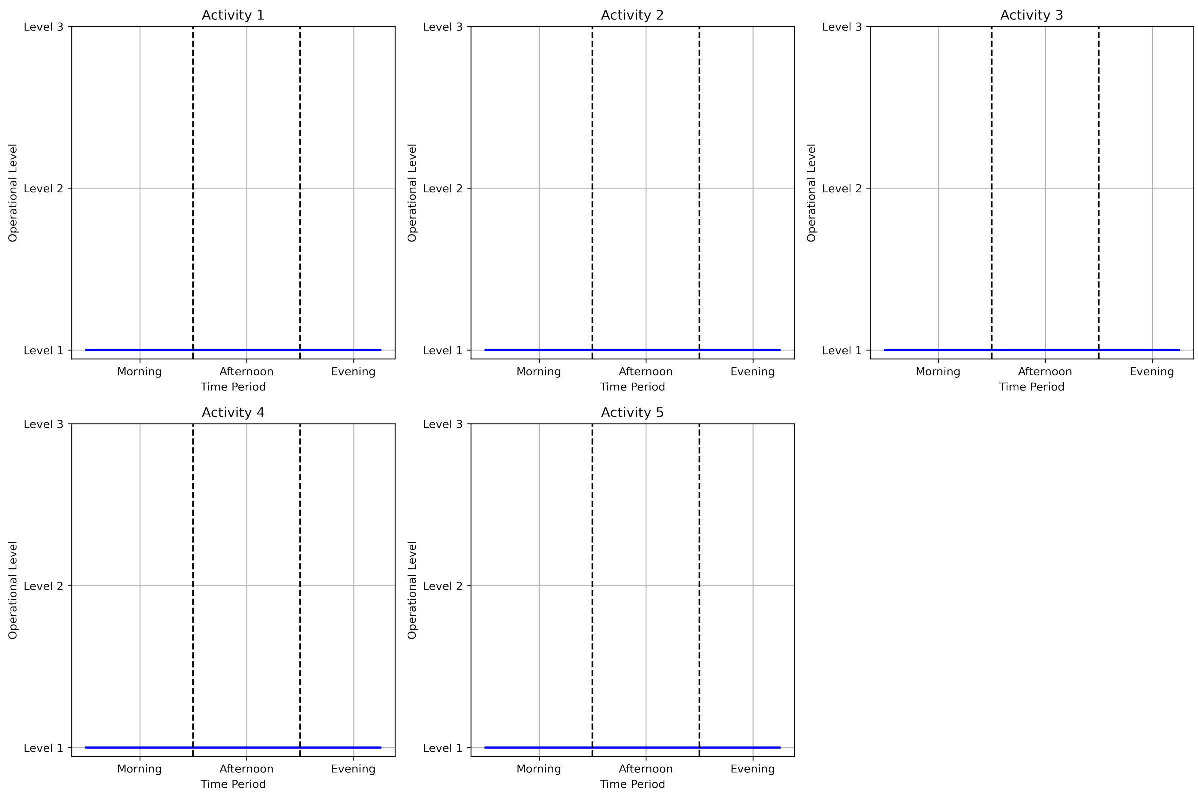
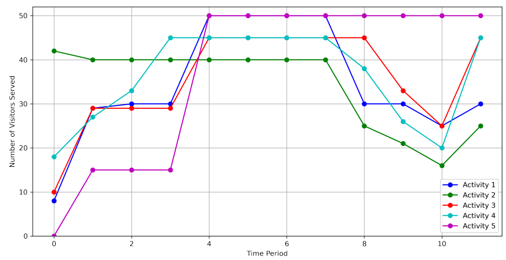


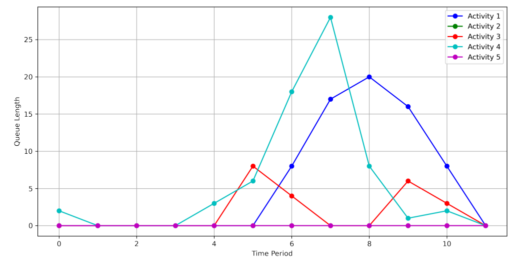
Figure 6: Operational levels for small crowd.

5.3 Large crowd scenario

The large crowd scenario simulates high-demand conditions by increasing visitor inflow to five times the baseline level. This scenario tests the system's ability to handle an unusually high number of visitors and evaluates whether current resource allocation and queue management strategies can prevent overcrowding. The results are shown in Figure 7, where Figure 7(a) displays the number of visitors served at each activity, and Figure 7(b) illustrates queue lengths. Although the reserve attempts to serve as many visitors as



(a) Visitors



(b) Queues

Figure 7: Visitors served and queue length for small crowd.

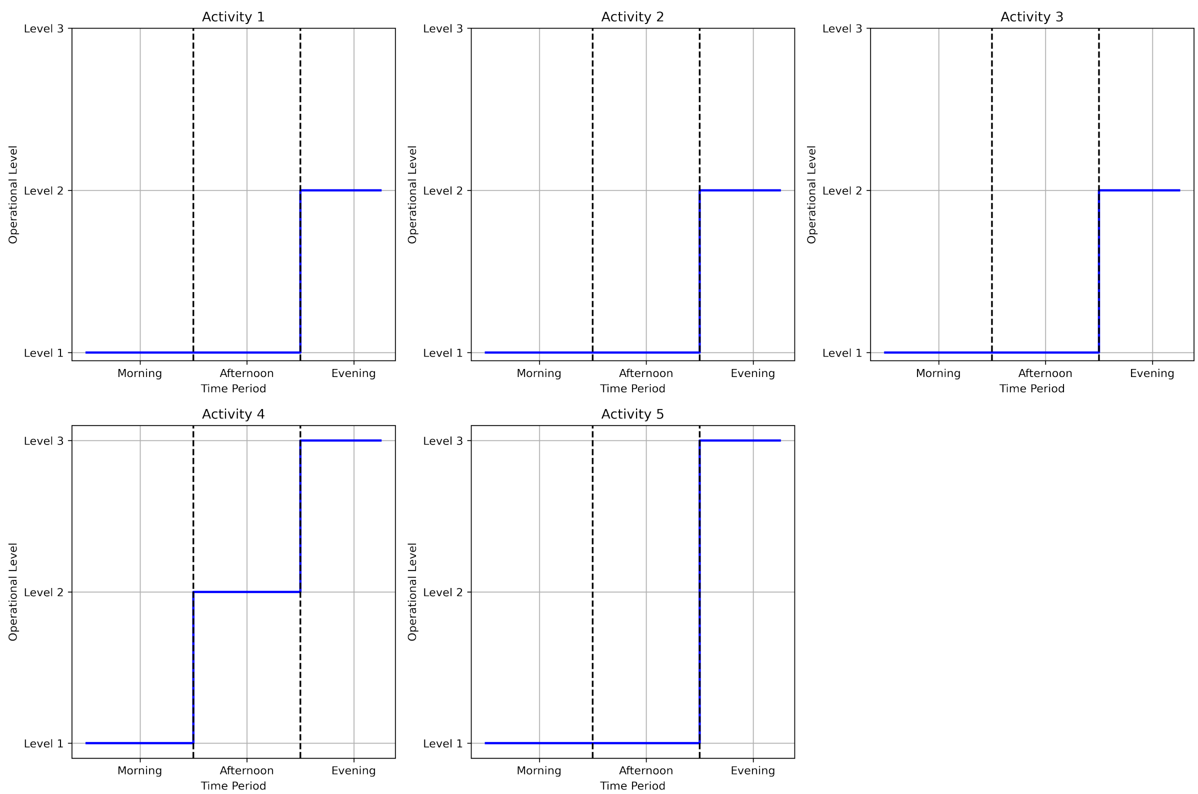


Figure 8: Operational levels for baseline crowd.

possible, demand often exceeds capacity, leading to long queues, especially during peak hours. Activities with limited capacity, such as Activity 4 in the afternoon, experience substantial wait times, revealing that the existing resources struggle to accommodate high visitor demand. As shown in Figure 8, operational levels are pushed to their maximum across several activities, underscoring the strain on resources during peak periods. This scenario presents sustainability challenges, as prolonged high visitor numbers could lead to overcrowding, negatively affecting the natural environment and the visitor experience. To mitigate these issues, management could consider implementing measures to prevent such scenarios, such as visitor caps, timed entry, or dynamically scaling resources during peak periods. Unfortunately, the current model does not determine the system's optimal carrying capacity.

6 Conclusions

For the MISG2024, we developed a capacity management model designed to manage the capacity of a tourist attraction. Mainly, we focused on Manyeleti Nature Reserve, a popular tourist attraction neighboring the Kruger National Park in Mpumalanga, South Africa. The developed model was designed to determine the tourist attraction's social carrying capacity to mitigate the negative impacts of over-tourism. The model aims to optimize the attraction's capacity and visitor flow, thus improving both operational efficiency and visitor satisfaction.

The management model was formulated as an optimization problem where the objective was to maximize visitor satisfaction across all activities that the attraction offers, as well as maximizing revenue collected by the attraction managers, while minimizing penalties incurred due to long ques. Further, the model was formulated as a mixed-integer linear programming problem, which posed significant computational challenges due to the combinatorial nature of the integer and binary decison variables. As such, we utilized the IBM CPLEX Optimization Studio to address these challenges and solve the model.

Due to the absence of real-world data, synthesized data was utilized for the simulations to visually present the obtained results. Statistical tools such as the skewed normal distribution was used to estimate visitor arrival patterns at the nature reserve. Markov chain was used to estimate visitor transitions between the activities in the nature reserve. These tools allow for real-time adjustments to the reserve's operations, making the model adaptable to dynamic visitor behavior.

The developed model was solved using these parameters for different crowd scenarios: (1) baseline, (2) case where there is a small crowd, and (3) case where there is a large crowd. Furthermore, heat maps were generated to visualize visitor densities at different times of the day, revealing congestion patterns and underutilized attractions in the nature reserve. These visualizations provide critical insights for park operators, who can use this data to adjust staffing, activity schedules, and queue management strategies to better manage visitor flow. Results indicated that activities 1 and 2 were popular in the morning, activity 4 in the afternoon, and activity 5 in the evening.

While the MISG study utilized synthesized data for the modeling and simulations, future extensions of the study should focus on using real-world data from these nature reserves to enhance the accuracy and applicability of the developed model. By incorporating real-time data on visitor arrivals, each activity usage, and tourists behavior, the capacity management model can be further refined to provide even more realistic and useful operational recommendations at any time of the day. Real-life data allow for a more realistic evaluation of visitor patterns which in-turn allows these nature reserve managers to to correctly forecast demand and make better informed decisions regarding capacity management.

The model proposed in this MISG study provides a flexible, data-driven approach for nature reserves to enhance revenue and visitor satisfaction. By incorporating predictive models and real-time optimization techniques, the model should adapt dynamically to changing operational needs and visitor patterns. For future implementations, utilizing real-data will be essential to maximize accuracy and efficiency.

In conclusion, this study establishes a strong foundation for optimizing capacity and managing visitor flow in tourist attractions. However, future studies should focus on validating the model with real-reserve data to ensure its practical applicability. This approach will support the effective implementation of the capacity management model in real-world settings, providing actionable insights that enhance operational efficiency, improve visitor satisfaction, and maximize revenue for nature reserves.

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