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Heuristic Scheduling Strategies for the Airport Check-In Counter Allocation Problem

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ABSTRACT

The post-pandemic resurgence in global air travel has placed renewed strain on airport infrastructure, establishing the check-in hall as a critical bottleneck for operational efficiency and passenger satisfaction. This study addresses the Airport Check-in Counter Allocation Problem (CCAP) within the specific context of Malaysian airports, proposing a robust heuristic scheduling framework to mitigate resource congestion. By integrating rule-of-thumb heuristics with fundamental dispatching algorithms, specifically First-Come-First-Serve (FCFS), Earliest Deadline First (EDF), and Shortest Job First (SJF). The research employs a discrete simulation to evaluate performance under two contrasting regulatory environments: a flexible *Mixed Counter* strategy and a stringent *Preferred Counter* policy. The comparative analysis reveals that the Heuristic-FCFS combination under flexible allocation rules yields the optimal outcome, achieving a peak resource utilization rate of 45.3% while minimizing idle dormancy. Conversely, the enforcement of airline-specific constraints resulted in significant resource fragmentation, necessitating a 35% increase in active counters and depressing utilization rates to approximately 33.5% across all algorithmic variants. These findings provide empirical evidence that while algorithmic optimization contributes to efficiency, the structural removal of categorical resource barriers offers the most significant potential for economic and operational improvement in airport management.

Keywords: Airport Check-in Counter Allocation; Heuristic Scheduling Algorithms; Resource Optimization; Operational Efficiency; Dispatching Rules.

INTRODUCTION

The global aviation sector is currently undergoing a significant resurgence, driven by a post-pandemic rebound in economic activity and household income. As passenger traffic volume approaches and exceeds historical peaks, airports are compelled to maximize throughput within existing physical infrastructures [1]. This recovery brings renewed focus to the passenger terminal's most critical bottleneck: the check-in hall. Studies indicate that the check-in process is a primary determinant of passenger satisfaction, with recent data suggesting that substantial operational delays often up to 80%, originate from inefficiencies in counter allocation and queue management [2]. Consequently, the Airport Check-in Counter Allocation Problem (CCAP) has regained prominence as a vital resource scheduling challenge, where the objective is to balance the minimization of operational costs with the maximization of service quality [3].

However, optimizing these resources is not merely a matter of increasing staff; it is a complex mathematical problem involving hard constraints such as adjacency requirements, airline-specific service level agreements, and stochastic arrival patterns [4]. While large operational hubs may utilize high-cost commercial solvers, there is a distinct need for agile, heuristic-based solutions suitable for specific airport contexts, such as the Kuala Lumpur International Airport (KLIA). This study addresses this necessity by proposing and evaluating a heuristic scheduling algorithm integrated with fundamental dispatching rules. By systematically addressing the trade-off between counter idleness and utilization, this project aims to provide a practical framework for enhancing airport efficiency and mitigating the economic risks associated with congestion [5].

A. The Evolution of Counter Allocation Strategies

The optimization of airport resources has evolved from static planning to dynamic, constraint-based modeling. Early approaches largely relied on integer programming to solve the CCAP, yet recent research highlights the limitations of these exact methods when faced with the variability of modern airport operations. Ornek et al. [4] demonstrated that while model-based heuristics can address operational constraints, the computational intensity increases significantly with problem size. Similarly, Ribeiro et al. [6] emphasized that slot allocation models must now account for stricter IATA guidelines and propagated delays, suggesting that traditional deterministic models are often too rigid for the fluid nature of daily operations.

B. Heuristics and Algorithmic Adaptation

To overcome the intractability of exact models, contemporary literature has shifted toward heuristic and meta-heuristic approaches. These methods prioritize "near-optimal" solutions that can be generated quickly. Sangaiah et al. [7] explored resource allocation using heuristic algorithms in IoT contexts, establishing a precedent for applying lightweight iterative logic to complex scheduling tasks. This cross-domain application is further supported by Li et al. [8], who analyzed task scheduling in cloud computing using ant colony optimization. Their findings suggest that while rule-based heuristics like First-Come-First-Serve (FCFS) are common, they often require hybridization with intelligent sorting mechanisms to maximize throughput.

C. Dispatching Rules: Priority and Deadlines

The integration of specific dispatching rules—specifically Earliest Deadline First (EDF) and Shortest Job First (SJF)—has shown promise in enhancing resource utilization. Gupta et al. [9] proposed a priority-based EDF algorithm that significantly improved memory utilization in computing systems, a concept directly applicable to the time-sensitive nature of flight check-in windows. However, Singh and Patra [10] noted that the time complexity of EDF can be a hurdle in real-time systems, advocating for algorithmic simplifications. Furthermore, Karthick et al. [11] addressed the issue of resource fragmentation in traditional scheduling, proposing clustering methods to reduce "starvation" or idle periods, which aligns with the objectives of minimizing open-but-empty counters in airport terminals.

D. Simulation and Operational Resilience

Given the stochastic nature of passenger flows, simulation remains the gold standard for validating allocation algorithms. Patel and Bhoi [12] demonstrated that iterative priority-based scheduling could be effectively evaluated through simulation to identify idle time inefficiencies. More specific to aviation, Otieno [13] and Brun et al. [14] utilized discrete event simulation to stress-test airport security and staff allocation strategies, revealing that simple, robust heuristics often outperform complex models during irregular operations. Finally, recent post-pandemic analyses [15] highlight that future algorithms must be adaptable to fluctuating demand, reinforcing the need for the flexible, heuristic-based framework proposed in this study.

The primary objective of this paper is to formulate and empirically evaluate a heuristic-based scheduling framework aimed at optimizing the Check-in Counter Allocation Problem (CCAP) within the specific operational constraints of Malaysian airports, notably Kuala Lumpur International Airport (KLIA). This study seeks to bridge the gap between theoretical complexity and practical application by integrating rule-of-thumb heuristics with fundamental dispatching algorithms: First-Come-First-Serve (FCFS), Earliest Deadline First

(EDF), and Shortest Job First (SJF). The overarching goal is to maximize counter utilization and mitigate operational inefficiencies, specifically by minimizing idle counter periods and ensuring the effective assignment of all flight groups. Through a systematic simulation and comparative analysis of these algorithmic combinations, the research intends to identify a robust allocation strategy that enhances resource efficiency and reduces passenger processing delays while adhering to strict daily flight scheduling constraints.

METHODOLOGY

The methodological framework employed in this study utilizes a discrete simulation approach designed to translate raw operational data into optimized resource allocation schedules. The research workflow is structured into three distinct phases: data pre-processing, algorithmic simulation under varying constraints, and a quantitative performance evaluation based on resource utilization metrics. This systematic process ensures that the proposed heuristic solutions are rigorously tested against both flexible and rigid operational scenarios to determine their practical efficacy in an airport environment.

A. Data Pre-processing and Feature Selection

To ensure computational efficiency and algorithmic stability, the raw flight dataset undergoes a rigorous pre-processing phase utilizing the Python Pandas library. Initial data refinement involves a manual dimensionality reduction process, wherein extraneous variables such as aircraft type and flight mode are excised. The dataset is reduced to three critical constraints essential for temporal allocation: the unique Flight Number (*FN*), the Scheduled Counter Open Time (*SCOT*), and the Scheduled Counter Close Time (*SCCT*). Following feature selection, the dataset is sanitized, which systematically identifies and eliminates records containing missing temporal values. This step is crucial for preventing runtime errors and ensuring the scheduling engine operates on a complete and valid vector of time constraints.

B. Experimental Scenarios and Operational Constraints

The simulation is designed to evaluate the algorithms under two contrasting regulatory environments, reflecting different levels of operational flexibility:

Mixed Counter Allocation: In this configuration, the algorithm operates under a universal allocation rule where no specific counters are reserved for airline categories. The system is permitted to assign any flight group to any available counter, governed strictly by a non-overlapping constraint. This scenario is intended to test the maximum potential resource utilization when airline-specific barriers are removed.

Preferred Counter Allocation: This configuration introduces categorical constraints to reflect real-world service level agreements. Specific counters are designated exclusively for major carriers, specifically AirAsia (AK) and Malaysia Airlines (MH); while remaining flights are allocated to general counters. This scenario challenges the algorithm to optimize resources despite the fragmentation caused by reserved capacity.

Across both scenarios, a foundational heuristic logic is enforced to prevent physical resource conflicts. This is mathematically defined by the Boolean expression:

$$(opentime_1 < closetime_2) \wedge (opentime_2 < closetime_1) \quad (1)$$

This is to ensure that the service window of a candidate flight does not intersect with an existing assignment on the target counter.

C. Algorithmic Sorting and Dispatching Rules

To determine the optimal processing sequence, the heuristic framework is integrated with three deterministic dispatching disciplines. The flight list is sorted prior to allocation based on the following criteria:

First-Come-First-Serve (FCFS): The flight list is sorted chronologically based on SCOT. This approach prioritizes tasks strictly in the order of passenger arrival, ensuring fairness in queue processing.

Earliest Deadline First (EDF): Heuristics guide the schedule by sorting flights based on SCCT. This strategy aims to mitigate delay propagation by prioritizing tasks that must be completed soonest to meet upcoming operational deadlines.

Shortest Job First (SJF): Tasks are sorted by their execution duration, calculated as the difference between the closing and opening times. By prioritizing shorter service windows, this method aims to maximize the frequency of counter turnover and throughput. By computing this difference using the Equation 2, the algorithm prioritizes flights with smaller operational windows, aiming to maximize the frequency of counter turnover.

$$processing\_time(t) = SCCT(t) - SCOT(t) \tag{2}$$

D. Schedule Tabulation and Visualization

Post-allocation, the assignment data is transformed into a comprehensive schedule matrix to facilitate granular temporal analysis. The operational timeline is discretized into five-minute intervals, spanning the full daily cycle from 00:00 to 23:55. A Pandas DataFrame is constructed where rows represent individual check-in counters and columns represent specific time slots. Cells corresponding to active service periods are populated with the associated flight number, while unoccupied intervals remain empty. This matrix structure allows for the immediate visual detection of resource fragmentation and idle gaps.

E. Performance Quantification Metrics

To objectively compare the efficiency of the Mixed versus Preferred scenarios, the study calculates two specific performance metrics derived from the structure of the schedule matrix:

Idle Counter Period: This metric quantifies the total duration during which resources remain dormant. It is calculated by aggregating the count of empty counters within the schedule table and multiplying this figure by the five-minute interval duration, providing a cumulative measure of wasted capacity.

$$Period_{idle} = Counter_{empty} \times 5\ minues \tag{3}$$

Percentage of Counter Utilization: Serving as the primary indicator of optimization success, this metric represents the proportion of time counters are actively engaged in processing. It is derived by calculating the ratio of used counters to the total capacity of the schedule (the sum of used and empty counters), with higher percentages signifying a more efficient and streamlined operational flow.

$$\%utilisation = \frac{Counter_{used}}{Counter_{empty}} \times 100 \tag{4}$$

RESULTS AND DISCUSSION

A. Analysis of *Mixed Counter* Scenario

The *Mixed Counter* scenario operates on the principle of maximum flexibility, where the algorithm is permitted to assign flights from any category to any available resource, governed strictly by the non-overlapping constraint. The visual representations of these schedules, are illustrated in Figure 1, 2, and 3, with distinct allocation patterns. The FCFS schedule (Figure 1) exhibits a chronological filling pattern that aligns naturally with passenger arrival flows, while the EDF (Figure 2) and SJF (Figure 3) schedules demonstrate more fragmented allocation patterns driven by deadline urgency and processing duration, respectively.

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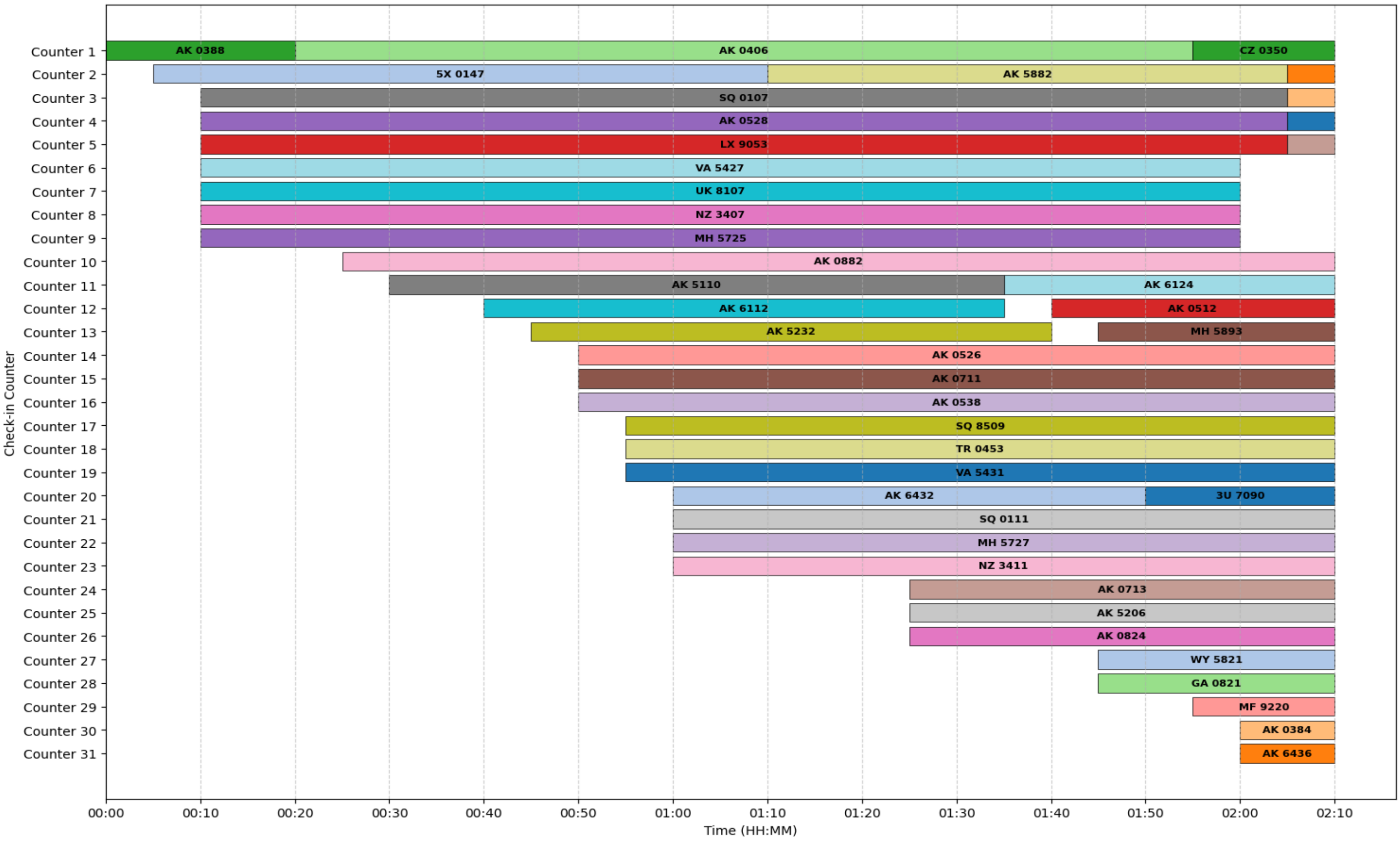

Fig. 1. FCFS schedule table for *Mixed Counter*

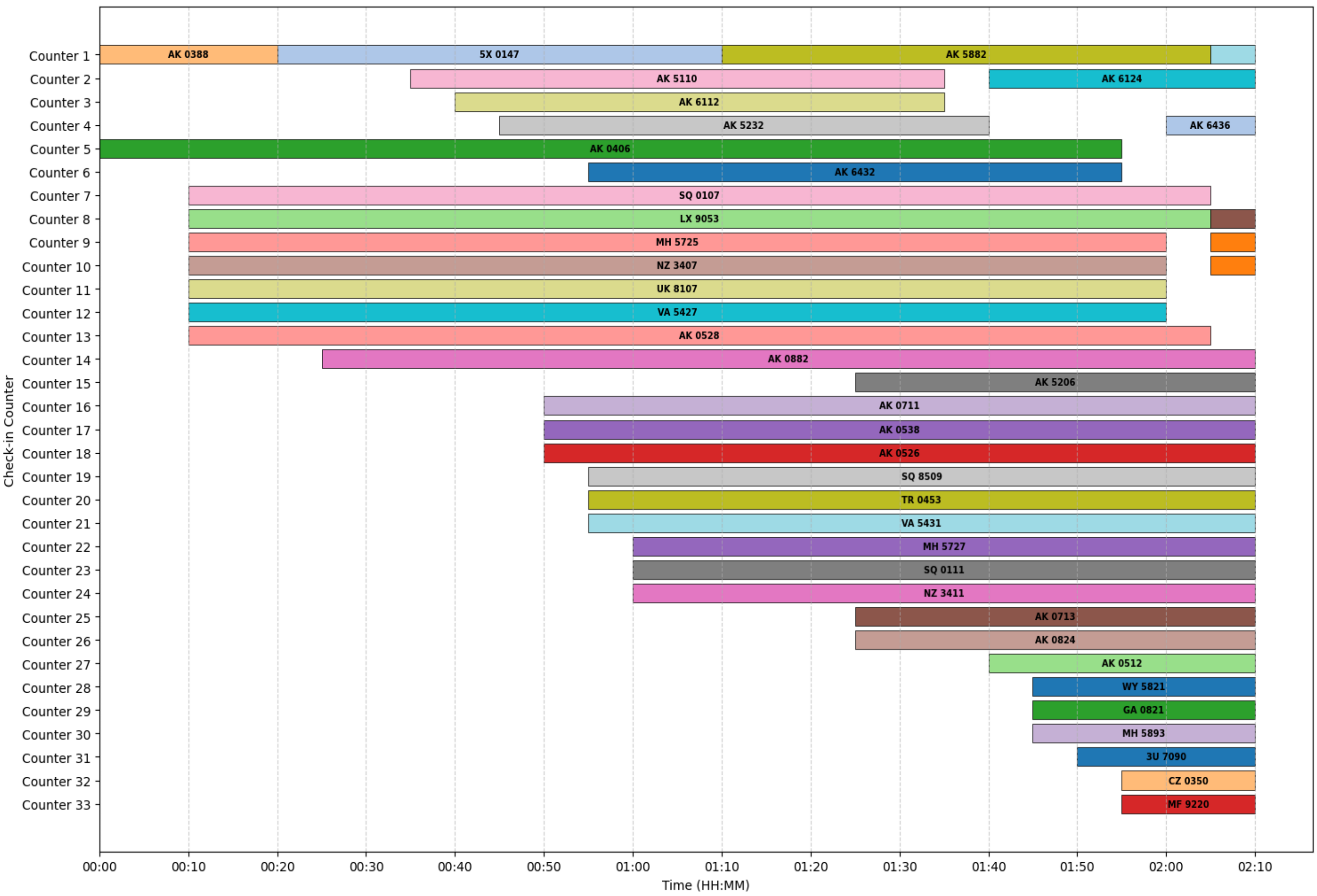

Fig. 2. EDF schedule table for *Mixed Counter*

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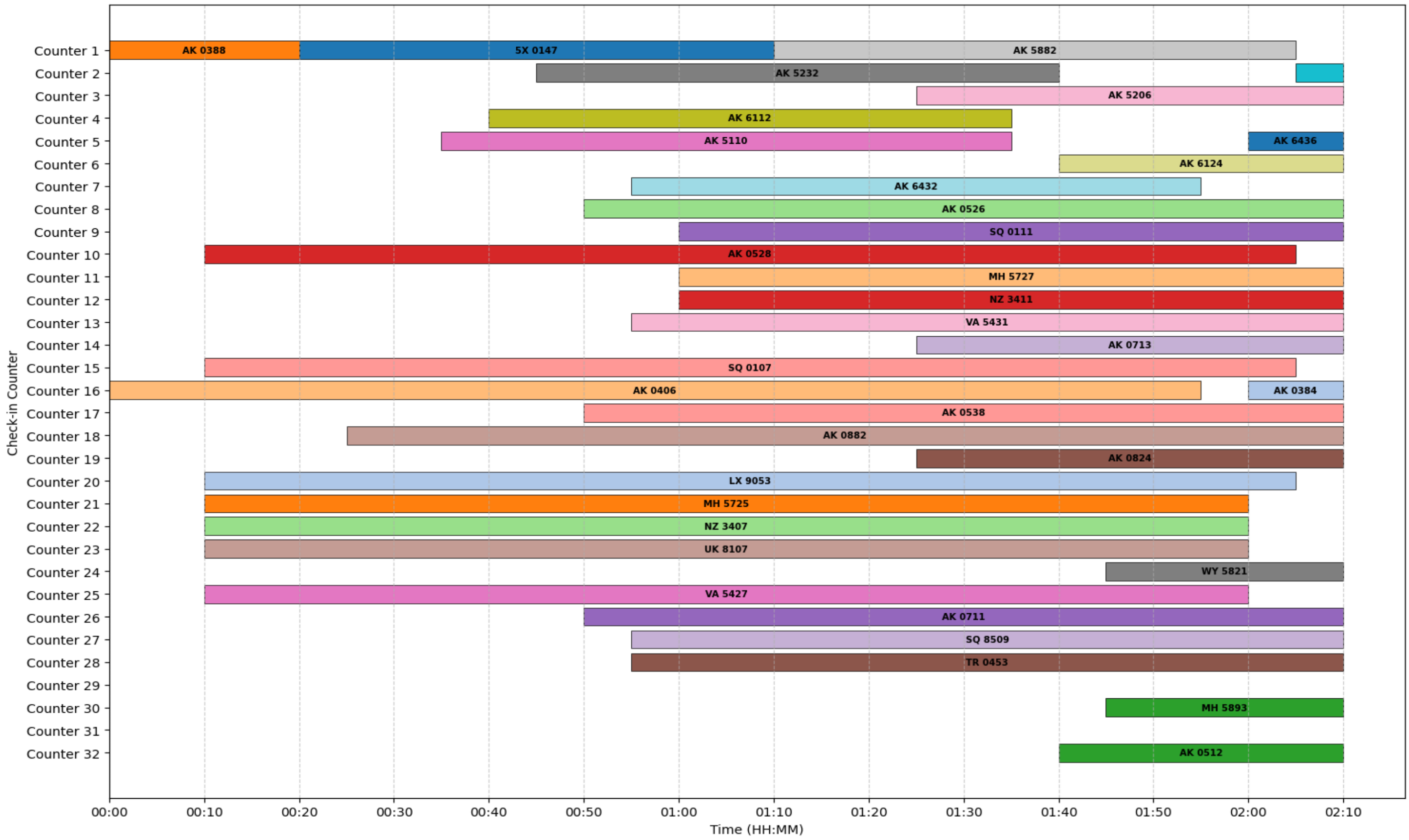

Fig. 3. SJF schedule table for *Mixed Counter*

Quantitative analysis of this scenario, as summarized in Table 1, reveals significant performance disparities between the dispatching rules. The combination of the Heuristic algorithm with the First-Come-First-Serve (FCFS) rule yielded the most favourable operational outcomes. This configuration achieved the highest counter utilization rate of 45.3% while necessitating the deployment of the fewest resources (45 counters). The corresponding idle counter period was recorded at 37,395 minutes. This suggests that in an unconstrained environment, processing flights based on their arrival sequence minimizes the creation of unusable time gaps between assignments.

Table 1. Comparison of the scheduling algorithms for *Mixed Counter*

Scheduling Algorithm	Number of Counters Used	Number of Empty Cells	Number of Filled Cells	Idle Counter Period (minute)	Percentage Counter Utilization
Heuristic + FCFS	45	7,189	5,951	37,395	45.3%
Heuristic + EDF	46	7,479	5,953	35,954	44.3%
Heuristic + SJF	51	8,939	5,953	44,695	40.0%

Conversely, the Shortest Job First (SJF) algorithm proved to be the least efficient method in the mixed environment. As indicated in Table 1, SJF required the highest number of resources (51 counters) and resulted in the lowest utilization rate of 40.0%. The increased idle time of 44,695 minutes associated with SJF implies that prioritizing short processing windows may lead to a fragmented schedule structure. This fragmentation likely creates small, unusable gaps between flights that are insufficient to accommodate larger flight groups, thereby forcing the system to open additional counters to meet demand. The Earliest Deadline First (EDF) algorithm served as a middle ground, utilizing 46 counters with a 44.3% utilization rate, striking a balance between the efficiency of FCFS and the throughput focus of SJF.

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B. Analysis of *Preferred Counter* Scenario

The introduction of categorical constraints in the *Preferred Counter* scenario, which reserves specific resources for AirAsia (AK) and Malaysia Airlines (MH), resulted in a marked shift in operational dynamics. Figures 4, 5, and 6 visually depict the impact of this segregation, where specific zones are heavily utilized while others remain dormant depending on the specific airline's schedule density.

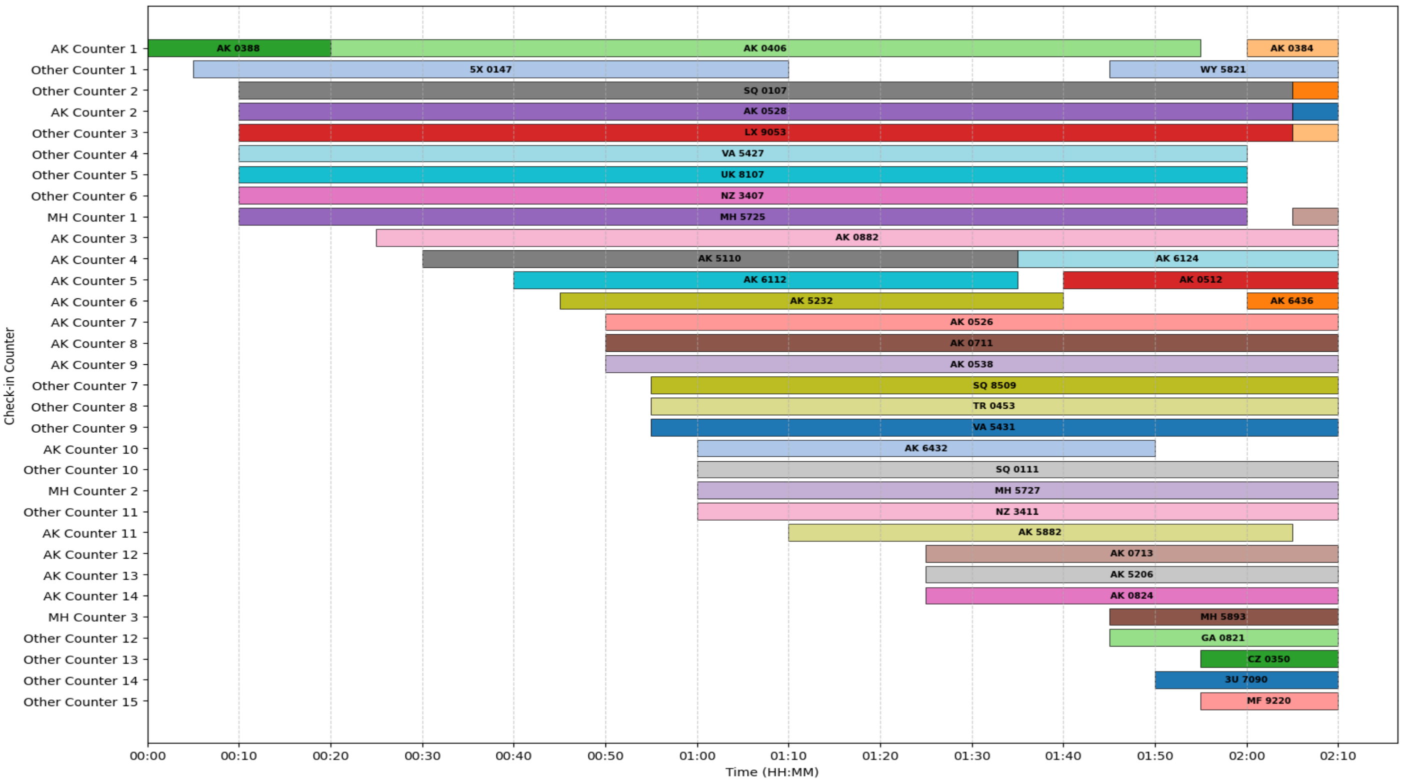

Fig. 4. FCFS schedule table for *Preferred Counter*

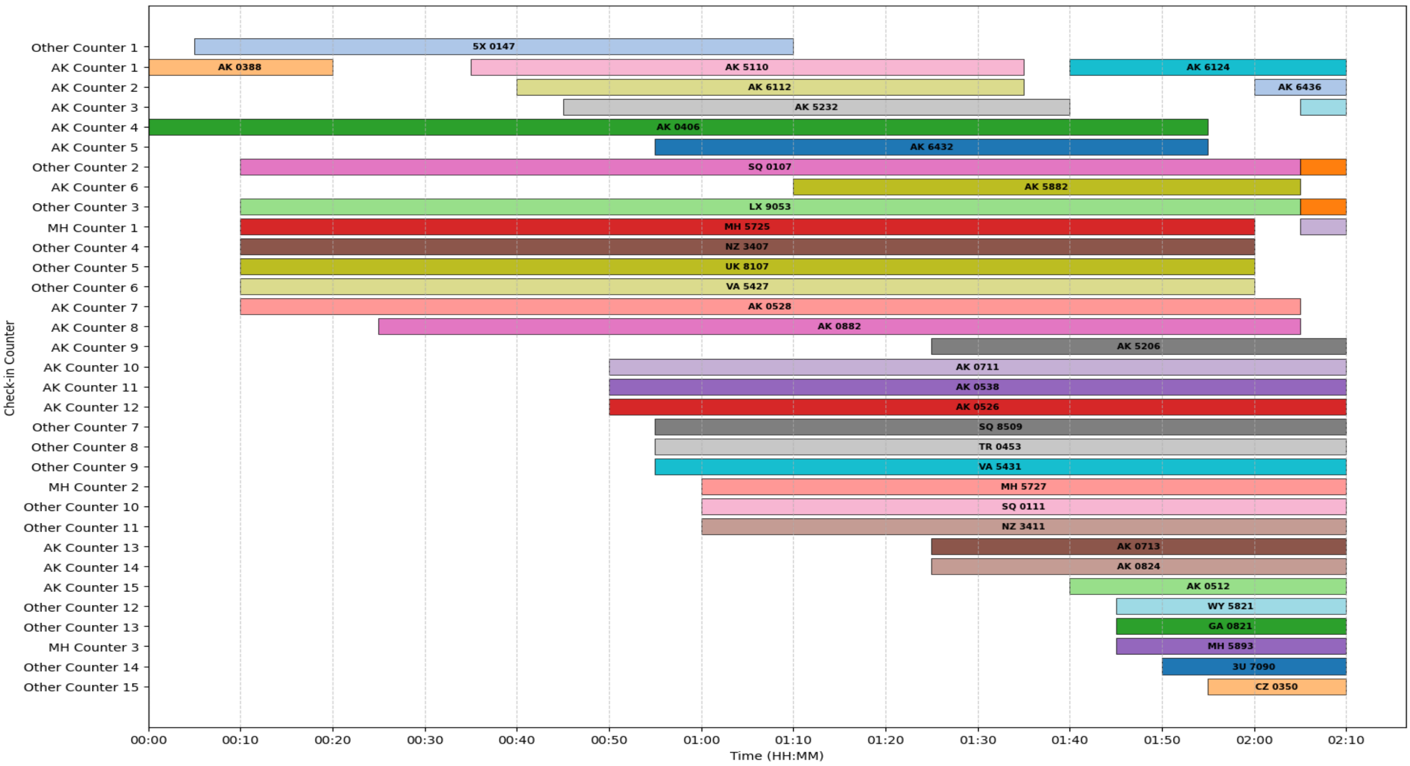

Fig. 5. EDF schedule table for *Preferred Counter*

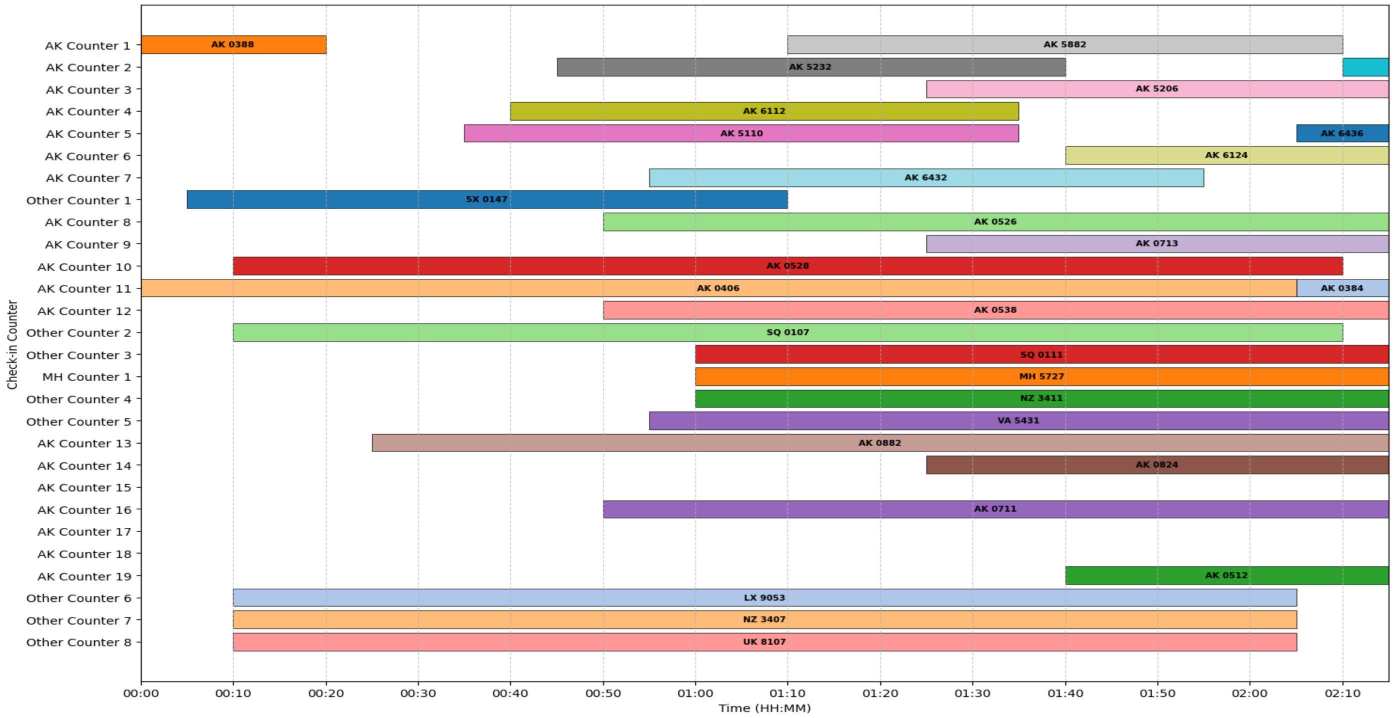

Fig. 6. SJF schedule table for *Preferred Counter*

The quantitative data presented in Table 2 demonstrates that the imposition of airline-specific zones overrides the efficiency gains usually offered by algorithmic sorting. Across all three algorithmic combinations (FCFS, EDF, and SJF), the simulation consistently required 61 counters to satisfy demand, a significant increase of roughly 35% compared to the optimal *Mixed Counter* scenario. Consequently, the percentage of counter utilization dropped drastically, stabilizing within a narrow range of 33.4% to 33.5%. Similarly, the idle counter periods surged to approximately 59,300 minutes for all three algorithms.

Table 2. Comparison of the scheduling algorithms for *Preferred Counter*

Scheduling Algorithm	Number of Counters Used	Number of Empty Cells	Number of Filled Cells	Idle Counter Period (minute)	Percentage Counter Utilization
Heuristic + FCFS	61	11,861	5,951	59,305	33.4%
Heuristic + EDF	61	11,853	5,953	59,265	33.5%
Heuristic + SJF	61	11,853	5,953	59,265	33.5%

This uniformity in results indicates that the *Preferred Counter* constraint acts as the dominant variable in the system. The rigidity of reserving counters prevents the algorithms from optimizing the schedule; for instance, an idle Malaysia Airlines (MH) counter cannot accept an overflow AirAsia (AK) flight. This structural bottleneck renders the choice of sorting algorithm (FCFS vs. EDF vs. SJF) statistically insignificant, as the constraints dictate the allocation more than the dispatching rule itself.

Comparative Evaluation and Implications

A synthesis of the data from both scenarios highlights a critical trade-off between operational flexibility and airline exclusivity. The transition from a Mixed to a Preferred allocation strategy resulted in a utilization efficiency drop of nearly 12 percentage points and required an additional 10 to 16 counters. The schedule tables corroborate these findings; the Mixed Counter tables exhibit a dense "waterfall" pattern of flight assignments, whereas the Preferred Counter tables show distinct pockets of inactivity.

In conclusion, the results identify the Heuristic + FCFS combination under Mixed Counter rules as the optimal strategy for maximizing resource utility, achieving a 45.3% utilization rate. However, for airports where airline segregation is mandatory, the findings imply that algorithmic optimization alone is insufficient to mitigate the inefficiencies caused by resource fragmentation. In such cases, the high volume of idle time suggests that common-use hybrid models or dynamic re-assignment of preferred counters during low-traffic periods may be necessary to improve the overall economic sustainability of check-in operations.

CONCLUSION

In conclusion, this study fulfills its primary objective of developing and validating a heuristic-based framework for the Airport Check-in Counter Allocation Problem (CCAP), specifically tailored to the operational nuances of the Malaysian aviation sector. The empirical results definitively establish that a flexible "Mixed Counter" strategy, governed by the First-Come-First-Serve (FCFS) dispatching rule, yields the optimal operational outcome, maximizing resource utilization at 45.3% while significantly reducing idle dormancy. Conversely, the simulation exposes the severe efficiency penalties imposed by "Preferred Counter" regulations; the segregation of airline-specific resources creates structural fragmentation that renders the choice of sorting algorithm statistically negligible, depressing utilization rates to approximately 33.5% across all tested variables. Therefore, while algorithmic optimization is valuable, this research underscores that the most significant gains in airport resource efficiency are contingent upon policy reforms that prioritize operational flexibility over rigid airline exclusivity, suggesting that future airport management strategies must balance service-level agreements with the economic imperative of shared resource pools.

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