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Optimizing Airlift Operations for Military Outposts: A Heuristic Approach to Enhancing Efficiency in Supplying Amazonian Border Platoons

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Abstract

To maintain Brazil's sovereignty in the Amazon, the Brazilian Army operates Special Border Platoons (PEF) in remote locations, with basic supplies primarily delivered by air, supported by the Brazilian Air Force. Utilizing concepts from the Packing Problems in Operational Research, this study presents a proposal to increase the efficiency of support operations for the PEFs through a mathematical model for aircraft loading during missions. The proposed model demonstrated a significant reduction in the number of required trips, optimizing cargo distribution and operational time. The study highlights the efficiency achieved through the application of an exact optimization model and a high-performance hybrid algorithm, in a case study applied to the PEFs in Surucucu and Auaris, contributing to the reduction of operational costs.

I. INTRODUCTION

To ensure territorial defense and integration, the Brazilian Army (Exército Brasileiro - EB) operates Border Special Platoons (Pelotões Especiais de Fronteira - PEF) in strategic locations, particularly in the Amazon region, under the coordination of the Amazon Military Command (Comando Militar da Amazônia - CMA). The survival and operation of these PEFs rely on the Brazilian Air Force (Força Aérea Brasileira - FAB), which provides essential air transport using C-98A Grand-Caravan and C-105 Amazonas aircraft [1], [2].

Due to aircraft load limitations and the significant volume of cargo destined for the PEFs, multiple trips are necessary to deliver all supplies to their destinations. A critical aspect of this process is the distribution of cargo for loading, currently performed empirically. There is no existing study focusing on optimizing the maximum load capacity, categorizing cargo by weight, or correlating it with the aircraft's capacity. Consequently, the aircraft undertakes numerous trips, resulting in high operational costs.

Various academic studies aim to maximize resources in public security operations due to their sensitivity and potential to improve efficiency with existing means. These include resource allocation during natural disasters [3], optimizing rescue routes [4], and transport missions [2], [5].

In scientific literature, vehicle loading problems have been extensively studied and are commonly referred to as the Bin-Packing Problem (BPP).

The BPP involves accommodating the maximum load into the minimum number of packages or bins [6], which, in this case, refers to aircraft. However, exact solutions to BPPs are often impractical. In such cases, heuristics or metaheuristics are employed to achieve satisfactory results [7].

Based on the Aeronautics Strategic Military Plan (Plano Estratégico Militar da Aeronáutica - PMAER), which seeks efficiency in resource utilization [8], this study proposes a mathematical model as a tool to enhance the efficiency of supply transportation to the PEFs using C-98A aircraft. The objective is to transport all necessary cargo with a minimal or near-minimal number of trips. Additionally, this study examines the impact of item granularity on the algorithm's efficiency.

II. LITERATURE REVIEW

A. Bin Packing Problems

Packing Problems, commonly referred to as the Bin-Packing Problem (BPP), are encountered in various real-world applications, particularly in vehicle loading optimization [9]. For an aircraft-related scenario, the BPP involves accommodating the maximum amount of cargo within the minimum number of aircraft.

BPPs can be further categorized based on dimensional constraints such as weight, height, width, and length. In the one-dimensional problem, the items to be allocated are characterized by a single variable, which, in this study, is weight. The value of this variable must not exceed the capacity of the container, here referred to as the bin [10].

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A key feature of Operations Research (OR) is the use of models, which facilitates analysis and decision-making by enabling experimentation with proposed solutions. Accordingly, the standard model for a one-dimensional BPP can be defined as follows: given i = {1,..., m} objects with respective weights w_j and j = {1,..., n} identical bins with finite capacity C, determine the allocation of n items such that $w_i \leq Cy_j$ for all j, while minimizing the number of bins required and adhering to the capacity constraints for each bin [9].

The mathematical formulation for the problem is expressed as:

Minimize: $\sum_{j=1}^{n} y_j$ (1)

Subject to: $\sum_{i=1}^{m} x_{ij} w_i \leq C y_j , \forall \text{ j}$ (2)

$\sum_{j=1}^{n} x_{ij} = 1 , \forall \text{ i}$ (3)

$y_i, x_{ij} \in \{0,1\}, \forall \text{ i, j}$ (4)

The Objective Function (OF) expressed in equation (1) seeks to minimize the total number of bins used. Equation (2) ensures that the capacity of each bin is not exceeded, while equation (3) requires that each object ii is allocated to exactly one bin jj. Lastly, the constraint in equation (4) enforces the integrality of the decision variables.

However, BPPs are characterized as optimization problems with high computational complexity, solvable only in nondeterministic polynomial time [7]. As a result, finding exact solutions to these problems is often intractable or unfeasible.

For this reason, most references in the literature on BPP focus on heuristics or metaheuristics. These approaches provide algorithms based on straightforward planning strategies that often yield satisfactory results.

B. Alternative to the Exact Model – Hybrid Algorithm

Greedy algorithms are commonly employed to solve BPPs due to their efficiency and simplicity. They provide a pragmatic approach where obtaining exact solutions may be computationally prohibitive. Although they do not guarantee the optimal solution, these algorithms often yield sufficiently good results in practice.

Several classical heuristics for solving one-dimensional BPPs remain the focus of study due to their straightforward implementation and quick resolution. Examples include the Next-Fit, analyzed by Saraiva e Schouery [11], the Best-Fit-Decreasing by Jangiti [12],]; and the Better-Fit, developed by Bhatia and Hazra [13]. In these heuristics, items are ordered based on limiting factors, and allocation rules are applied to distribute items into bins. These methods aim to simplify the decision-making process.

However, these algorithms face limitations, such as a tendency to converge to locally suboptimal solutions. To address these limitations, researchers have integrated heuristics with metaheuristics, seeking solutions closer to the global optimum [14].

The Next-Fit (NF) algorithm, without altering the sequence of items, places the first item in the first bin and checks if subsequent items fit in the same bin as the last item placed. If so, the item is added to the bin; otherwise, the bin is closed, and a new one is opened to accommodate the item [11].

The Best-Fit-Decreasing (BFD) algorithm [12] also orders items in decreasing size but attempts to place each item in the bin that will leave the smallest empty space. If no existing bin can accommodate the item, a new bin is opened. The Better-Fit (BF) [13] follows a similar logic to BFD but includes an evaluation phase with item permutation to further optimize allocation, potentially reducing the number of bins used.

The rationale behind descending ordering is that prioritizing larger items increases the likelihood of efficiently filling bins, avoiding wasted space that smaller items might not be able to utilize later.

Through extensive simulations using real-world data, Tlili and Krichen [15] demonstrated that BFD consistently outperforms other heuristics in resource utilization and packing efficiency. Additionally, a distinguishing feature of BFD is that it tends to allocate the fewest items to the last bin compared to other heuristics, further optimizing resource distribution.

Metaheuristics are high-level optimization approaches that combine heuristics with flexible frameworks adaptable to different problem types [16]. These methods balance exploring new solutions with exploiting the best-known ones to efficiently find optimal or near-optimal solutions, even for large-scale and highly complex problems.

Genetic Algorithms (GA) represent a metaheuristic inspired by natural evolution, employing processes analogous to selection, crossover, and mutation to evolve solutions for complex problems. Initially, a population of candidate solutions is randomly generated. Solutions are evaluated using a fitness function, and the best ones are selected for reproduction. During crossover, parts of the selected solutions are combined to create new ones, while mutation introduces small random changes to maintain genetic diversity. This iterative process continues until a satisfactory solution is found or a stopping criterion is met, aiming for problem optimization [7], [14], [16].

Fan et al. [7] and Munien et al. [14] introduced hybrid algorithms by combining GA with BF and BFD. Their studies demonstrated superior performance, showing that these hybrids achieved optimal results more frequently than competing metaheuristics, while also requiring less computational time.

The alternative model for BPP development in this study will thus be a GA combined with BFD and BF, forming a high-performance hybrid algorithm (HPHA).

III. INPUT DATA

This study focuses on the Border Special Platoons (PEFs) of Surucucu and Auaris, Roraima, managed by the 7th Jungle Infantry Battalion (7° BIS) based in Boa Vista. Unlike other PEFs with terrestrial access, these remote locations in the Amazon rely exclusively on aerial resupply.

Data collection involved the operators of the C-98A aircraft stationed at the Boa Vista Air Base (BABV) and the 7th Air Transport Squadron (7° ETA), based in Manaus but servicing the entire northern region. The Brazilian Army (EB) provided additional data through the 7th BIS.

Records reveal an average demand of 13,873 kg of supplies for a PEF with 60 personnel, transported in approximately 200 boxes across 25 trips over a 15-day period.

To evaluate the proposed model, data from the 7th BIS was used, including a list of 200 items totaling 13,873 kg. Additional datasets with 50, 100, 150, 350, 500, and 750 items were generated by randomizing weights while maintaining the original total weight of 13,873 kg. This allowed for analyzing the impact of granularity on the performance of the exact and proposed algorithms.

In this study, where the goal is to distribute items across trips, the bin size corresponds to the aircraft's fixed loading capacity per trip. For safety reasons, C-98A operations in the Amazon region are restricted to daylight hours, limiting flights to the period between sunrise and sunset. Analysis of Boa Vista's daylight hours during 2019–2023 [17] indicates a consistent operational window of 12 hours per day.

Each trip consists of a round trip, with the aircraft returning to Boa Vista on the same day. Pre-flight ground procedures take one hour. The total travel time for each destination includes the round-trip flight duration plus ground operations time at both ends.

For example, a trip from Boa Vista to Surucucu involves 1 hour of preparation before departure, 1 hour and 10 minutes for the outbound flight, 1 hour of preparation at Surucucu, and 1 hour and 10 minutes for the return flight, totaling 4 hours and 20 minutes.

To optimize the flight schedule in the second phase of this study, the bin will represent a day of air operations, with a "size" of 13 hours, starting one hour before sunrise and ending at sunset.

IV. METODOLOGIA

A. First Phase

The proposed model aims to maximize delivery efficiency for the PEFs using C-98A aircraft from the FAB. Initially, the goal is to minimize the number of trips required to meet the supply demands of two remote locations. Subsequent analysis explores the feasibility of combining trips to both locations to further reduce the total number of flights.

A subsequent stage evaluates the possibility of a single trip serving both locations, aiming to minimize the total number of trips. In this stage, minimizing the number of trips becomes a system constraint, while the objective shifts to minimizing the weight of items transported in one of the trips. This second optimization follows the mathematical model below:

$$\begin{aligned}
&\underline{\text{Minimize:}} && \textstyle\sum_{i=1}^{m} x_{i1} w_i && (5)\\
&\underline{\text{Subject to:}} && \textstyle\sum_{i=1}^{m} x_{ij} w_i \leq C y_j \text{ , } \forall \text{ j} && (6)\\
& && \textstyle\sum_{j=1}^{n} x_{ij} = 1 \text{ , } \forall \text{ i} && (7)\\
&\textstyle\sum_{i=1}^{n} y_j = \text{Minimum number of trips} \rightarrow 1^{\underline{a}}\ \text{OF} && && (8)\\
& && y_i, x_{ij} \in \{0,1\}, \forall \text{ i, j} && (9)
\end{aligned}$$

In this notation, the OF (5) minimizes the weight of items transported in the first trip. Equation (6) ensures that the aircraft's load capacity remains constant, limited by its weight restrictions. Equation (8) guarantees that the number of trips matches the minimum previously determined in the first OF, which minimizes the total number of trips.

The algorithm execution is limited to a maximum of 30 minutes (1,800 seconds). If this time is exceeded, the High-Performance Hybrid Algorithm (HPHA) will be employed, focusing on the bin with the smallest weight. For each location, the minimum number of trips and the minimum load per trip will be defined. Subsequently, the feasibility of a Combined Trip (CT) is evaluated—a single trip passing through both locations and carrying the minimum required load for each.

The CT is feasible if the combined minimum loads for Surucucu and Auaris do not exceed the aircraft's capacity. For this route, the aircraft's load capacity must be reassessed due to the longer flight path, which imposes stricter weight constraints compared to individual trips.

If a CT is feasible, the trip calculation is adjusted, accounting for one less trip to each location and one shared trip serving both. The total number of trips is then given by: $Z_{\text{Auaris}} + Z_{\text{Surucucu}} - y * Z_{Combined\ Trip}$, where y is a binary variable (0 or 1) indicating whether the CT was performed. This solution determines the minimum number of trips needed to meet the supply demands of both PEFs.

B. Second Phase

After the first phase establishes the total number of trips required, the second phase focuses on achieving maximum delivery efficiency. Here, a new BPP is presented, with the objective of minimizing delivery time, defined as the minimum number of days required to complete all trips.

In this problem, trips are treated as "items," each associated with two or three values depending on whether the CT is performed. The optimization seeks the best distribution of trips across available flight hours in each day, minimizing the total number of operational days.

$$\begin{aligned}
&\underline{\text{Minimize:}} && \textstyle\sum_{j=1}^{n} D_j && (10)\\
&\underline{\text{Subject to:}} && \textstyle\sum_{i=1}^{m} v_{ij} t_i \leq HD_j \text{ , } \forall \text{ j} && (11)\\
& && \textstyle\sum_{j=1}^{n} v_{ij} = 1 \text{ , } \forall \text{ i} && (12)\\
& && D_i \text{ , } v_{ij} \in \{0,1\}, \forall \text{ i, j} && (13)
\end{aligned}$$

The OF in (10) minimizes the total number of days used. Equation (11) ensures that all flights v_i, with durations t_i, fit within the available flight hours H in the operational days D_j . Equation (12) requires that each flight i is assigned to exactly one operational day D_j. Lastly, constraint (13) enforces the integrality of decision variables.

If calculations exceed 30 minutes, the HPHA will again be applied. The goal remains to maximize operational efficiency while adhering to the constraints imposed by the problem's structure.

VI. RESULTS

Currently, the 7th Jungle Infantry Battalion (7° BIS) schedules the bimonthly distribution of supplies to the PEFs using a sequential loading method that fills the aircraft to its capacity before dispatching, a process analogous to the NF algorithm. For this reason, NF serves as a reference for comparison with the proposed model. Trips are planned chronologically to meet supply demands, following the same NF logic, and CT are not considered in the current planning process.

Table I presents the results of the implemented process. Results are marked with "-" when a solution could not be obtained, and fields marked with "*" indicate that the processing time exceeded the established limit. Times are recorded in seconds, and in the CT column, "S" denotes yes, and "N" denotes no.

TABLE I. RESULTS OF THE IMPLEMENTED PROCESS

	Responses	**Auaris Trips**	**Surucucu Trips**	**Load Auaris**	**Load Surucucu**	**CT**	**Travel Days**
50 items list	*Next-Fit*	35	39	-	-	N	25
	Exact Model	-	-	-	-	-	-
	Exact Mod. time	*	*	-	-	-	-
	HPHA	26	25	348	181	N	22
	HPHA time	4	4	-	-	-	5
100 items list	*Next-Fit*	34	27	-	-	N	25
	Exact Model	-	-	-	-	-	-
	Exact Mod. time	*	*	-	-	-	-
	HPHA	25	24	505	285	N	21
	HPHA time	9	8	-	-	-	4
150 items list	*Next-Fit*	36	30	-	-	N	24
	Exact Model	25	24	-	-	N	22
	Exact Mod. time	138	146	*	*	-	23
	HPHA	25	24	376	192	N	22
	HPHA time	12	12	-	-	-	4
200 items list	*Next-Fit*	29	26	-	-	N	24
	Exact Model	25	24	322	107	S	21
	Exact Mod. time	692	574	595	627	-	23
	HPHA	25	24	327	73	S	21
	HPHA time	9	9	-	-	-	2
350 items list	*Next-Fit*	34	27	-	-	N	25
	Exact Model	25	24	289	78	N	21
	Exact Mod. time	1322	1317	1534	1637	-	22
	HPHA	25	24	329	78	S	21
	HPHA time	32	29	-	-	-	3
500 items list	*Next-Fit*	25	24	-	-	N	21
	Exact Model	-	-	-	-	-	-
	Exact Mod. time	*	*	-	-	-	-
	HPHA	25	24	314	73	S	21
	HPHA time	71	62	-	-	-	3
750 items list	*Next-Fit*	25	24	-	-	N	21
	Exact Model	-	-	-	-	-	-
	Exact Mod. time	*	*	-	-	-	-
	HPHA	25	24	314	73	S	21
	HPHA time	71	62	-	-	-	3

The computational effort was measured using a computer equipped with an AMD® Ryzen™ 5 1500X Quad-Core processor at 3.50 GHz and 16 GB of RAM. The Next-Fit (NF) heuristic and the hybrid model were implemented in Python, while the exact model was developed in AMPL using the CBC (Coin-or Branch and Cut) solver. The discussion of the results presented in Table I will follow in the subsequent sections.

A. Distribution of Items per Trip

For all analyzed lists, the proposed model improved the number of required trips, whether using the exact model or the HPHA. This improvement was significant compared to traditional approaches such as the NF algorithm. The data used were obtained from interviews with members of the EB and the FAB and included variations in items across five distinct configurations: 50, 100, 150, 200, 350, 500, and 750 items, simulating different load granularities.

The results indicated that for the configuration of 200 items, which most accurately reflects current operational demand, both the heuristic and exact models reduced the number of trips compared to the NF method. While the exact model was effective, it faced execution challenges when the number of items increased to 500 or more, resulting in processing times exceeding the stipulated 30-minute (1,800 seconds) limit. This highlights the complexity of processing a larger number of variables in the system. Additionally, the exact algorithm encountered difficulties in scenarios with low granularity, making it challenging to find the optimal solution.

In comparison, the heuristic approach proved faster, delivering solutions in significantly less time, typically within seconds. The HPHA demonstrated high efficiency, yielding results identical to the exact model whenever a direct comparison was feasible.

For the 350-item list, the exact model required 1,322 seconds to complete, whereas the heuristic model completed the task in just 32 seconds. This underscores the practical utility of heuristics in operational contexts where quick decision-making is critical. The heuristic model's results were also comparable to the exact model in terms of trips saved, showing a reduction of three trips for Surucucu and nine trips for Auaris compared to the NF method.

These results highlight the model's adaptability to varying load sizes, with the proposed heuristic offering a viable alternative when time constraints are a priority. The model's effectiveness in reducing the number of trips and optimizing cargo distribution is evident, with the 200-item configuration being most representative of actual operations.

B. Trip Distribution by Days

Once the total number of trips to be performed has been defined, the second model determines the minimum number of days required to complete the total number of necessary trips.

Given that trips from Boa Vista to Surucucu take an average of 1 hour and 10 minutes, the calculation for the model will then consist of the round-trip time of 2 hours and 20 minutes, plus the ground time before takeoff of 1 hour, plus the ground time at the Surucucu location of 1 hour. Each trip from Boa Vista to Surucucu enters the proposed BPP model as an "item" of 4 hours and 20 minutes.

Trips from Boa Vista to Auaris, in turn, take an average of 1 hour and 40 minutes. The calculation for the model will then consist of the round-trip time of 3 hours and 20 minutes, plus the ground time before takeoff of 1 hour, plus the ground time at the Surucucu location of 1 hour. Each trip from Boa Vista to Surucucu enters the proposed BPP model as an "item" of 5 hours and 20 minutes.

The CT that departs from Boa Vista, passes through both locations and returns, will be composed of the average time from Boa Vista to Surucucu, plus the average time from Surucucu to Auaris, which is 00:35h, plus the time from Auaris to Boa Vista. The calculation for the model will then consist of the total flight time of the route, which is 3 hours and 25 minutes, plus the ground time before takeoff of 1 hour and the ground time of the intermediate landings, of 1 hour each. Each trip from Boa Vista to Surucucu enters the proposed BPP model as an "item" of 6 hours and 25 minutes.

Thus, according to the answers obtained from the previous simulations, the data was inserted into the proposed trip distribution model. As an example, in the analysis of the list of 200 items, the 24 trips from Boa Vista to Auaris representing the "items" of 05:20h, the 23 trips from Boa Vista to Surucucu representing the "items" of 04:20, and 01 CT representing the "item" 06:25h. As a bin for the BPP of the model, the value of 13:00h was established, given the daily operating time available for the trips.

To determine the efficient distribution of trips, the proposed algorithm was applied, which configures the trips within the daily operational limits. The results indicated that the proposed model required fewer days to complete all trips compared to the empirical approach. Specifically, for the mentioned list, the result was a saving of 3 days compared to the traditional sequential method.

Thus, the mathematical model proved to be effective in reducing the total number of operating days, potentiating the use of aircraft and optimizing the daily operating window. And again, whenever it was possible to compare, the HPHA demonstrated identical results to the exact model.

V. DISCUSSION OF RESULTS

In this section, the analysis will focus specifically on the list of 200 items, which reflects the current and most accurate situation of cargo operations for the PEFs, followed by a brief comparative analysis of the other item lists.

A. Analysis of the Current Distribution Condition

To compare the efficiency of the empirical method, given by the NF, with the proposed model, the air effort required to perform a trip, measured in flight hours, is used.

The analysis focuses on the efficiency of the proposed model for the distribution of 200 items, showing a 13% reduction in air effort compared to the traditional method, saving approximately 20 hours. The model primarily focuses on the weight of the items, without considering the volume, which was not a constraint in this specific study.

A limitation identified in the process is that the model concentrates predominantly on the weight of the items as a restrictive variable, while the volume, which is generally a significant constraint in packing problems, did not appear as a limiting factor in this specific context. Despite the excellent results presented by the exact model, the resolution time still presents challenges when applied to maximization problems with a large amount of cargo.

Alternatively, the proposed heuristic method proved to be highly effective, generating results comparable to those of the exact model but in a substantially shorter time interval, normally on the order of seconds for all simulations.

The methodology currently employed for trip distribution is based on a sequence that does not optimize the use of daily operational time, similar to the application of the NF algorithm in each transport mission. In contrast, the proposed model achieved a saving of three days in the total number of journeys required, due to the optimization in the allocation of cargo.

B. Analysis of Other Lists

Through the diversity of the tested lists, it was possible to observe that an increase in the granularity of the items can improve packing efficiency. This occurs because more granular items allow for a more precise fit within the aircraft's space limits, reducing the number of trips required.

However, this greater granularity also brings with it an increase in computational complexity, as demonstrated in the simulations with 500 and 750 items, where the processing time required for the exact model frequently exceeded the established limits. The heuristic model, on the other hand, maintained a rapid and effective response capacity, even in the face of greater complexity, confirming its applicability and robustness in a dynamic and demanding operational context.

The analysis of the list configurations also shows that the high granularity of the items, specifically in lists that exceed 500 items with a combined weight of 13,873 kg, potentiates the effectiveness of heuristic models in the search for optimal solutions. This translates into a more precise fit of the items within the aircraft's capacities, which contributes to the reduction of trips and operational costs. Notably, even in configurations of even denser lists, with 750 items, it was observed that simple strategies such as the NF could achieve results comparable to those of the HPHA, highlighting the ability of these models to efficiently handle increased complexity, even under rigorous processing constraints.

VI. CONCLUSION

This study focused on logistics optimization for the PEFs in Surucucu and Auaris, achieving significant reductions in the number of trips and the use of air resources. The implementation of the model resulted in a saving of 20 hours and 30 minutes of air effort and 3 operational days, demonstrating substantial improvements in logistical efficiency.

This study confirmed that the detailing and variation of the sizes and weights of the items have a direct impact on the capacity to accommodate them in the aircraft and, by extension, on the number of trips required. More sophisticated optimization techniques, such as the proposed heuristic model, have shown not only feasibility but superiority in various test scenarios, providing efficient solutions in considerably reduced operational timeframes.

In addition, the application of the trip optimization model offered a framework capable of maximizing the utilization of space and available flight time, contributing to a significant reduction in the total number of days required to complete all logistical missions. This optimization was achieved through the reformulation of how cargo and trips are planned and executed, replacing sequential and less efficient approaches with strategies that explore the potential of packing algorithms.

Beyond applications to PEFs, the approach developed in this study has significant potential to be adapted in humanitarian aid missions, where logistical efficiency is equally critical. For example, Operation Yanomami carried out in 2023 to deliver food to the indigenous people, and the missions to support the state of Rio Grande do Sul in 2024 with the delivery of donations from all over the country to those displaced by the floods.

In these contexts, resource optimization can play a vital role in maximizing the desired impact, saving lives, alleviating human suffering, and minimizing costs.

A proposal for future studies is the development of models that consider different loading contexts, such as National Air Transport Lines and humanitarian aid missions carried out by the FAB. Analyzing real data comparatively in these situations can provide a way to further improve the efficiency of air transport operations, ensuring optimal use of available resources and reducing operational costs.

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