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DATA-DRIVEN APPROACH FOR OPERATIONAL EVALUATION OF AIRSPACE DESIGN

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"IN THE END... We only regret the chances we didn't take,
the relationships we were afraid to have,
and the decisions we waited too long to make."
— Lewis Carroll

Resumo

O avanço do Gerenciamento de Tráfego Aéreo, com a implementação de novas estruturas de espaço aéreo, sistemas e procedimentos, é crucial para a melhoria do desempenho econômico e ambiental da aviação. Para isso, são necessárias avaliações operacionais detalhadas de diferentes soluções de desenho e gestão do espaço aéreo através de análise avançada de dados. Este estudo analisa as operações no espaço aéreo terminal para os principais aeroportos brasileiros usando dados históricos de larga escala de rastreamento de voos e informações aeronáuticas. Primeiramente, um método de classificação de trajetória é desenvolvido para identificar o uso real de procedimentos operacionais padrão de chegada pelos voos. Diversos indicadores de desempenho são então propostos para avaliar o uso real da estrutura do espaço aéreo terminal e quantificar a eficiência e a conformidade das trajetórias de voo. Os resultados revelam uma distribuição não uniforme do tráfego nos procedimentos de chegada para a maioria dos aeroportos, bem como uma elevada variabilidade de desempenho entre aeroportos e seus respectivos procedimentos. De forma geral, é possível observar que os procedimentos mais utilizados estão associados a níveis mais altos de conformidade da trajetória, enquanto aeroportos mais movimentados mostram trajetórias menos aderentes. Indicadores específicos são criados para avaliar o novo desenho de espaço aéreo, baseado no conceito Point Merge, no Aeroporto Internacional de São Paulo/Guarulhos. Os resultados mostram uma utilização significativa, porém desbalanceada, dos arcos de sequenciamento do sistema Point Merge para a absorção de atrasos durante as operações táticas. Destaca-se também preferências do controle de tráfego aéreo e oportunidades de aperfeiçoamento no gerenciamento de atrasos.

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Abstract

Advancing Air Traffic Management with the implementation of novel airspace structures, systems and procedures is crucial to enhancing the economic and environmental performance of aviation. This requires detailed operational evaluations of different airspace design and management solutions through advanced data analysis. This work analyzes the terminal airspace operations for the major Brazilian airports using large-scale historical aircraft tracking data and aeronautical information data. A trajectory classification method is first developed to identify the actual use of standard operational procedures by arrival traffic. Several performance indicators are then proposed to evaluate the actual utilization of the terminal airspace structure and to quantify trajectory efficiency and conformance. The results reveal an uneven distribution of traffic across arrival procedures for most airports and a high variability in performance across airports and their procedures. Overall, we observe that the most frequently used procedures are generally associated with higher levels of trajectory conformance, while busier airports show less adherent trajectories. Specific indicators are created to analyze the novel Point Merge airspace design at Sao Paulo/Guarulhos International Airport. The results show a significant but unbalanced utilization of the Point Merge sequencing legs for delay absorption during tactical operations. The findings also highlight air traffic control preferences and opportunities for further improvements in delay management.

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1 Introduction

Globally, initiatives to modernize Air Traffic Management (ATM) systems are advancing, incorporating novel technologies, systems, and procedures to handle anticipated increases in air traffic volume and diversity. In the Global Air Navigation Plan, the International Civil Aviation Organization (ICAO) outlines a systematic framework (known as Aviation Systems Block Upgrades - ASBU) for the ATM system modernization and proposes a performance-based approach to identify improvement areas, prioritize investments, and measure the impacts of new solutions (ICAO, 2019). To this goal, several Key Performance Indicators (KPIs) have been proposed to help quantify, analyze and improve the economic, operational and environmental performance of ATM. Operational performance is a major focus, with various KPIs evaluating the safety, efficiency, and predictability of flight operations across multiple phases and airspace regions (ICAO, 2024).

A region of airspace that poses challenges for operational performance management is the Terminal Maneuvering Area (TMA). The TMA (often referred to as terminal airspace) is the designated controlled airspace where aircraft are guided during critical phases of flight, such as arrival and departure. The high density and complexity of terminal operations, constrained by airport and airspace capacity, frequently lead to inefficiencies that impact system-level performance, especially during the arrival phase.

To continuously improve the performance of flight operations during these complex flight phases, the terminal airspace is often redesigned, introducing novel concepts and operational procedures. One example is the Point Merge (PM) system, an innovative operational concept for managing arrival flows developed by the Eurocontrol Experimental Center in 2006 (EUROCONTROL, 2021). As one of the ICAO's ASBU components, it has been implemented in more than 30 airports worldwide. In Brazil, this concept was introduced in the structure of arrival procedures at Sao Paulo/Guarulhos International Airport (SBGR) with the major redesign of the Sao Paulo terminal area (known as TMA-SP Neo) implemented in 2021 by the Brazilian Department of Airspace Control (DECEA, 2021).

Typically, airspace redesign projects rely on fast-time and real-time simulations to assess the operational impacts of novel procedures before implementation. However, actual operations are often characterized by a higher level of variability than simulated operations in controlled environments due to the impacts of constraints that cannot be easily modeled and incorporated into simulation models (e.g., weather impacts). Therefore, once implemented, evaluating the actual operational use and performance of an airspace structure based on actual data is critical for continued improvement in airspace design and management.

In this work, we combine historical aircraft tracking data and aeronautical information data to perform a detailed characterization of air traffic performance in terminal airspace, using the top ten Brazilian airports in aircraft movements as study case. First, we develop a flight trajectory classification approach to evaluate the actual use of the terminal airspace structure by arrival flights. Then, we quantify the air traffic performance using standard KPIs recommended by ICAO as well as novel indicators proposed to evaluate the level of conformance of flight operations. The results contribute to a better understanding of flight trajectory behavior and performance in the terminal area, highlighting air traffic control preferences and opportunities for further operational improvements.

2 Literature Review

Extensive previous research has delved into quantifying and analyzing air traffic operational performance towards offering key insights into its influencing factors, pinpointing areas for improvement and informing decision-making. Gulding *et al.* (2010) used operational databases from the US and Europe and presented indicators to assess efficiency, punctuality, and predictability across different phases of flight. Leones *et al.* (2018) also proposed indicators to capture the different perspectives of ATM performance, considering factors like fuel consumption, schedule adherence, sector capacity, and environmental impact. Zhang *et al.* (2018) proposed a sector capacity assessment method based on airspace utilization efficiency, rather than air traffic controller workload. Their research aimed at creating indicators such as flight miles in the sector per hour to help build up the correlation between airspace efficiency and dense air traffic flow.

Given the density and complexity of the terminal area, many studies have focused on the analysis of operational performance for this particular airspace. Polishchuk e Smetanová (2023) performed a comprehensive quantitative assessment of arrival operations within TMAs, using historical flight data from several European airports to propose and validate new performance metrics. Lemetti *et al.* (2019) evaluated flight performance for arrivals at Stockholm Arlanda Airport, using indicators of punctuality and fuel consumption, concluding that deviations from flight plans are a major cause of arrival delays and additional fuel burn. Inefficient vertical profiles during descent led to significant fuel waste, emphasizing the need for optimized continuous descent operations (CDO). Murça *et al.* (2018) performed a detailed comparative analysis of terminal airspace design, utilization and performance for the New York, Sao Paulo and Hong Kong multi-airport systems, investigating how differences in airspace structure and operational procedures impact efficiency, capacity and predictability. Zanin (2020) and Pasutto *et al.* (2020) analyzed trajectories of aircraft arriving at large European airports, highlighting a high variability in performance across airports and within operations at the same airport.

Hardell *et al.* (2023b) utilized open-source ADS-B data to measure the use of PM sequencing procedures at seven airports worldwide. Their analysis revealed that the arcs are underused at most airports, suggesting that PM systems could handle greater traffic volumes. In a separate study, Hardell *et al.* (2023a) employed ADS-B data to evaluate the performance of PM implementation at Oslo Gardermoen Airport, comparing various metrics for flights that did and did not use PM. Mutlu (2021) assessed the impact of the 2018 redesign of the Istanbul terminal area, which introduced a PM system, on airspace complexity and safety.

This study contributes to the literature with a detailed characterization of air traffic performance in terminal airspace for the top ten Brazilian airports in terms of aircraft movements in 2023. Each airspace design is unique, requiring thorough evaluation for continued operational improvement. The analysis includes a detailed characterization of the novel PM procedures for SBGR arrivals after the TMA-SP redesign implemented in 2021. We propose novel indicators to evaluate the terminal airspace utilization and the level of conformance of flight operations to standard procedures. While trajectory conformance is a fundamental aspect of predictability analysis, it has not been considered in previous studies, which focus on other key performance areas such as efficiency.

3 Methodology

3.1 Case Study

This work focused on the performance of arrival operations for the top ten Brazilian airports in terms of scheduled movements, based on the Active Regular Flight (VRA) database of the National Civil Aviation Agency (ANAC) for the year 2023.

3.1.1 São Paulo/Guarulhos International Airport (SBGR)

São Paulo/Guarulhos International Airport (SBGR) handled 276,809 aircraft operations in 2023, making it the busiest airport in South America. A significant redesign of the São Paulo terminal area, known as TMA-SP Neo, was undertaken in 2021 to enhance capacity and reduce the air traffic control complexity and workload. A key element of this redesign was the implementation of a PM system. The PM consists of a systematic technique for sequencing, merging, and spacing the arriving aircraft without the need to resort to vectoring, aimed at improving situational awareness and predictability. When an aircraft is on the arc, the pilot waits for the controllers' "direct to" instruction to the merge point. This system operates based on a specific route structure, as illustrated in Figure 3.1, utilizing a merge point and predefined sequencing legs, allowing for effective delay management and ensuring safe separation during high-traffic conditions. SBGR has two parallel runways, designated as 10L/28R and 10R/28L, which are separated by 375 m.

3.1.2 São Paulo/Congonhas Airport (SBSP)

São Paulo/Congonhas Airport (SBSP) is the second busiest airport in Brazil in terms of passenger traffic. This airport is located 8.7 km from the São Paulo's city center. In 2023, SBSP recorded 232,359 operations. SBSP has two parallel runways, designated as 17L/35R and 17R/35L, which are separated by 220 m.

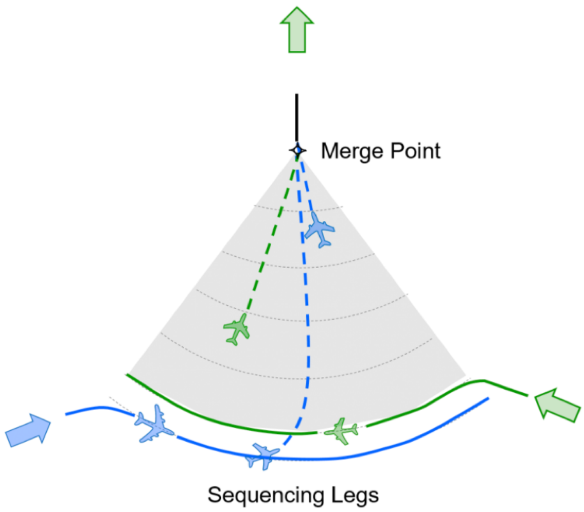

FIGURE 3.1 – Horizontal profile of the Point Merge system.
Source: (EUROCONTROL, 2021)

3.1.3 Brasília/Presidente Juscelino Kubitschek International Airport (SBBR)

Brasília/Presidente Juscelino Kubitschek International Airport (SBBR) handled 148,759 aircraft movements in 2023, holding the third position. It is located in the capital of Brazil, in the center-west region of the country, serving the highest number of flights in the region. SBBR has two parallel runways, designated as 11L/29R and 11R/29L, which are separated by 1800 m.

3.1.4 Viracopos/Campinas International Airport (SBKP)

The third airport in aircraft movements in the São Paulo state and the fourth in Brazil, Viracopos/Campinas International Airport (SBKP) performed 126,090 operations in 2023. It has 71 direct (non-stop) national and worldwide destinations. This airport is also a cargo hub airport, playing a vital role in transporting goods. It has a modern infrastructure for handling cargo, focusing on electronics, pharmaceuticals, and automotive products. SBKP has a single runway, designated as 15/33.

3.1.5 Rio de Janeiro/Santos Dumont Airport (SBRJ)

Located in Rio de Janeiro's downtown, the second most populous city in Brazil, attracting both business and leisure travelers, Rio de Janeiro/Santos Dumont Airport (SBRJ) is the fifth airport in number of operations in 2023, with 123,225 flights. This airport, the first civil airport in Brazil, specializes in domestic flights, particularly short-distance ones, due to its short runway. It serves frequent routes between Rio de Janeiro and other major Brazilian cities, such as São Paulo (Rio-São Paulo Air Shuttle), Brasília, Belo Horizonte, among others. SBRJ has two parallel runways, designated as 02L/20R and 02R/20L, which are separated by 75 m.

3.1.6 Belo Horizonte/Confins International Airport (SBCF)

Belo Horizonte/Confins International Airport (SBCF) is the sixth in number of operations in 2023, with 98,943 aircraft movements. It is located about 40 km from downtown Belo Horizonte, in an area that facilitates access to northern Minas Gerais and other regions of the state (the biggest state in the Southern region of Brazil). Located further from the densest urban areas, it can operate without the space and noise limitations that affect airports in densely populated areas. The airport is an important hub for both domestic and international flights. It offers connections to several cities in Brazil and direct international flights to destinations in South America, Europe, and North America. SBCF is also an important airport for cargo transportation. It serves sectors such as mining and agribusiness, which are of great economic importance to Minas Gerais. SBCF has a single runway, designated as 16/34.

3.1.7 Recife/Guararapes International Airport (SBRF)

Recife/Guararapes International Airport (SBRF) is the seventh airport in number of operations in 2023. With 87.353 aircraft movements, it ranks first in the country's northeast region. Because of its strategic geographical position, the airport is an important connection for domestic and international flights. SBRF is also one of the most important airports for cargo in the Northeast region. SBRF has a single runway, designated as 18/36.

3.1.8 Salvador/Deputado Luís Eduardo Magalhães International Airport (SBSV)

Salvador/Deputado Luís Eduardo Magalhães International Airport (SBSV) is located in the capital of Bahia state, being the eighth airport in number of operations in 2023, with 77,644 flights. SBSV offers a wide range of domestic and international routes and also serves as an important hub for regional connections in the Northeast region. SBSV has two runways, designated as 10/29 and 17/35.

3.1.9 Porto Alegre/Salgado Filho International Airport (SBPA)

Porto Alegre/Salgado Filho International Airport (SBPA) is located in the capital of Rio Grande do Sul state. With 72,930 aircraft movements in 2023, it holds the ninth position. SBPA serves as the main air transportation hub in the South region, especially for business and tourism travel, both within the state and between other southern airports. The airport offers a wide range of domestic flights, connecting Porto Alegre to major Brazilian capitals. SBPA has a single runway, designated as 11/29.

3.1.10 Curitiba/President Afonso Pena International Airport (SBCT)

Curitiba/President Afonso Pena International Airport (SBCT) is located in the Paraná state, holding the tenth position, with 60,562 aircraft movements in 2023. Although it is located in Sao José dos Pinhais, it serves the capital of Paraná, Curitiba, and its metropolitan area. The airport offers a wide range of domestic flights. There are also international flights, mainly to destinations in South America, such as Buenos Aires. SBCT is an essential hub for cargo transportation and the distribution of manufactured products, especially from the automotive, electronics, and agricultural sectors. SBCT has two crossing runways, designated as 15/33 and 11/29.

3.2 Data Description and Preprocessing

This study used flight tracking data and aeronautical information data to analyze the actual operations in light of the current airspace structure.

The actual flight tracking data for arrival operations at all airports was collected from FlightRadar24 and contains flight data for the entire year of 2023 (FLIGHTRADAR24, 2024). The database holds multiple flight information such as: flight ID, time, latitude, longitude, altitude, speed, aircraft type, origin airport, and destination airport. Data preprocessing was performed to clean, filter and transform the raw flight tracking dataset into a structured dataset of arrival trajectories within the terminal area (modeled as the cylindrical volume with a radius of 100 NM extending from the airport).

Aeronautical information data collected from AISWEB (DECEA, 2024) was also used to create a dataset with the Standard Terminal Arrival Procedures (STAR) at those airports, containing information such as latitude, longitude, heading, distance between waypoints, flight level, for each arrival procedure. Similarly, data preprocessing was performed to obtain a structured dataset of standard arrival trajectories within the terminal area.

3.3 Trajectory Classification

A trajectory classification approach was developed to identify the arrival pattern followed by each flight operation. For this, a data resampling and scaling process was performed so that each actual trajectory was represented with a vector of 60 observations containing the horizontal profile within the terminal area. The same process was performed for each standard arrival procedure. Then, for each flight, we computed the Euclidean distance between its actual trajectory vector and the standard procedure vectors, identifying the one with the minimum distance as the arrival procedure used by the flight.

3.4 Terminal Airspace Utilization

Based on the trajectory classification results, we calculated the percentage of traffic associated with each arrival procedure to analyze the actual utilization of the terminal airspace. A novel Airspace Utilization (AU) indicator was created to measure the degree of concentration in the distribution of traffic across the main arrival patterns in the terminal area, inspired by the Herfindahl–Hirschman Index (HHI) (RHOADES, 1993). In econometric studies, this index is usually used to measure the level of market concentration on a given flight route (ALMEIDA; OLIVEIRA, 2023). The highest value that this index can reach is one, indicating full market dominance by one company, and the minimum value depends on the number of companies that serve the same route (GUTERRES, 2003). The AU indicator is defined in Equation 3.1. Similarly, the higher the indicator, the higher the traffic concentration in the airspace analyzed.

$$AU = \sum_{i=1}^{N} s_i^2 \tag{3.1}$$

Where:

N is the number of arrival procedures that connect distinct arrival gates with the airport;

s_i is the traffic share, expressed as a fraction, of arrival procedures that connect arrival gate i with the airport.

3.5 Trajectory Conformance

To evaluate the predictability of arrival trajectories, we developed a new Trajectory Conformance (TC) indicator. During the trajectory classification step, we computed, for each flight, the Euclidean distance between its actual trajectory vector and the standard procedure vectors, identifying the one with the minimum distance as the arrival procedure used by the flight. The conformance is then calculated as the Euclidean distance between the arrival trajectory and the corresponding arrival procedure, being normalized between 0 and 1 with min-max normalization, as defined in Equation 3.2. The higher the TC indicator, the lower the conformance of the actual flight trajectory to the standard procedure.

$$TC_{normalized} = \frac{TC_{flight} - TC_{min}}{TC_{max} - TC_{min}} \tag{3.2}$$

3.6 Temporal Efficiency

To quantify the efficiency of arrival trajectories, we used a KPI recommended by ICAO. The Additional Flight Time (AFT) indicator computes the difference between the actual flight time and a reference unimpeded time in the terminal area, as defined in Equation 3.3. This indicator measures the delay incurred due to tactical air traffic control for sequencing, metering and spacing the flights in the terminal area. The reference time is defined as the 20^{th} percentile of the historical distribution of flight times for each arrival pattern and aircraft category, providing a proxy for an unimpeded arrival process.

$$AFT_i = time_i - ref_{pc,i} \tag{3.3}$$

Where $time$ is the actual flight time in the terminal area for flight i and ref_{pc} is the reference time for the corresponding arrival pattern p and aircraft category c of flight i.

3.7 Point Merge System Evaluation

Specific indicators were also created to evaluate the utilization of the new PM system at SBGR.

A PM Use indicator was defined as the percentage of flights that used the main PM structure of SBGR. To assess if a given flight trajectory passed through the PM sequencing legs, we identified segments in the arrival trajectory with a constant distance to the merge point SANPA, followed by a direct segment to this waypoint.

Finally, we developed a PM Arc Utilization indicator that evaluates the extent to which the sequencing arcs are used for delay absorption. For this, we added circles of 3 NM radius around the waypoints that define the arcs and analyzed the presence of trajectory points within at least one of the circles. The indicator is then calculated by the ratio of the length of the PM arc actually flown before descending and the total length of the PM arc. In other words, it divides the number of waypoints that the aircraft has flown in the PM arc by the total number of waypoints that define the sequencing leg.

4 Results and Discussion

4.1 Operational Analysis of Terminal Airspace Design

This section presents and discusses the results of terminal airspace utilization, trajectory conformance and temporal efficiency for each airport analyzed in this work.

4.1.1 SBGR

4.1.1.1 Standard Arrival Procedures

Figure 4.1 shows the standard arrival procedures at SBGR. It is observed that they connect four main arrival gates with the runways 10/28, either through the main PM arc structure around the merge point SANPA or through direct segments. To improve readability, instead of using the actual name of the arrival procedure, we created a coding scheme that indicates the combination of arrival gate (North- N; Northwest- NW; South- S; and East- E) and runway configuration and if the procedure is part of the main PM structure or not. For instance, the first arrival procedure shown in red in Figure 4.1 connects the North (N) arrival gate with runway 10R through the inner arc of the main PM structure. By that, it is identified as N-10-PM.

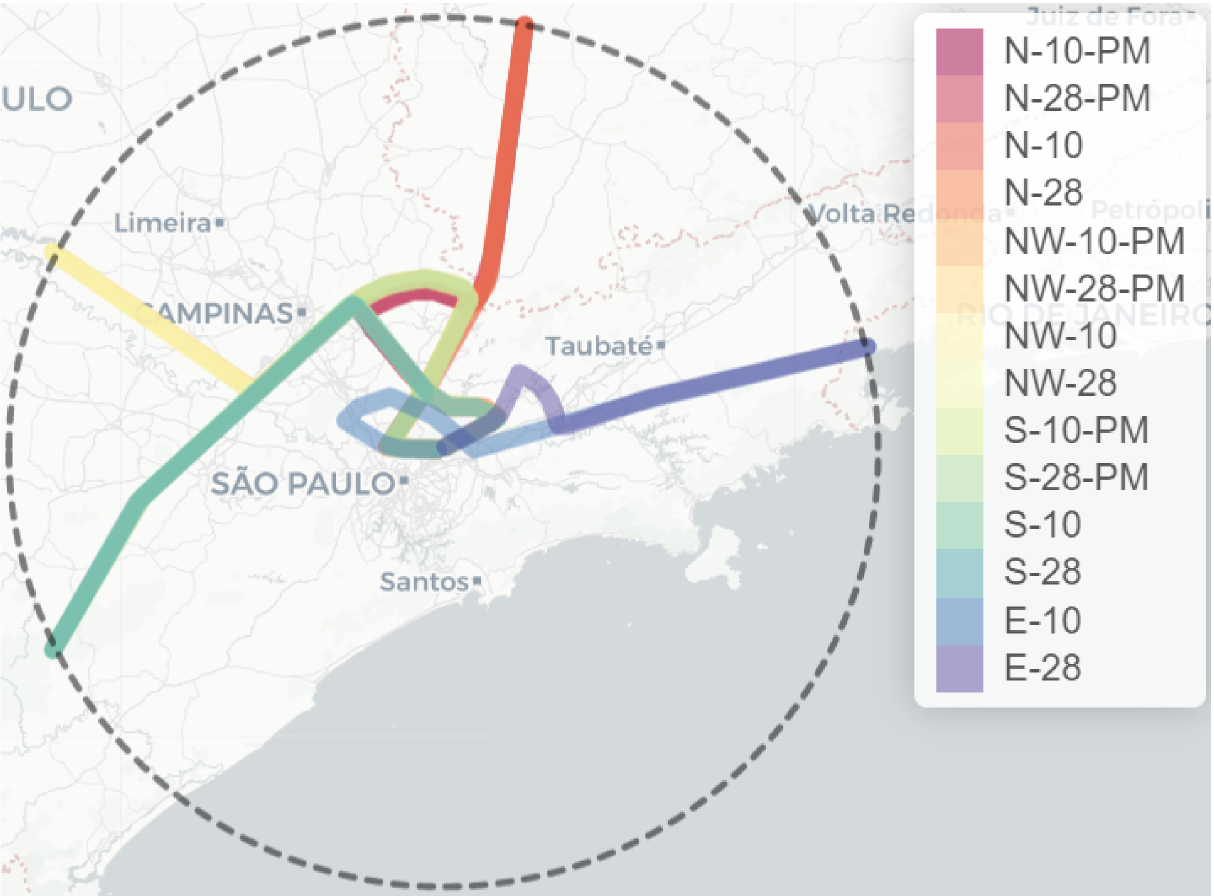

FIGURE 4.1 – SBGR arrival procedures.

4.1.1.2 Analysis of Terminal Airspace Utilization

The application of the trajectory classification algorithm enabled the characterization of the actual utilization of the terminal airspace. Figure 4.2 shows the distribution of flight operations by arrival pattern. The results reveal an uneven distribution of air traffic across arrival procedures. The dominant traffic flow pattern for SBGR corresponds to arrivals from the North gate to runway 09R. It is observed a high concentration of arrivals through the North (N) gate, which accounts for 49.9% of the operations. The South (S) gate represents the second major flow, accounting for 23.6% of the operations. Finally, 17% of the flights arrive through the Northwest (NW) gate and the remaining 9.5% use the East (E) gate.

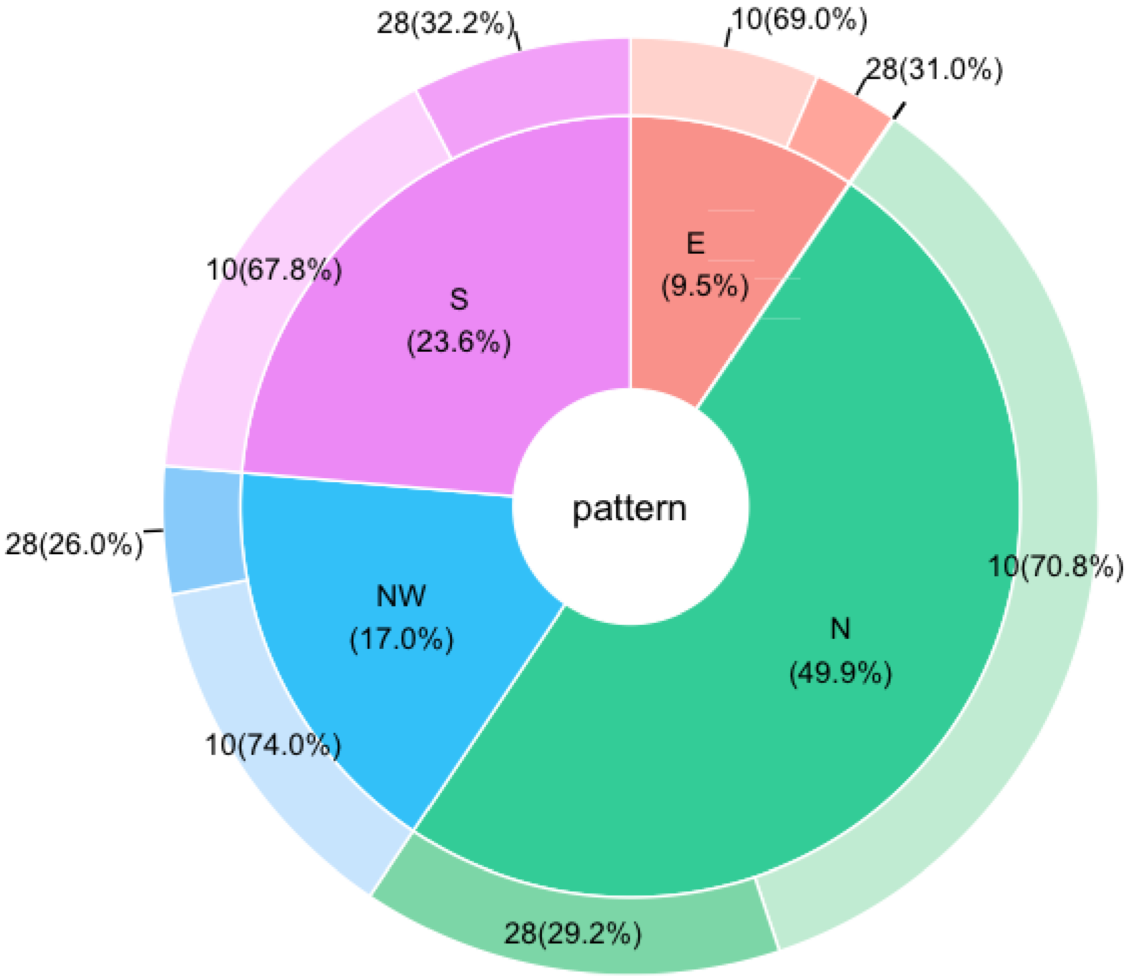

FIGURE 4.2 – Distribution of flight operations by arrival pattern at SBGR.

4.1.1.3 Analysis of Trajectory Conformance

Figure 4.3 shows the distributions of flight trajectory conformance by arrival pattern. Overall, we observed low variability for this indicator, indicating a dependable level of trajectory conformance across arrival patterns. Nevertheless, the East arrival patterns consistently showed slightly lower normalized conformance values than the other patterns, suggesting better adherence of actual trajectories to standard procedures for this traffic flow.

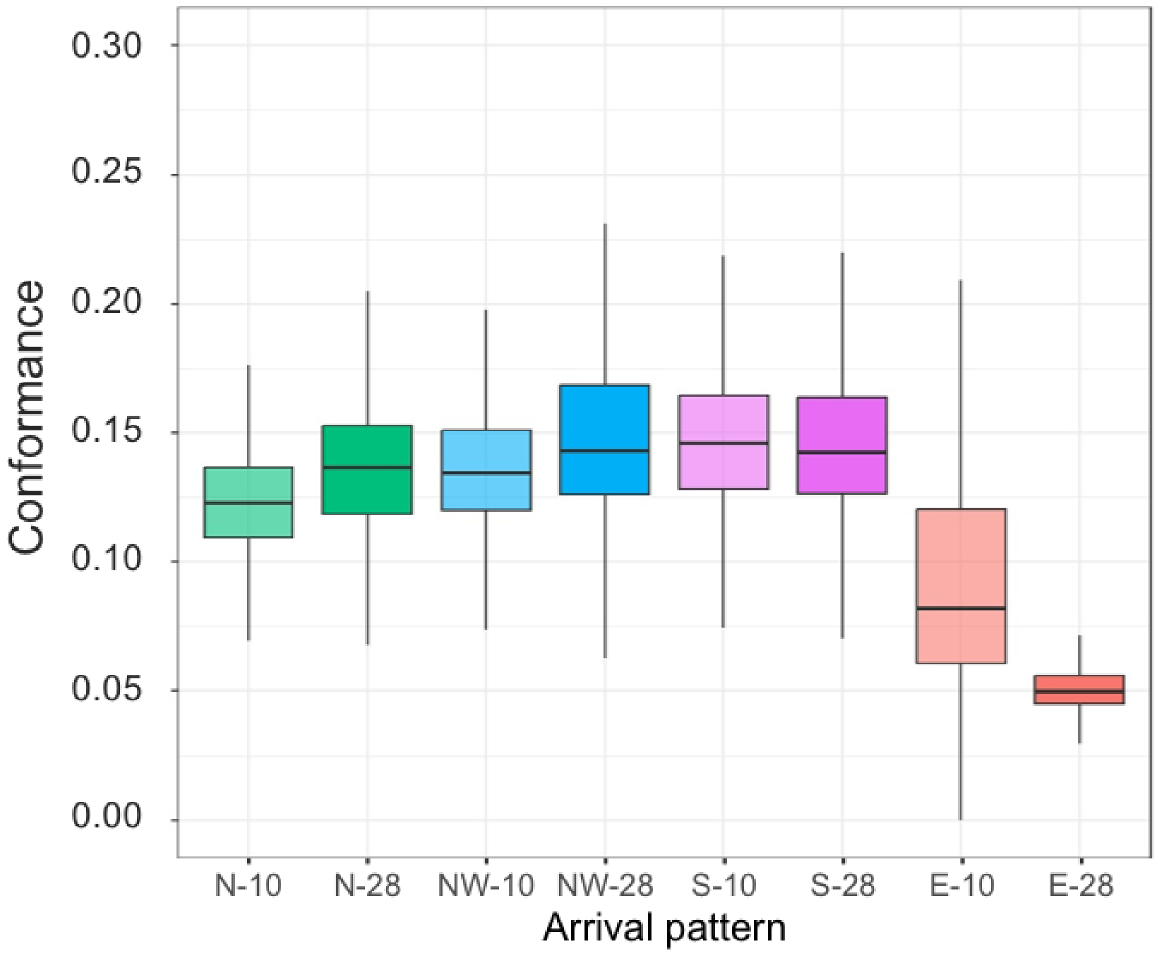

FIGURE 4.3 – Boxplots of trajectory conformance for SBGR arrival patterns.

4.1.1.4 Analysis of Point Merge Use

Table 4.1 presents the frequency of use of the PM structure at SBGR. It indicates that more than 50% of the South (S) and Northwest (NW) arrival traffic follows the PM procedures. A lower usage rate of PM procedures was observed for the major North (N) arrival traffic. For instance, 34% of the traffic coming from the north and landing on runway 10R absorbed some delay in the PM structure. These results might suggest an air traffic control preference for using the outer sequencing leg to delay the South and Northwest flows during the sequencing process, highlighting a potential opportunity for improvement to achieve a more equitable distribution of delays across arrival patterns. Finally, we also observed that the least frequent runway configuration (arrivals on runway 28L) was associated with increased use of the PM structure.

TABLE 4.1 – Use of the main PM structure at SBGR.

Arrival pattern	*Percentage*
N-10	34.0%
N-28	42.8%
NW-10	52.5%
NW-28	67.8%
S-10	51.0%
S-28	66.6%

4.1.1.5 Analysis of Point Merge Arc Utilization

Figure 4.4 shows the utilization of the inner and outer sequencing arcs of the main PM structure at SBGR as the percentage of flights that traversed a given percentage of the arc length. For instance, the graph indicates that 34.6% of the flights that used the outer sequencing arc traversed at most 25% of the arc. It is worth noting that the inner arc is part of the N-PM arrival procedures while the outer arc is part of the S-PM and NW-PM procedures, as shown in Figure 4.1. Interestingly, the results show that despite the lower usage rate of the PM structure for the major North arrival flow (Table 4.1), when it is used, flights tend to spend more time in the sequencing leg. Figure 4.4 indicates that 45.8% of the North arrival traffic that used the PM structure traversed more than 75% of the inner arc length. By contrast, 25.4% of South and Northwest arrival traffic that used the PM structure flew more than 75% of the outer arc length. The combined results of PM structure use and PM arc utilization suggest that the inner arc is more likely utilized during peak traffic periods, indicating a high use of the delay absorption capacity provided by the PM during these periods.

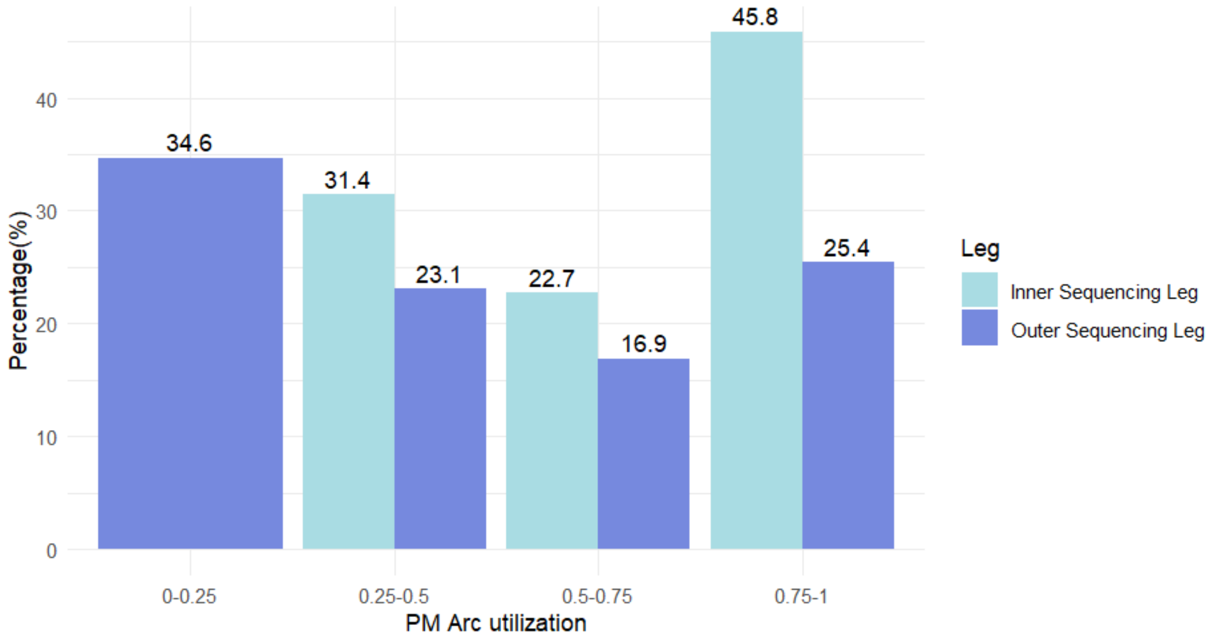

FIGURE 4.4 – Utilization of the inner and outer arcs of the main PM structure at SBGR.

4.1.1.6 Analysis of Additional Flight Time

Figure 4.5 shows the distributions of additional flight time by arrival pattern. We observed a high variability in temporal efficiency across arrival patterns and within the same pattern. For instance, the median value of additional flight time was approximately 2 min for the dominant arrival pattern (N-10), but reached almost 7 min for other traffic patterns. The South and Northwest flows consistently showed higher values of additional time than the North and East flows, suggesting that they are more likely to absorb queueing delays in the terminal area.

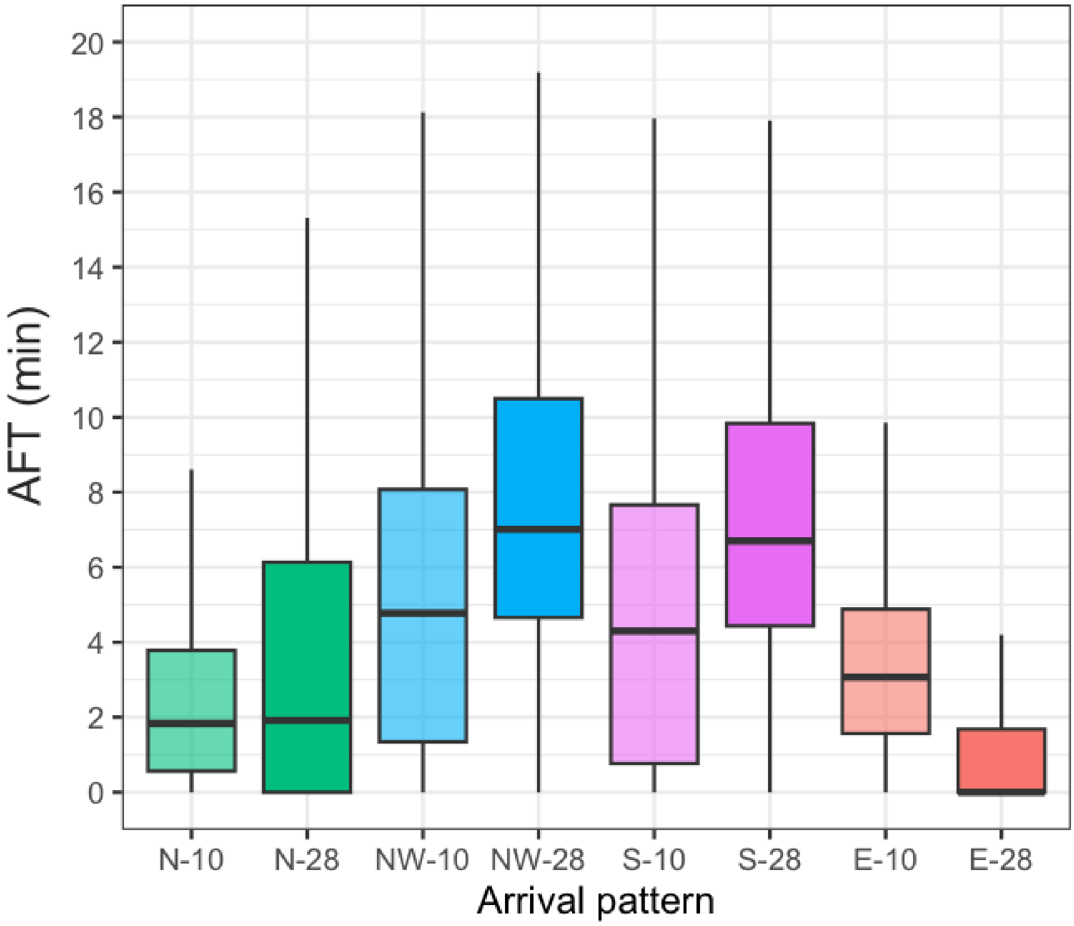

FIGURE 4.5 – Boxplots of additional flight time for SBGR arrival patterns.

4.1.2 SBSP

4.1.2.1 Standard Arrival Procedures

Figure 4.6 shows the standard arrival procedures at SBSP. This airport's arrival procedures connect four arrival gates with the runways 17/35. The procedures are labeled with a coding scheme similar to SBGR's, which indicates the combination of arrival gate (North-N; Northwest-NW; South-S; and East- E) and runway configuration.

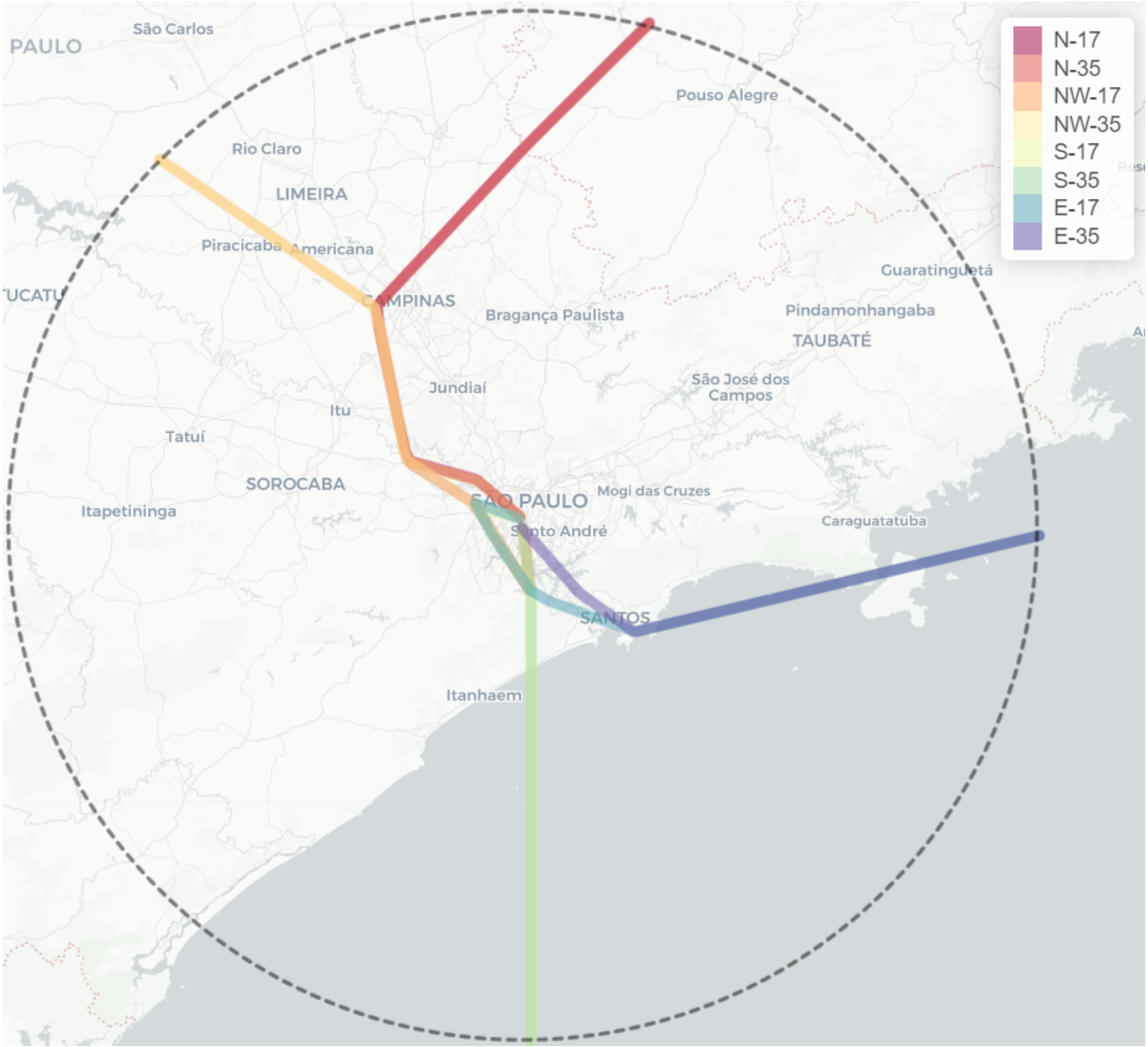

FIGURE 4.6 – SBSP arrival procedures.

4.1.2.2 Analysis of Terminal Airspace Utilization

Figure 4.7 shows the distribution of flight operations by arrival pattern. The results reveal a more even distribution of air traffic across arrival procedures, when compared with SBGR. The dominant traffic flow pattern for SBSP corresponds to arrivals from the North gate to runway 17R. The North (N) gate accounts for the highest share of 34.8% of the operations. The South (S) gate represents the second major flow, accounting for 28.9% of the operations. Finally, 23.3% of the flights arrive through the East (E) gate and the remaining 13% use the Northwest (NW) gate. It is also observed that the distribution of arrivals per runway is close to 60% for runway 17R and 40% for runway 35L.

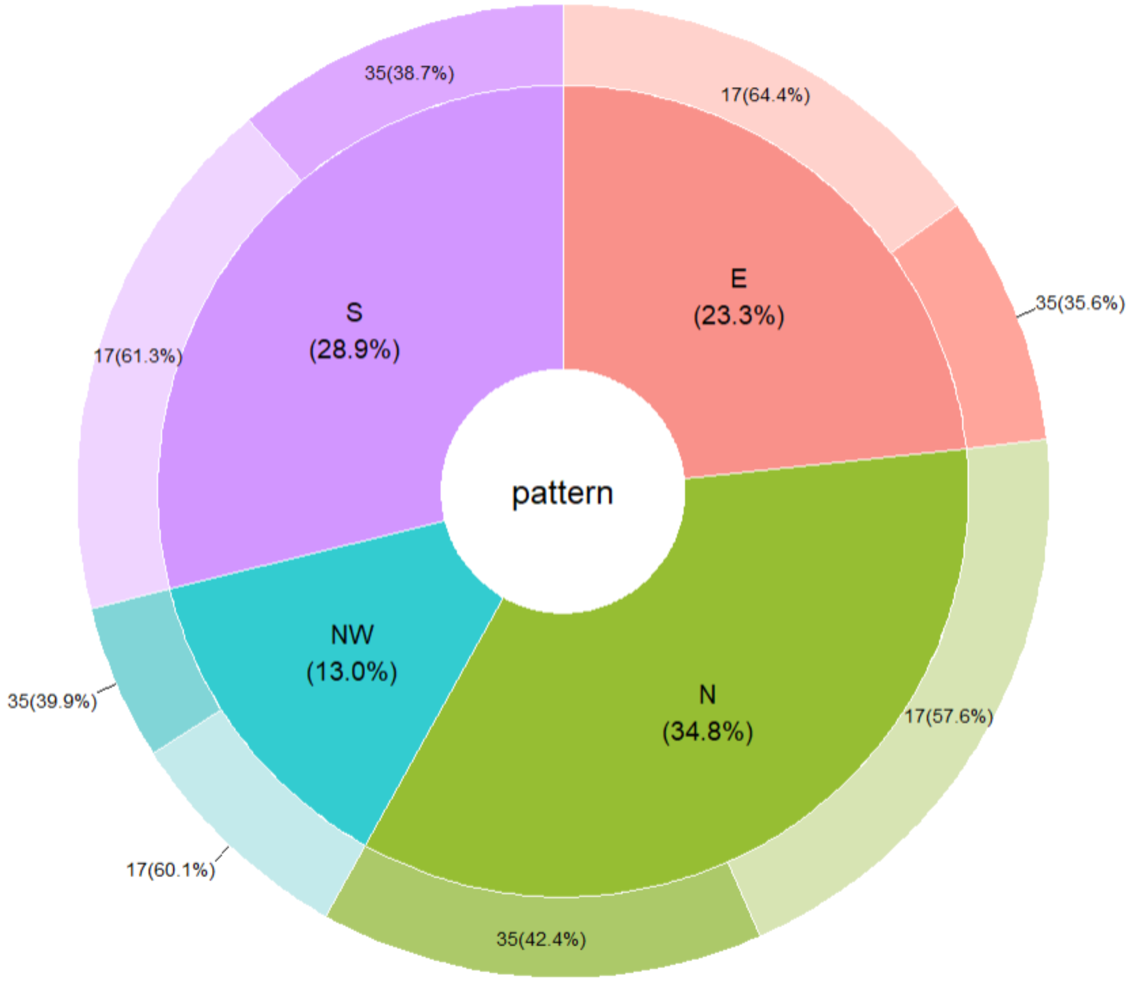

FIGURE 4.7 – Distribution of flight operations by arrival pattern at SBSP.

4.1.2.3 Analysis of Trajectory Conformance

Figure 4.8 shows the distributions of flight trajectory conformance by arrival pattern in SBSP. Overall, we observed higher variability in trajectory conformance across arrival patterns when compared to SBGR, indicating a less dependable level of performance for this indicator. Arrival flows to runway 17 are generally observed to have higher adherence to standard procedures, except for the East flows. The North and South arrival patterns consistently showed higher normalized conformance values than the Northwest and East patterns, suggesting lower adherence of actual trajectories to standard procedures for the dominant flows that receive the highest proportion of traffic.

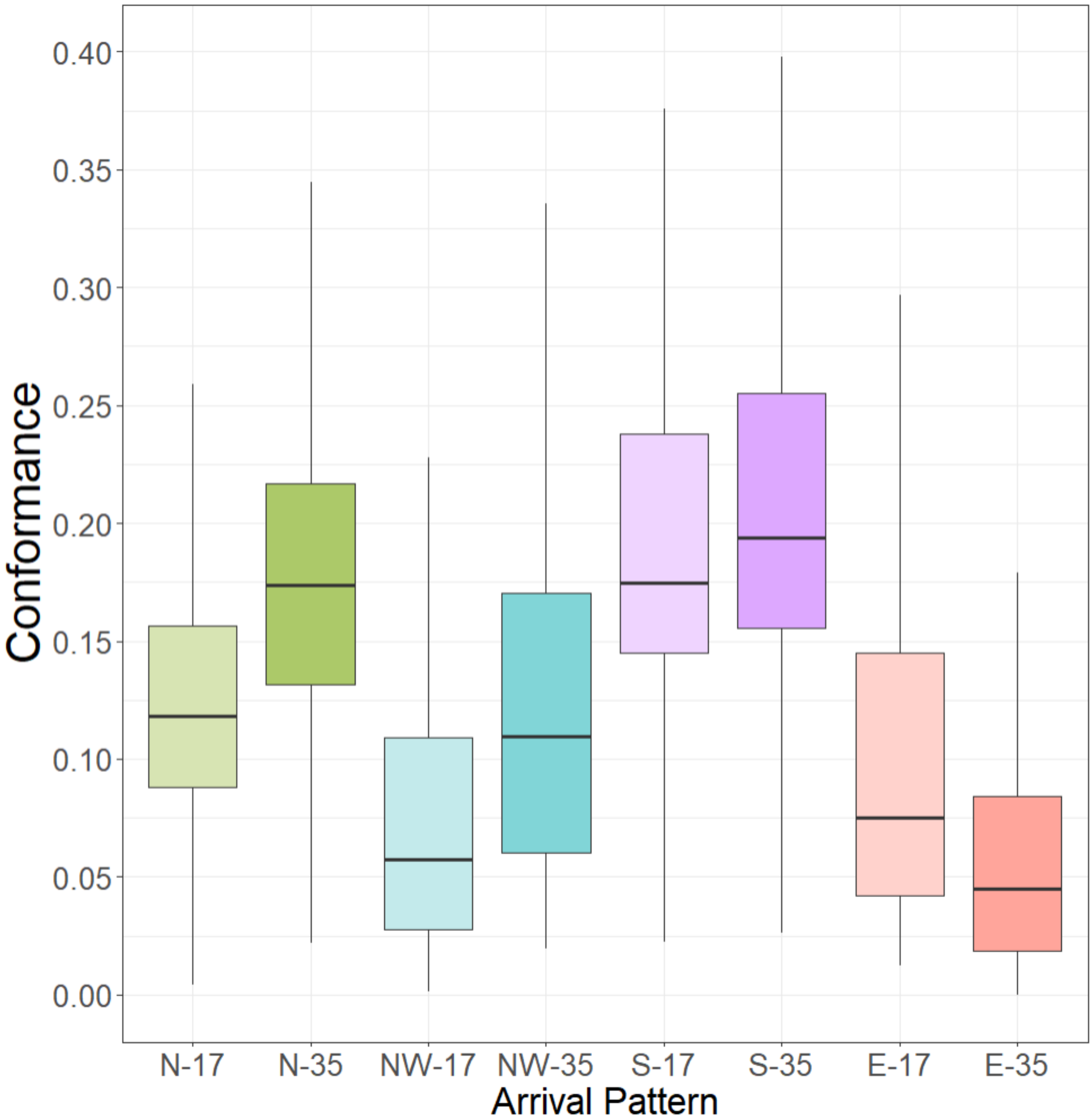

FIGURE 4.8 – Boxplots of trajectory conformance for SBSP arrival patterns.

4.1.2.4 Analysis of Additional Flight Time

Figure 4.9 shows the distributions of additional flight time by arrival pattern. We observed high variability in temporal efficiency within the same pattern but a regular distribution of additional times per procedure. For instance, the median value of additional flight time was approximately 3.5 min for the dominant arrival pattern (N-17), and the boxplots for the Northwest, South and East flows consistently showed approximately the same additional time values, suggesting an even distribution of delays in the terminal area.

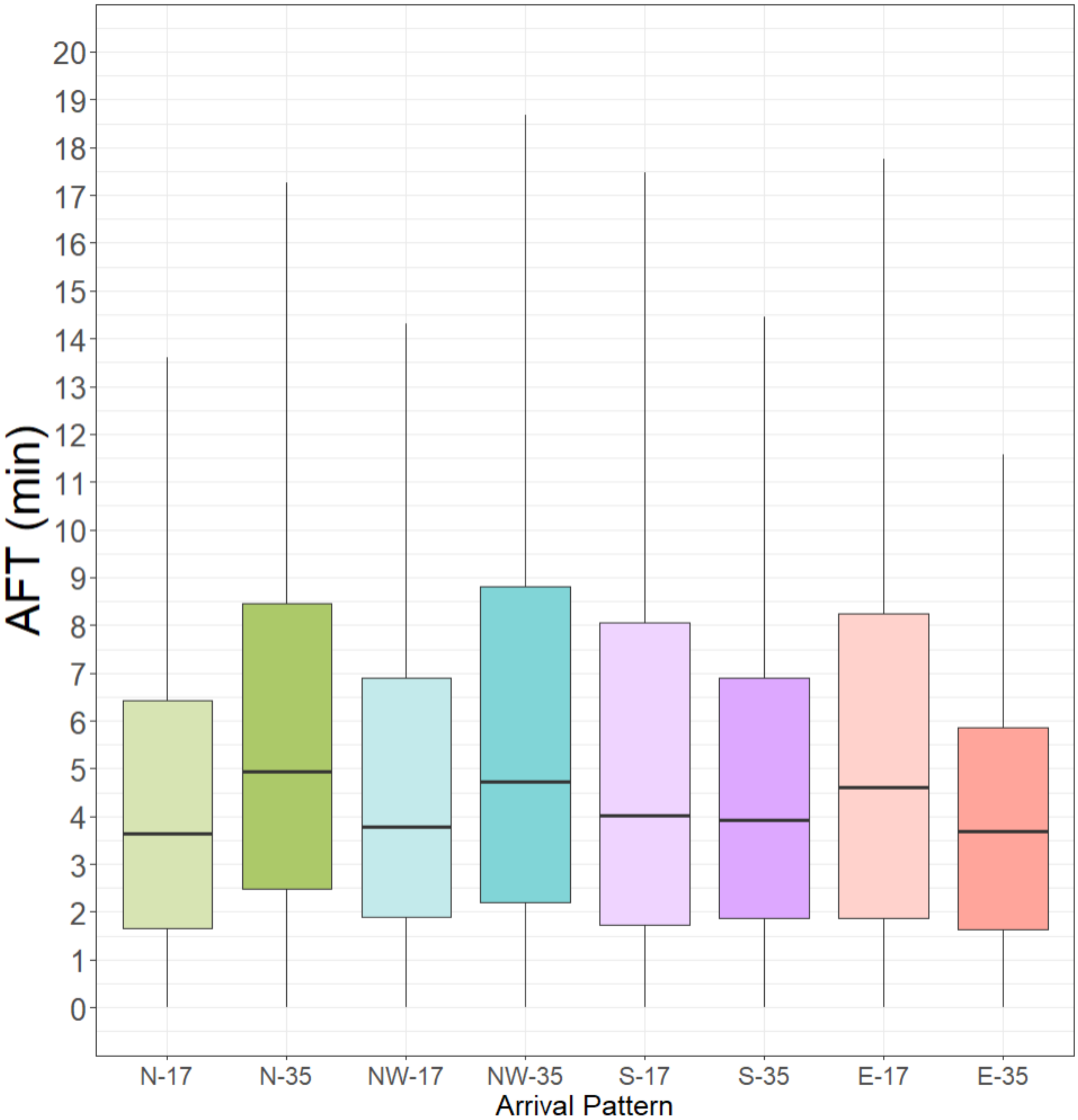

FIGURE 4.9 – Boxplots of additional flight time for SBSP arrival patterns.

4.1.3 SBBR

4.1.3.1 Standard Arrival Procedures

Figure 4.10 shows the standard arrival procedures at SBBR. This airport's arrival procedures are distributed in five main arrival regions. For each arrival region, multiple procedures connect different arrival gates with the runways 11/29. To improve readability, we used numbers to distinguish procedures starting at different arrival gates within the same arrival region. The coding scheme is similar to those before, with the combination of arrival region (North-N; Northwest-NW; South-S; Southeast-SE; and Southwest-SW), arrival gate and runway configuration.

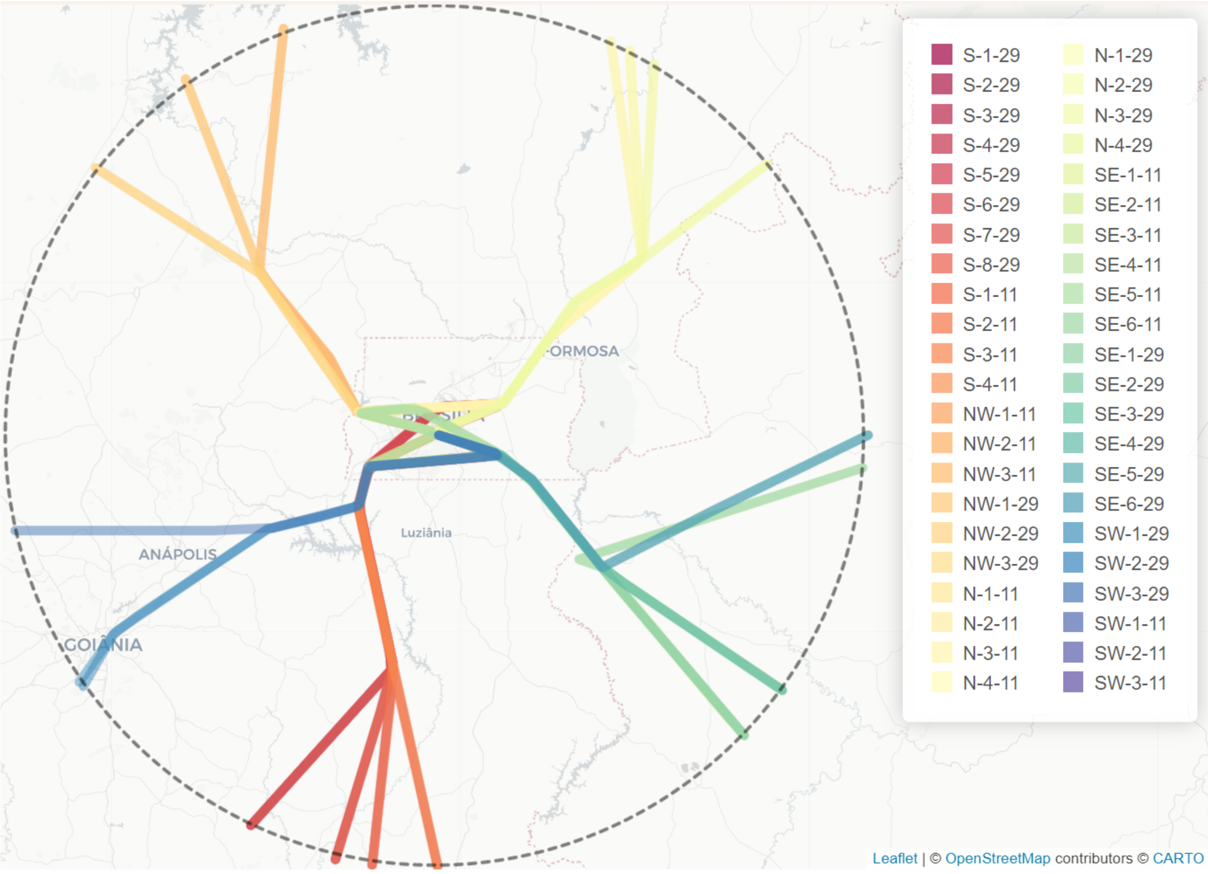

FIGURE 4.10 – SBBR arrival procedures.

4.1.3.2 Analysis of Terminal Airspace Utilization

Figure 4.11 shows the distribution of flight operations by arrival pattern. The results reveal an uneven distribution of air traffic across arrival regions. The dominant traffic flow pattern for SBBR corresponds to arrivals from the South gate to runways 11L/R. It is observed the highest concentration of arrivals in the South (S) gate, which accounts for 37.55% of the operations. The Southeast (SE) gate represents the second major flow, accounting for 21.63% of the operations. The North (N) and Northwest (NW) gates account for 17.37% and 17.07% of the operations, respectively, showing a similar volume of traffic. Finally, 6.38% of the flights arrive through the Southwest (SW) gate. It is also observed that the distribution of arrivals per runway is close to 70% for runways 11L/R and 30% for runways 29L/R. The dominant South arrival pattern is related to flights from Sao Paulo area airports, such as SBGR, SBSP, and SBKP. These flights use SBBR airport as a destination or hub airport (the biggest domestic hub) due to this airport's geographical location at the center of the country, serving as a great connection point for other areas of Brazil.

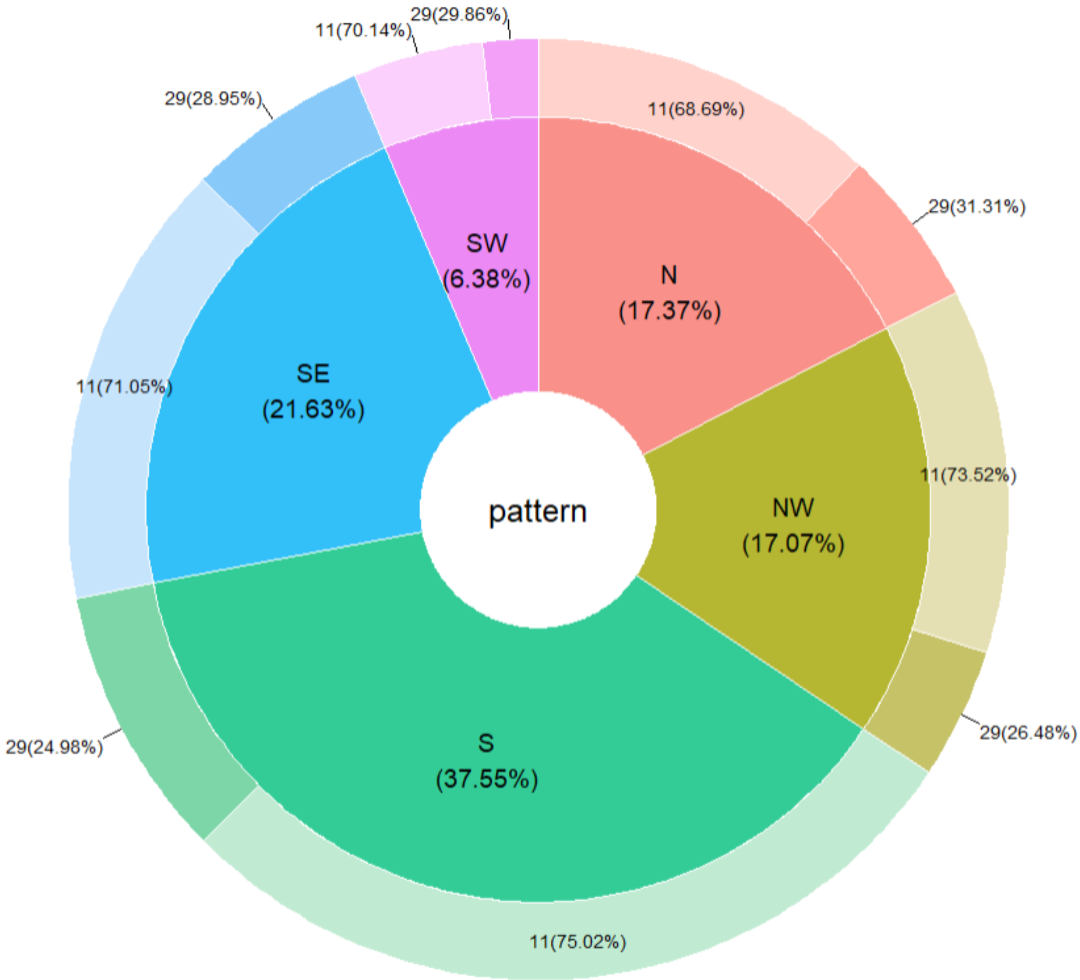

FIGURE 4.11 – Distribution of flight operations by arrival pattern at SBBR.

4.1.3.3 Analysis of Trajectory Conformance

Figure 4.12 shows the distributions of flight trajectory conformance by arrival pattern in SBBR. Conformance values fluctuate a lot depending on the arrival pattern. The S-11 arrival pattern showed the lowest normalized conformance value, indicating higher adherence of actual trajectories to standard procedures for this traffic flow. The analysis of terminal airspace utilization showed that this procedure accounts for the highest traffic volume, potentially suggesting that the dominant arrival flow is prioritized during tactical air traffic control at SBBR.

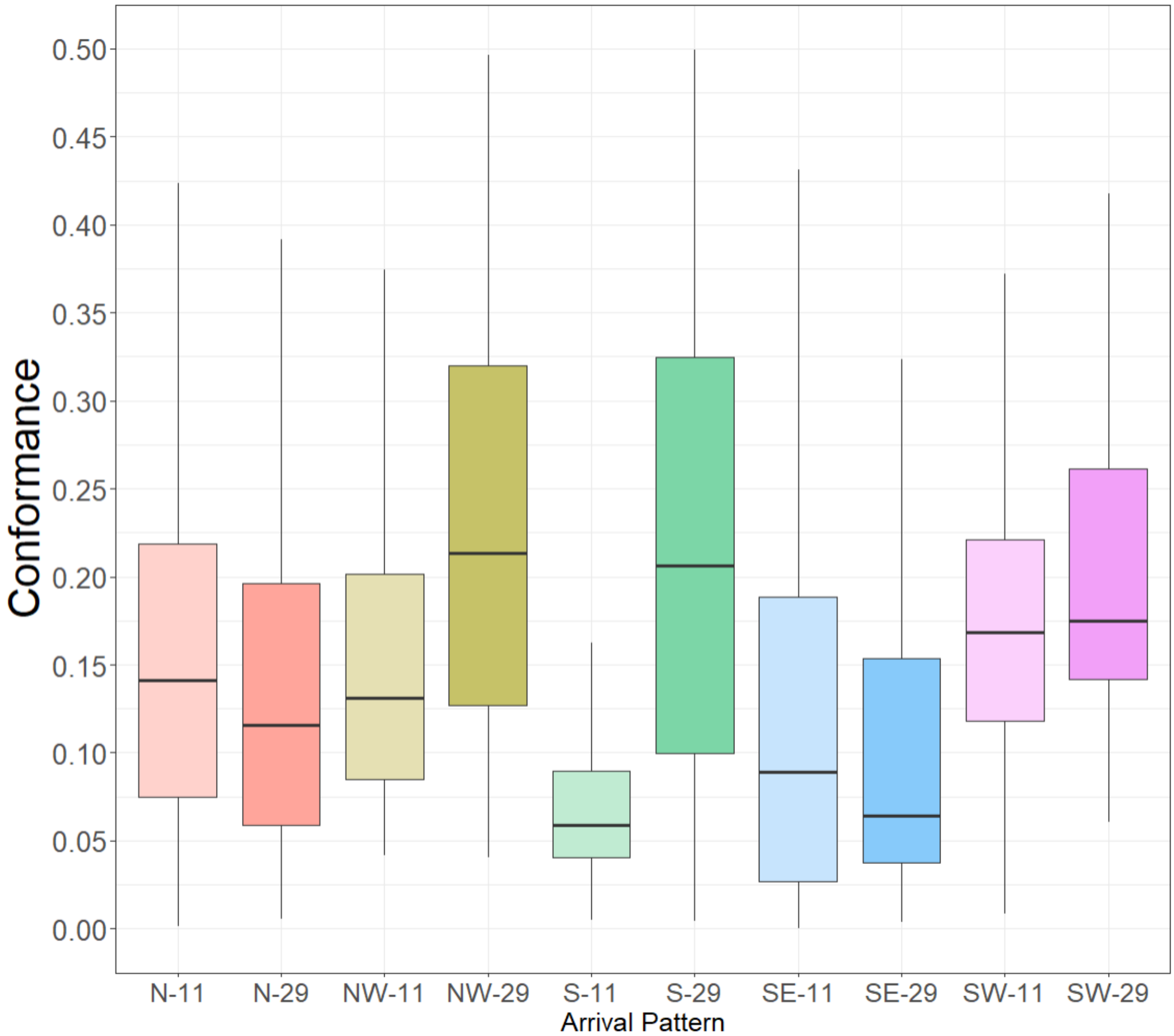

FIGURE 4.12 – Boxplots of trajectory conformance for SBBR arrival patterns.

4.1.3.4 Analysis of Additional Flight Time

Figure 4.13 shows the distributions of additional flight time by arrival pattern. We observed low variability in temporal efficiency across arrival patterns and within the same pattern, except for the Southwest flows. The median value of additional flight time was approximately 1.5 min for the dominant arrival pattern (S-11). The Southwest flows showed higher variability, with median value close to 3 min and third quartile over 9 min.

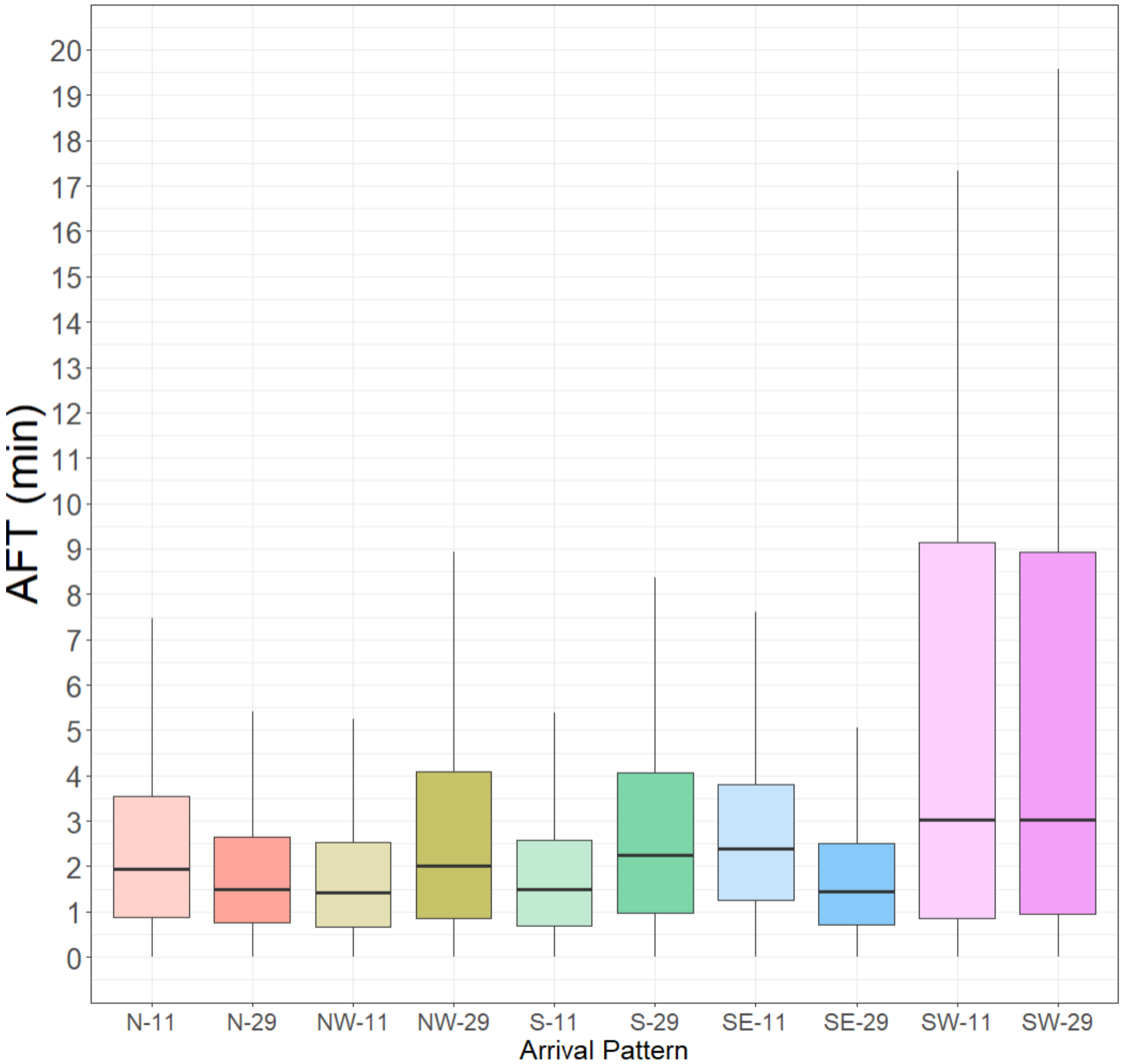

FIGURE 4.13 – Boxplots of additional flight time for SBBR arrival patterns.

4.1.4 SBKP

4.1.4.1 Standard Arrival Procedures

Figure 4.14 shows the standard arrival procedures at SBKP. This airport's arrival procedures connect four arrival gates with the runways 15/33. The coding scheme is similar to SBGR's, with the combination of arrival gate (North-N; Northwest-NW; South-S; and East- E) and runway configuration.

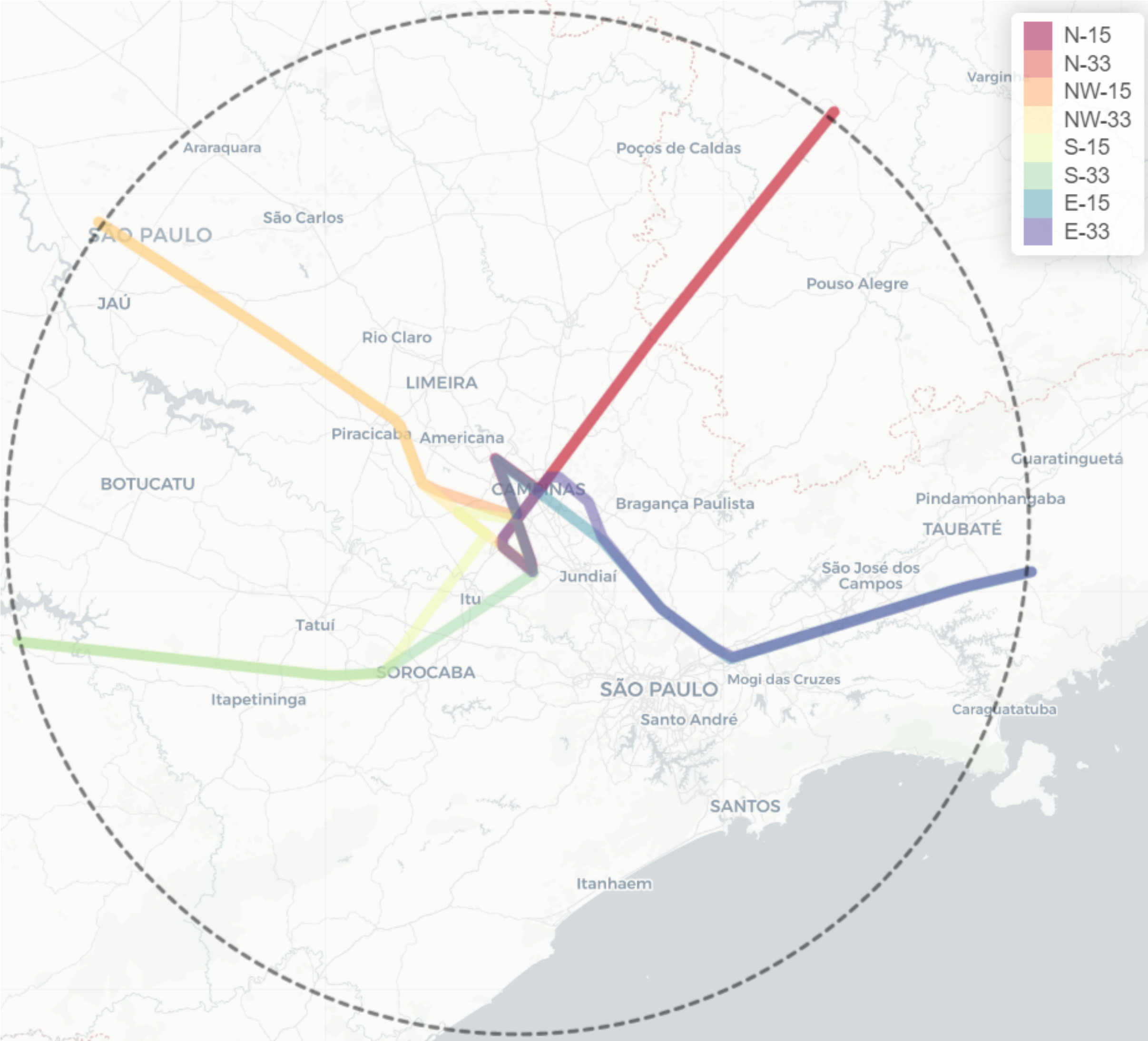

FIGURE 4.14 – SBKP arrival procedures.

4.1.4.2 Analysis of Terminal Airspace Utilization

Figure 4.15 shows the distribution of flight operations by arrival pattern. The dominant traffic flow pattern for SBKP corresponds to arrivals from the South gate to runway 33. It is observed a higher concentration of arrivals through the South (S) gate, which accounts for 37.2% of the operations. The North (N) and Northwest (NW) gates have similar traffic levels, accounting for 28.0% and 25.8% of the flights, respectively. Finally, the remaining 9% use the East (E) gate. It is also observed that the distribution of arrivals per runway is close to 70% for runway 15 and 30% for runway 33 for most of the arrival patterns, except for the South arrival traffic, which more frequently uses runway 33.

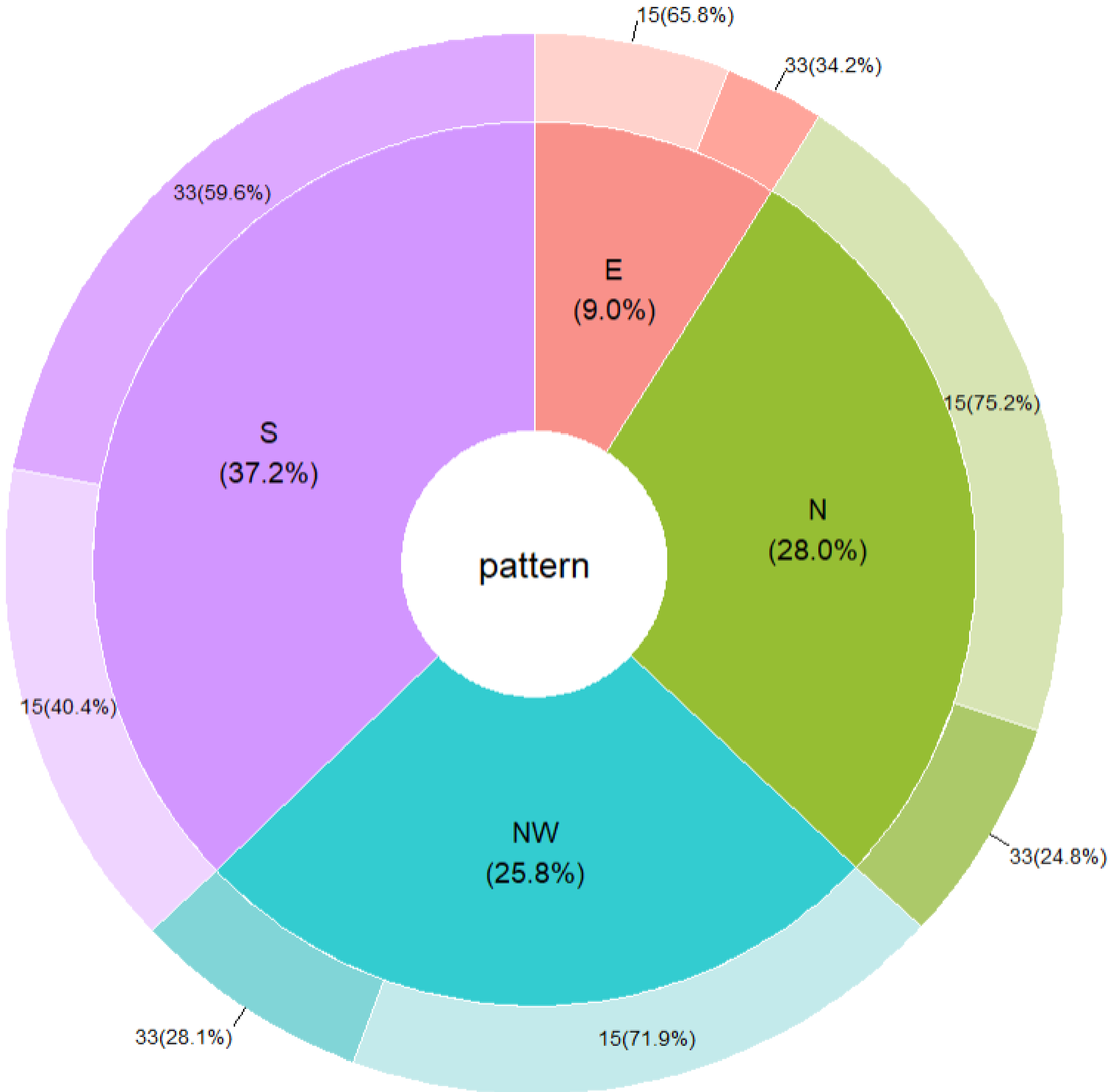

FIGURE 4.15 – Distribution of flight operations by arrival pattern at SBKP.

4.1.4.3 Analysis of Trajectory Conformance

Figure 4.16 shows the distributions of flight trajectory conformance by arrival pattern. SBKP's arrival trajectories show high adherence to standard procedures, with median values of normalized conformance lower than 0.05 for most of the patterns. The South arrival patterns consistently showed higher normalized conformance values, suggesting lower adherence of actual trajectories to standard procedures for the dominant traffic flows at SBKP.

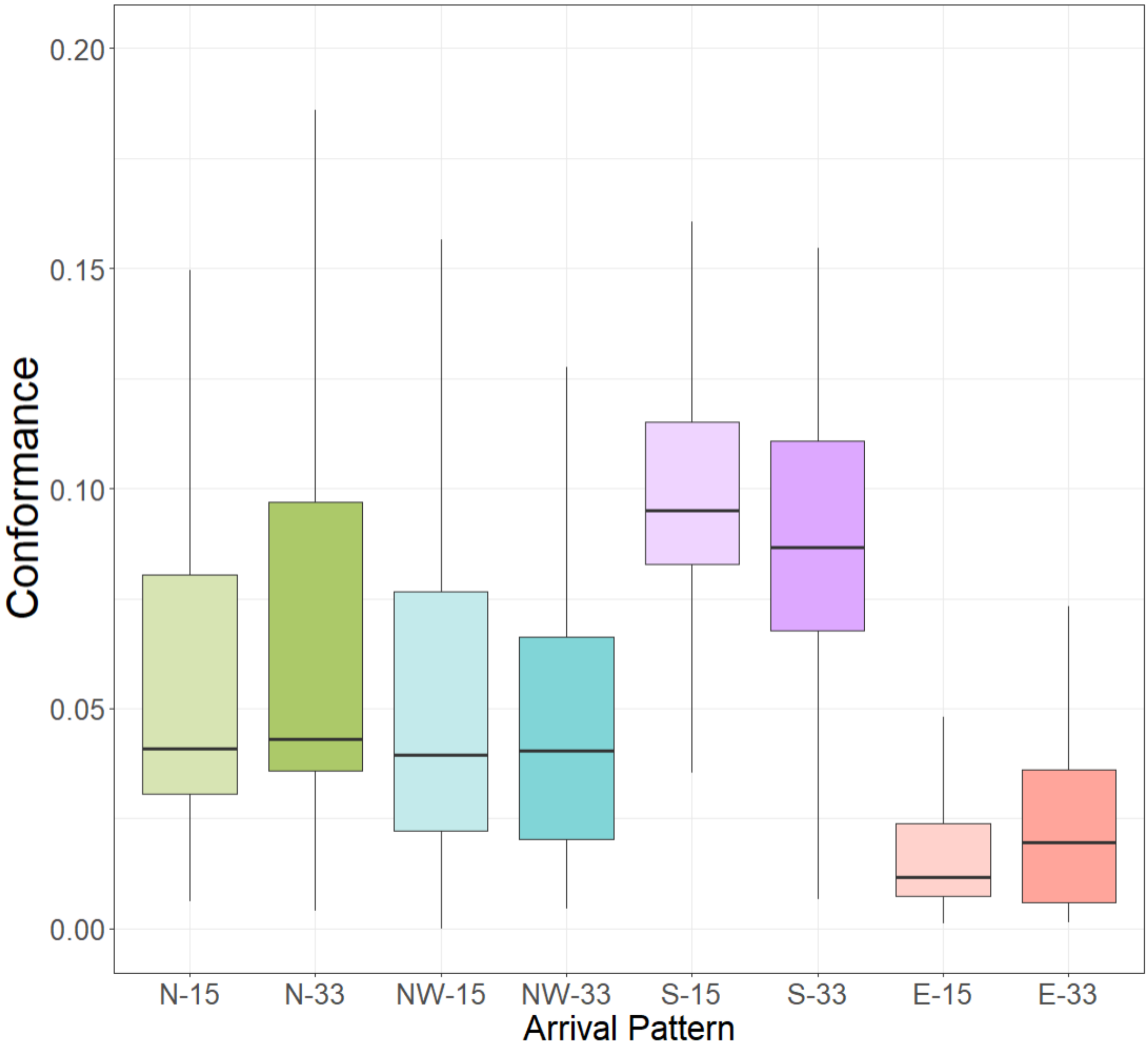

FIGURE 4.16 – Boxplots of trajectory conformance for SBKP arrival patterns.

4.1.4.4 Analysis of Additional Flight Time

Figure 4.17 shows the distributions of additional flight time by arrival pattern. We observed low variability in temporal efficiency across arrival patterns. For instance, the median additional flight time for the dominant arrival pattern (S-33) was approximately 2.5 minutes, and the boxplots for the Northwest and South flows consistently showed approximately the same values. These results suggest an almost even delay distribution in the terminal area.

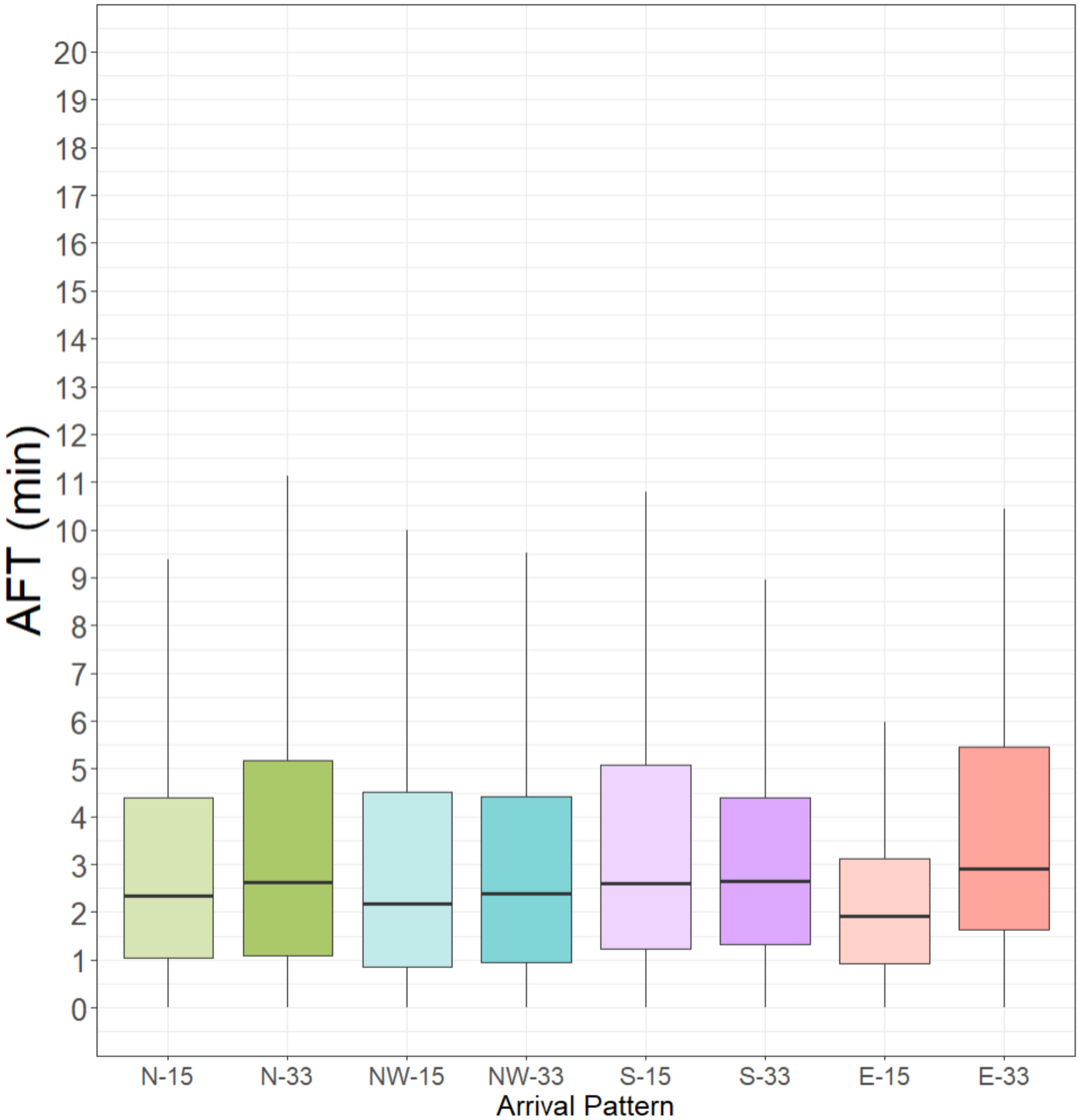

FIGURE 4.17 – Boxplots of additional flight time for SBKP arrival patterns.

4.1.5 SBRJ

4.1.5.1 Standard Arrival Procedures

Figure 4.18 shows the standard arrival procedures at SBRJ. This airport's arrival procedures connect four arrival regions with the runways 02/20, mainly using one arrival gate. For the South arrival region, however, there are multiple procedures connecting different arrival gates with the runways 02/20. The coding scheme is similar to those before, with the combination of arrival region (North-N; Northwest-NW; South-S; and Southwest-SW), arrival gate (for the South region) and runway configuration.

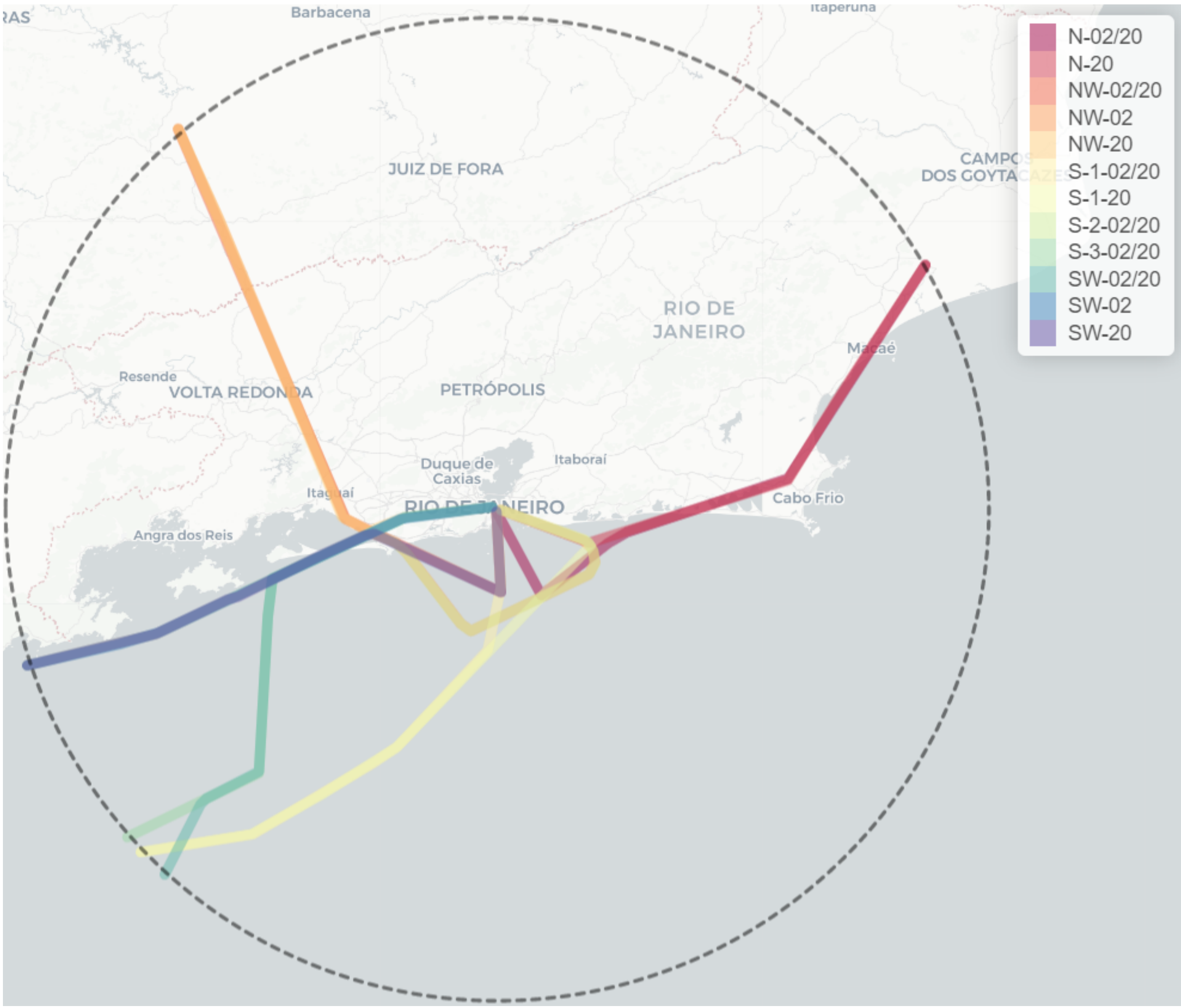

FIGURE 4.18 – SBRJ arrival procedures.

4.1.5.2 Analysis of Terminal Airspace Utilization

Figure 4.19 shows the distribution of flight operations by arrival pattern. The results reveal an uneven distribution of air traffic across arrival procedures. The dominant traffic flow pattern for SBRJ corresponds to arrivals from the Southwest gate to runway 20. It is observed a high concentration of arrivals through the Southwest (SW) gate, which accounts for 54.1% of the operations. The Northwest (NW) gate represents the second major flow, accounting for 20.5% of the operations. Finally, 15.7% of the flights arrive through the North (N) gate and the remaining 9.7% use the South (S) gate. It is also observed that runway 20 is the most frequently used.

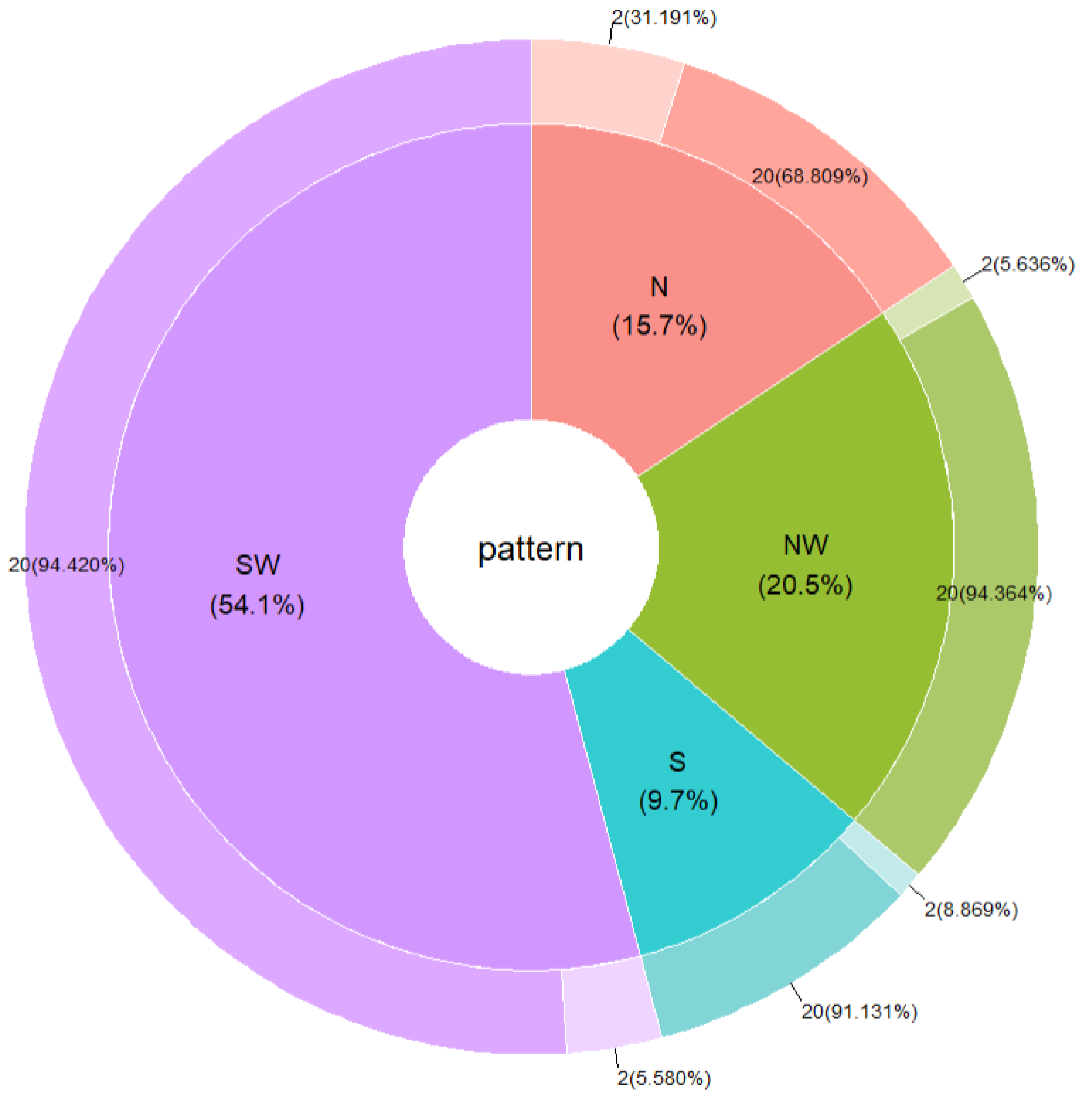

FIGURE 4.19 – Distribution of flight operations by arrival pattern at SBRJ.

4.1.5.3 Analysis of Trajectory Conformance

Figure 4.20 shows the distributions of flight trajectory conformance by arrival pattern. Overall, we observed a high variability for this indicator across arrival patterns. The SW-20 arrival pattern consistently showed lower normalized conformance values than the other patterns, suggesting better adherence of actual trajectories to the standard procedure for this traffic flow. The analysis of terminal airspace utilization showed that this procedure accounts for the highest density of flights. As also observed at SBBR, this potentially suggests prioritization of the dominant arrival flow during tactical air traffic control.

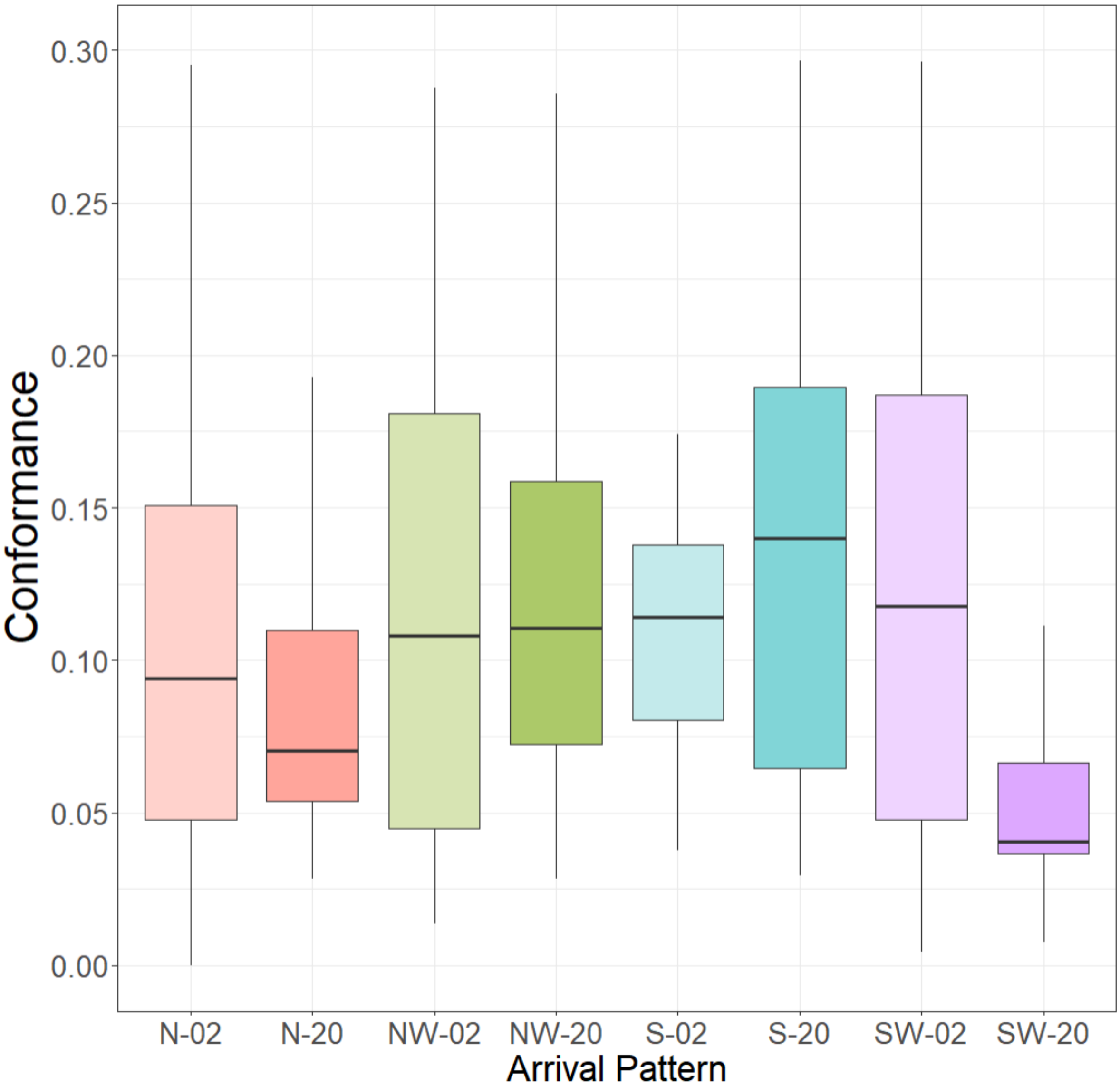

FIGURE 4.20 – Boxplots of trajectory conformance for SBRJ arrival patterns.

4.1.5.4 Analysis of Additional Flight Time

Figure 4.21 shows the distributions of additional flight time by arrival pattern. We also observed a high variability in temporal efficiency across arrival patterns and within the same pattern. For instance, the median value of additional flight time was approximately 1 min for the dominant arrival pattern (SW-20) but reached almost 4.5 min for other traffic patterns.

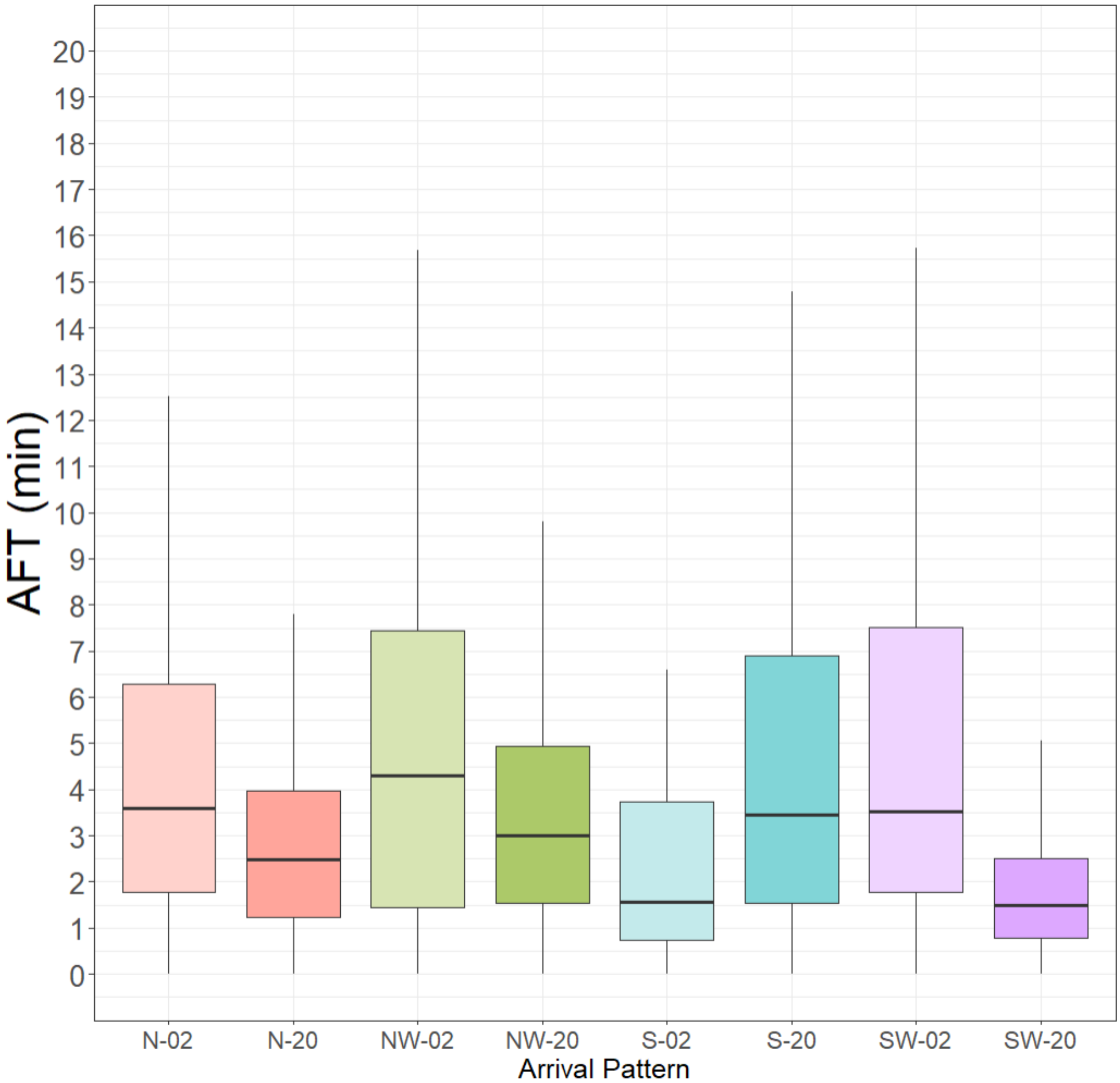

FIGURE 4.21 – Boxplots of additional flight time for SBRJ arrival patterns.

4.1.6 SBCF

4.1.6.1 Standard Arrival Procedures

Figure 4.22 shows the standard arrival procedures at SBCF. This airport's arrival procedures connect five arrival regions with the runways 16/34, mainly using one arrival gate. For the Northwest and North regions, however, there are multiple procedures connecting different arrival gates with the runways 16/34. The coding scheme is similar to those before, with the combination of arrival region (North-N; Northwest-NW; South-S; Southeast-SE; and East-E), arrival gate (for the North and Northwest regions) and runway configuration.

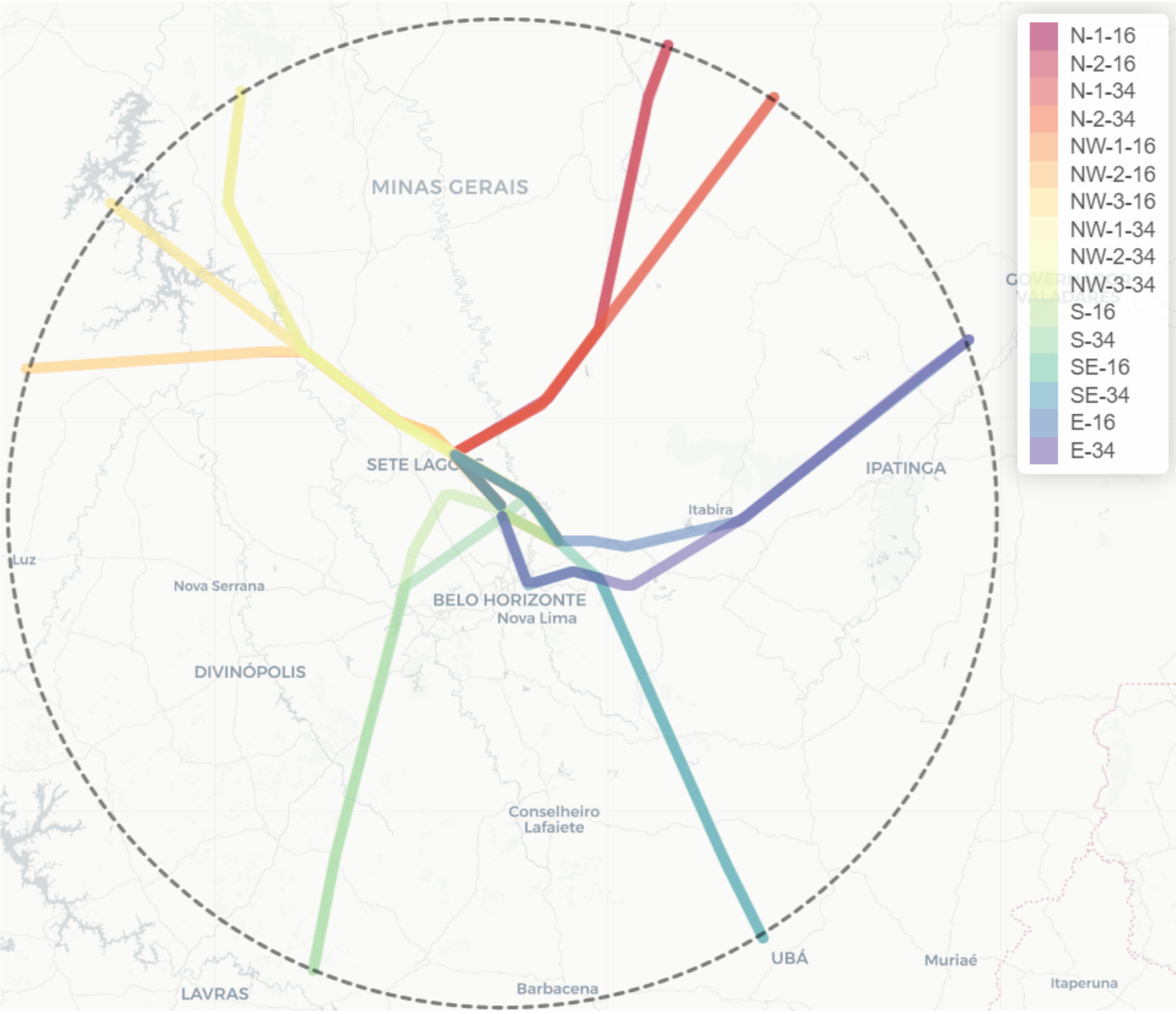

FIGURE 4.22 – SBCF arrival procedures.

4.1.6.2 Analysis of Terminal Airspace Utilization

Figure 4.23 shows the distribution of flight operations by arrival pattern. The dominant traffic flow pattern for SBCF corresponds to arrivals from the South gate to runway 16. The South (S) gate concentrates the highest number of arrivals, accounting for 40.3% of the operations. The Northwest (NW) gate represents the second major flow, accounting for 22.0% of the operations, followed by the North (N) gate, with 20.1% of the arrivals. Finally, 9.6% of the flights arrive through the Southeast (SE) gate and the remaining 8.0% use the East (E) gate.

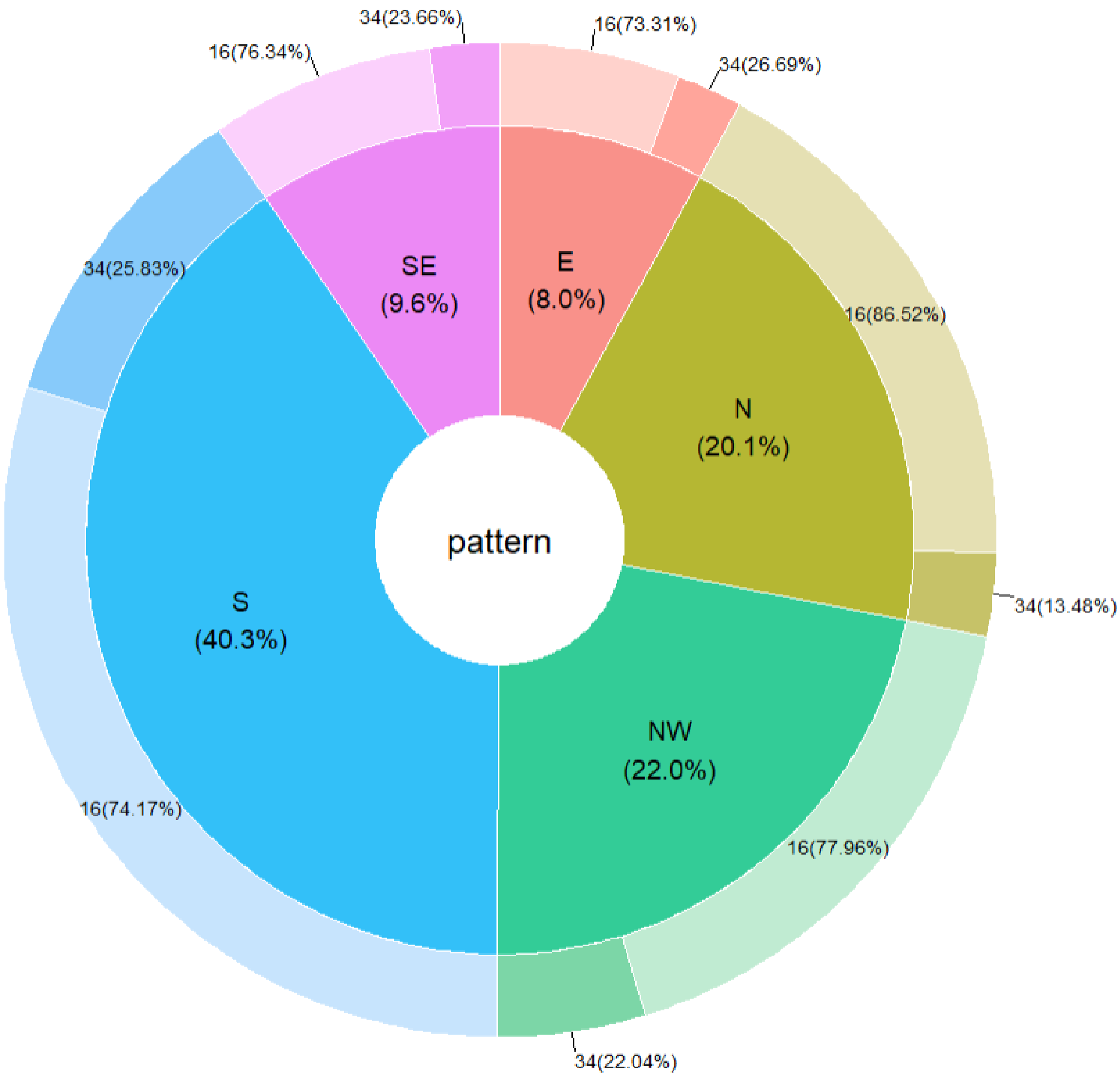

FIGURE 4.23 – Distribution of flight operations by arrival pattern at SBCF.

4.1.6.3 Analysis of Trajectory Conformance

Figure 4.24 shows the distributions of flight trajectory conformance by arrival pattern. Overall, arrival patterns associated with runway 16 presented lower conformance values than those associated with runway 34, indicating better adherence of actual trajectories to standard procedures when runway threshold 16 is used for arrivals. The East arrival patterns consistently showed higher normalized conformance values than the other patterns, indicating that flights are more likely to deviate from standard procedures when arriving from the East.

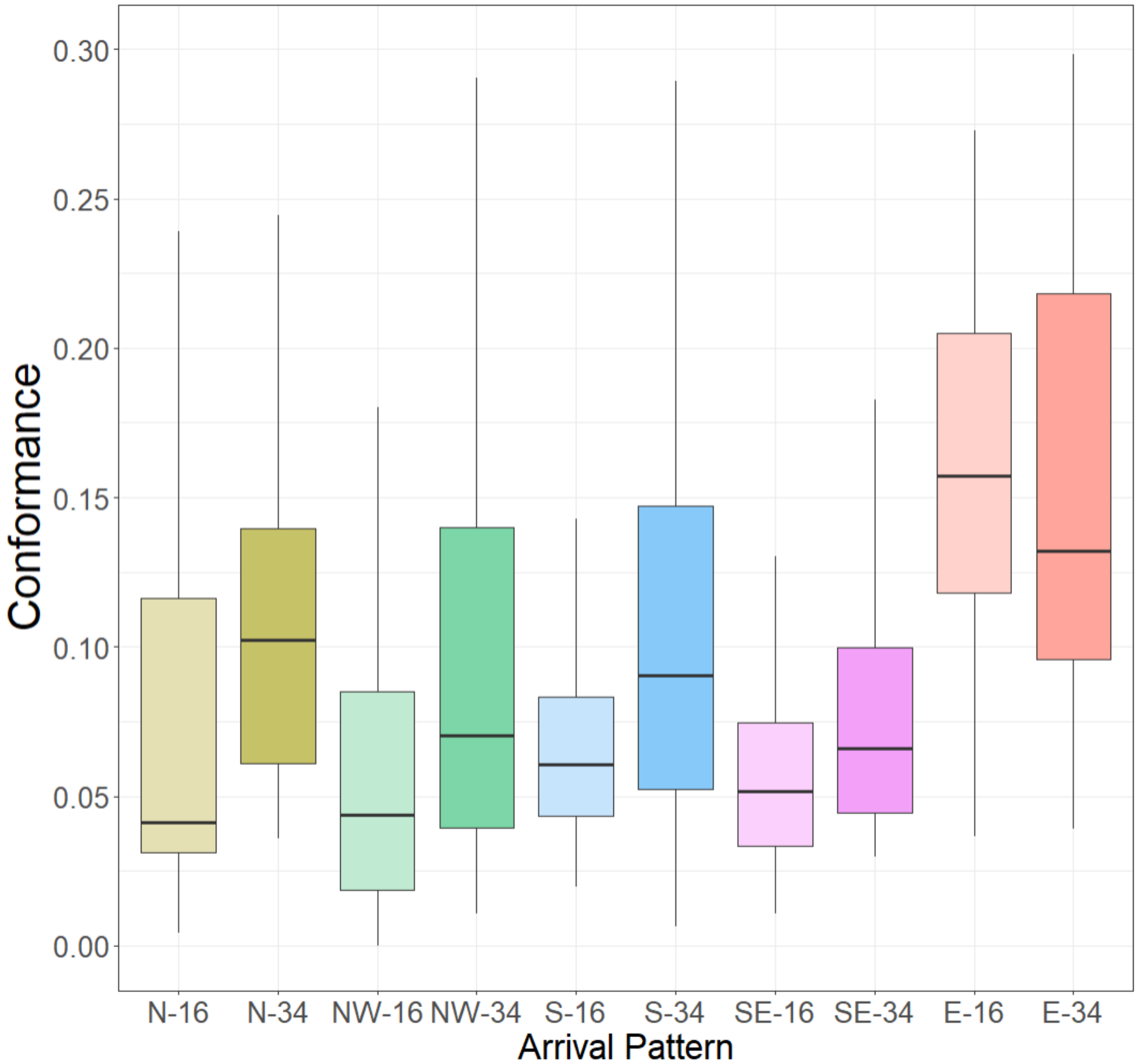

FIGURE 4.24 – Boxplots of trajectory conformance for SBCF arrival patterns.

4.1.6.4 Analysis of Additional Flight Time

Figure 4.25 shows the distributions of additional flight time by arrival pattern. We observed a low variability in temporal efficiency across arrival patterns, with a median value of additional flight time close to 2 min for the majority of arrival patterns. However, the N-34 arrival pattern stood out with the highest median value (4 min) as well as higher performance variability.

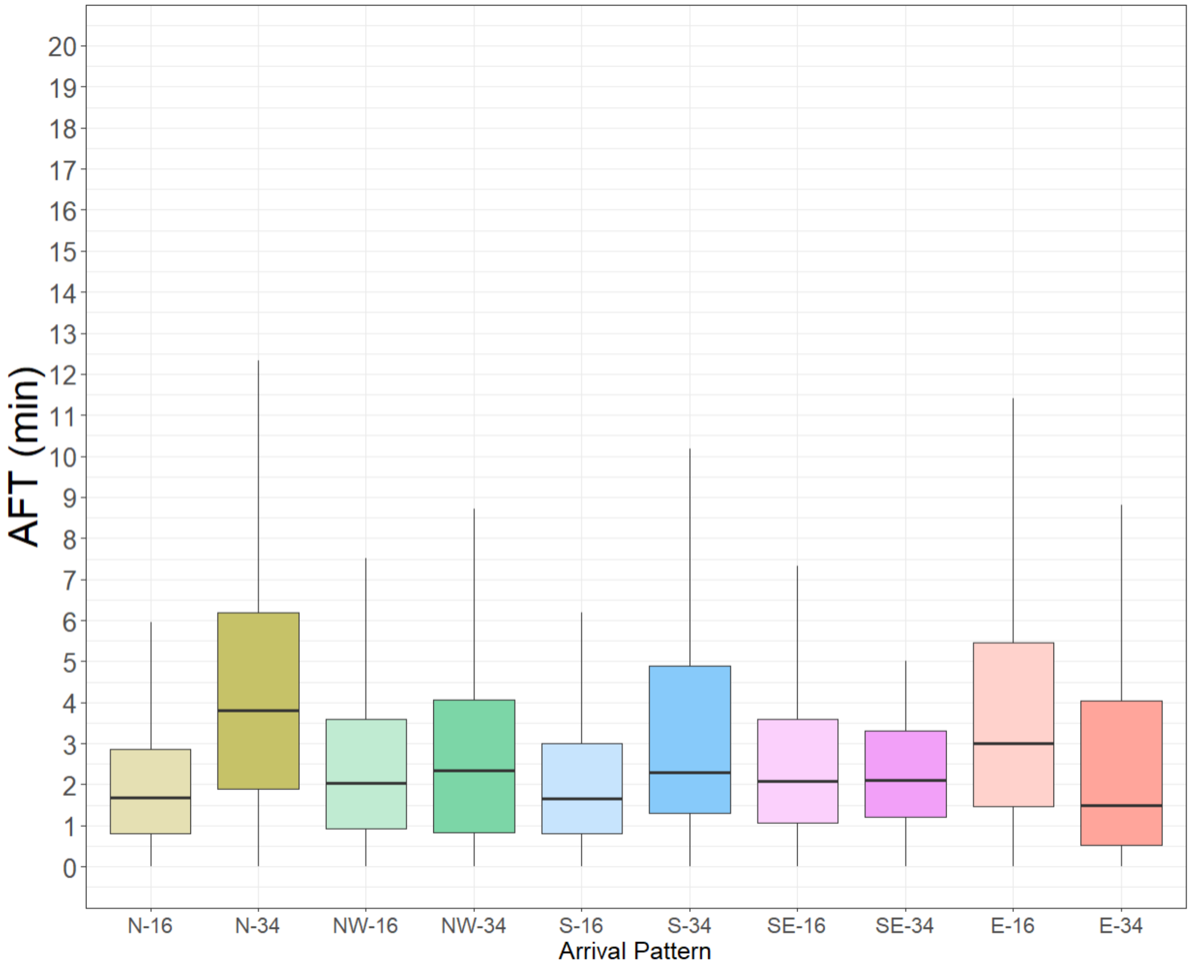

FIGURE 4.25 – Boxplots of additional flight time for SBCF arrival patterns.

4.1.7 SBRF

4.1.7.1 Standard Arrival Procedures

Figure 4.26 shows the standard arrival procedures at SBRF. This airport's arrival procedures connect three arrival regions with the runways 18/36 through multiple arrival gates. The coding scheme is similar to those before, with the combination of arrival region (North-N; Northwest-NW; and South-S), arrival gate and runway configuration.

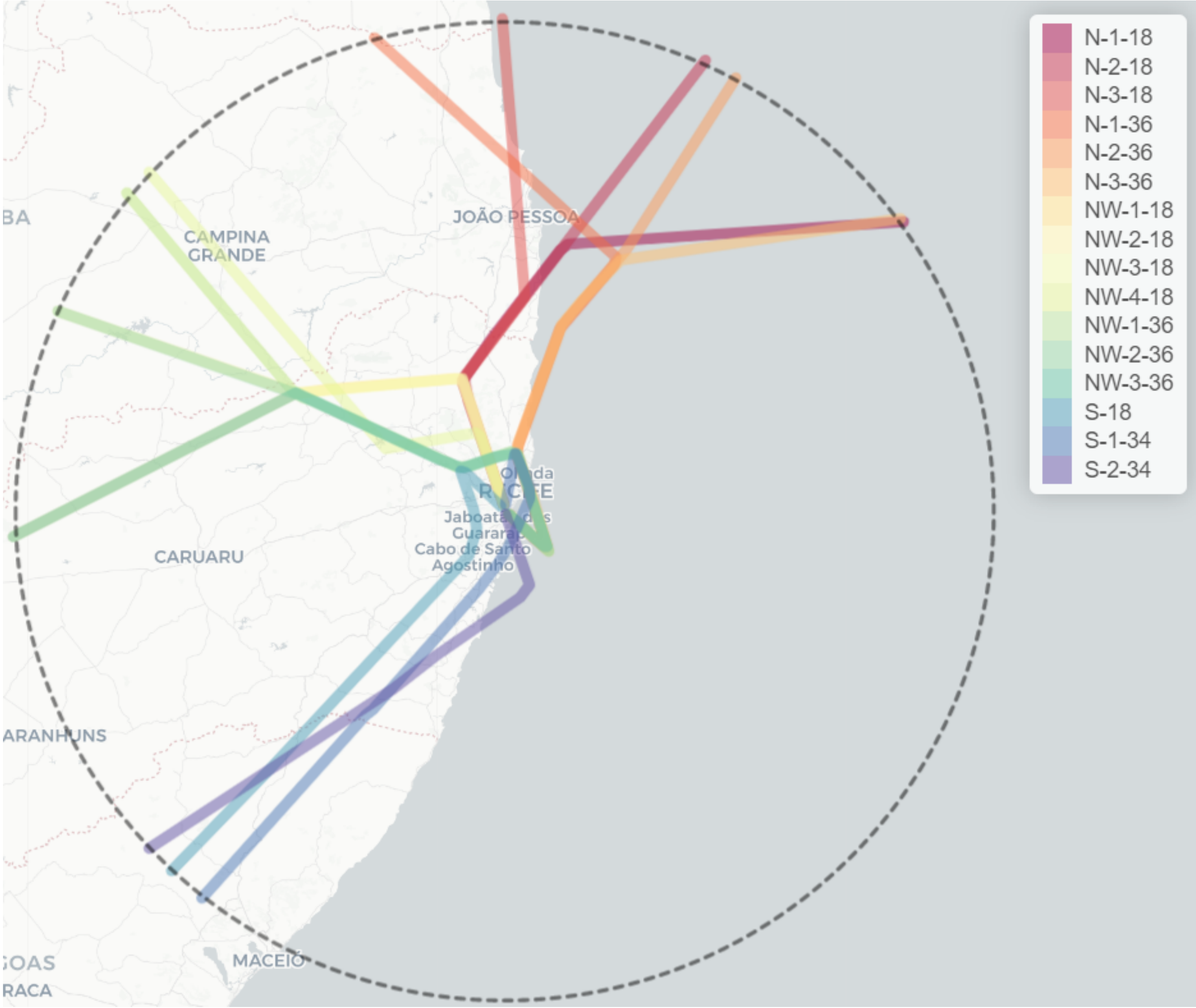

FIGURE 4.26 – SBRF arrival procedures.

4.1.7.2 Analysis of Terminal Airspace Utilization

Figure 4.27 shows the distribution of flight operations by arrival pattern. The results reveal a very uneven distribution of air traffic across arrival procedures. The dominant traffic flow pattern for SBRF corresponds to arrivals from the South gates to runway 18. It is observed a high concentration of arrivals through the South (S) gate, which accounts for 62% of the operations. The Northwest (NW) gate represents the second major flow, accounting for 25% of the operations. Finally, 12% of the flights arrive through the North (N) gate. It is also observed that runway 18 is used more than 95% of the time for the major flows.

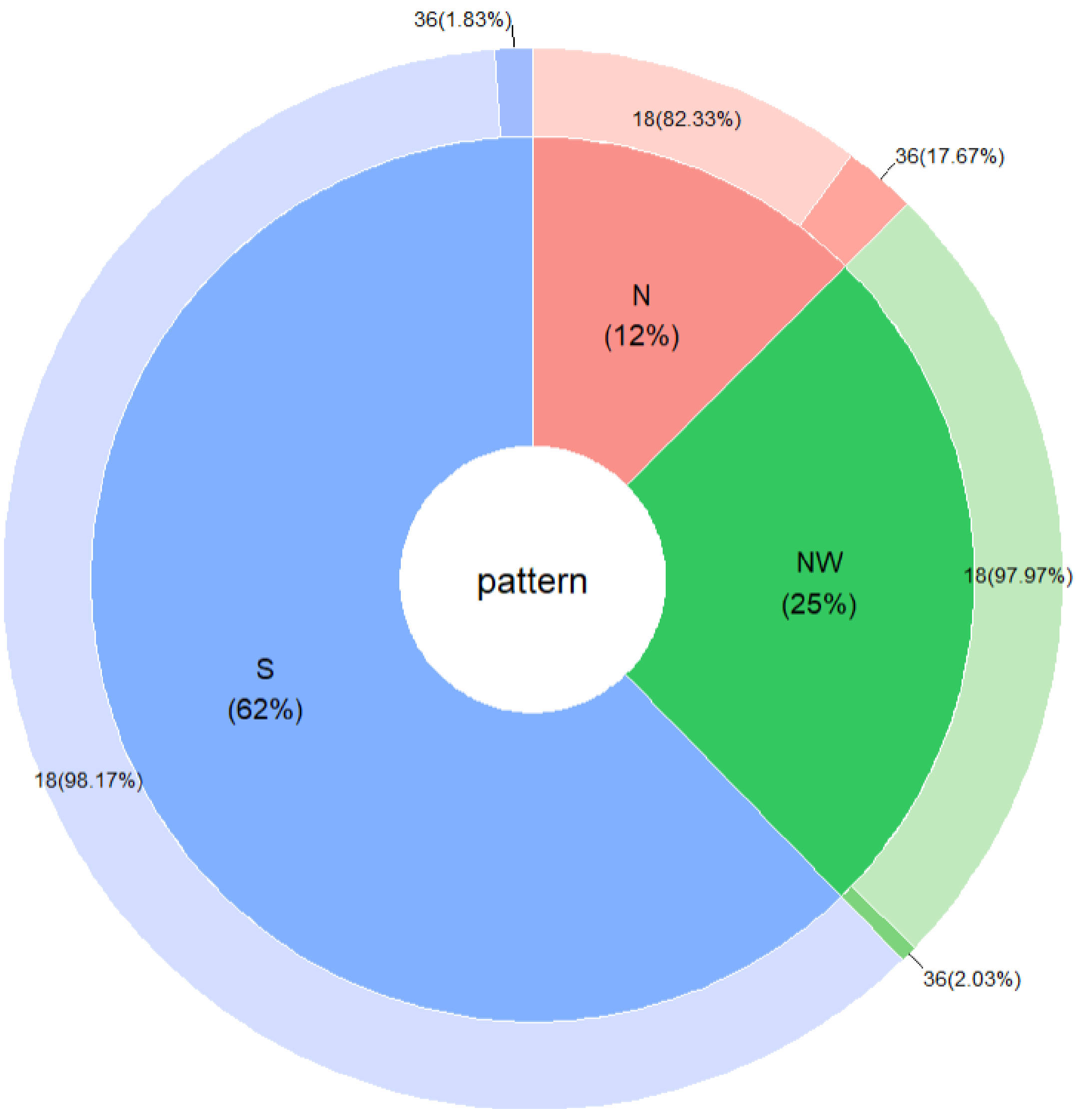

FIGURE 4.27 – Distribution of flight operations by arrival pattern at SBRF.

4.1.7.3 Analysis of Trajectory Conformance

Figure 4.3 shows the distributions of flight trajectory conformance by arrival pattern. Overall, we observed higher conformance values than most of the airports and a high variability for the indicator across arrival patterns and within the same pattern, indicating a lower level of predictability for arrival trajectories at SBRF.

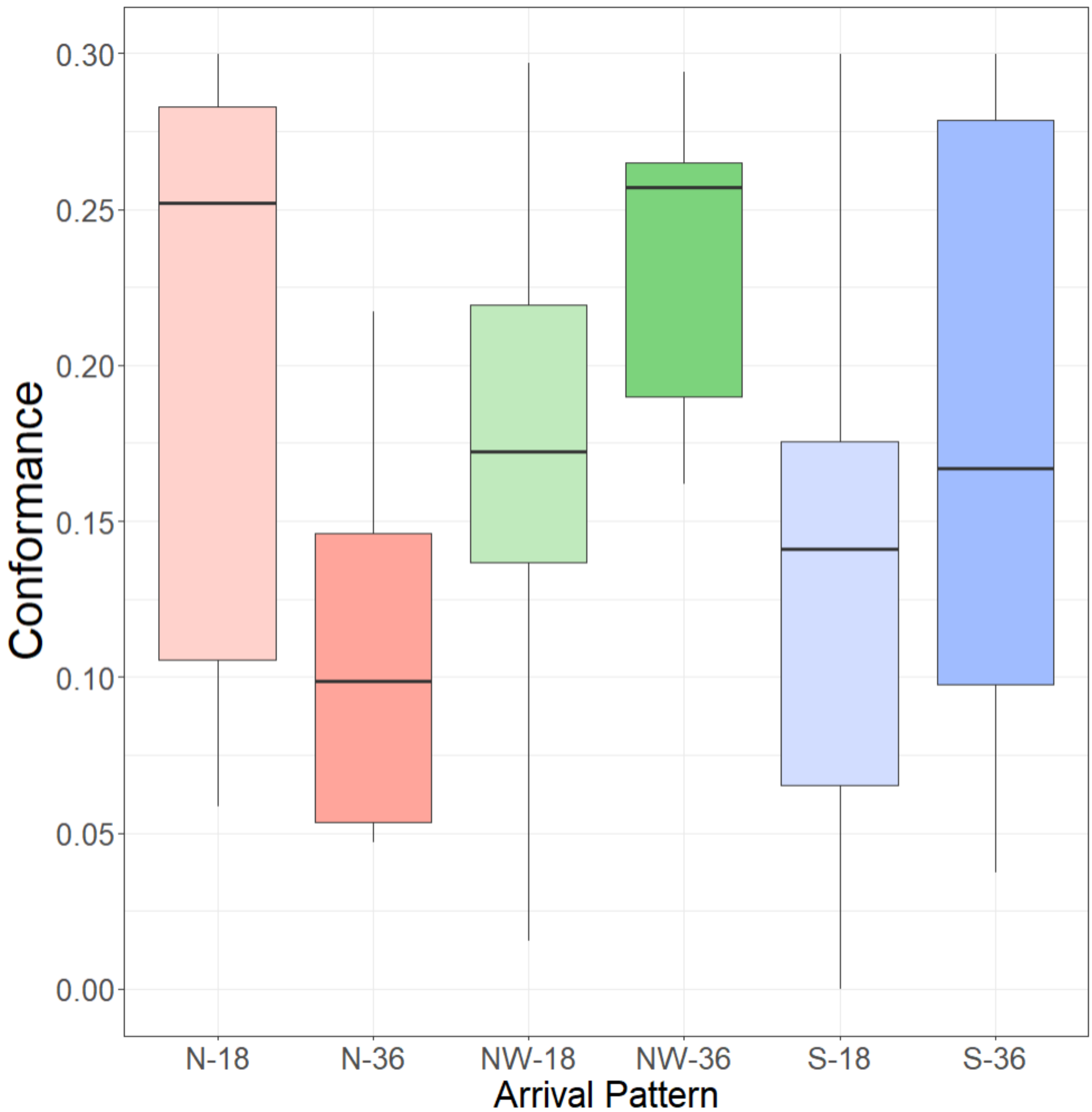

FIGURE 4.28 – Boxplots of trajectory conformance for SBRF arrival patterns.

4.1.7.4 Analysis of Additional Flight Time

Figure 4.29 shows the distributions of additional flight time by arrival pattern. We observed low variability in temporal efficiency for most of the arrival patterns. The median value of additional flight time was approximately 1.5 min for the dominant arrival pattern (S-18), and 3.5 min for the lowest performing pattern (S-36).

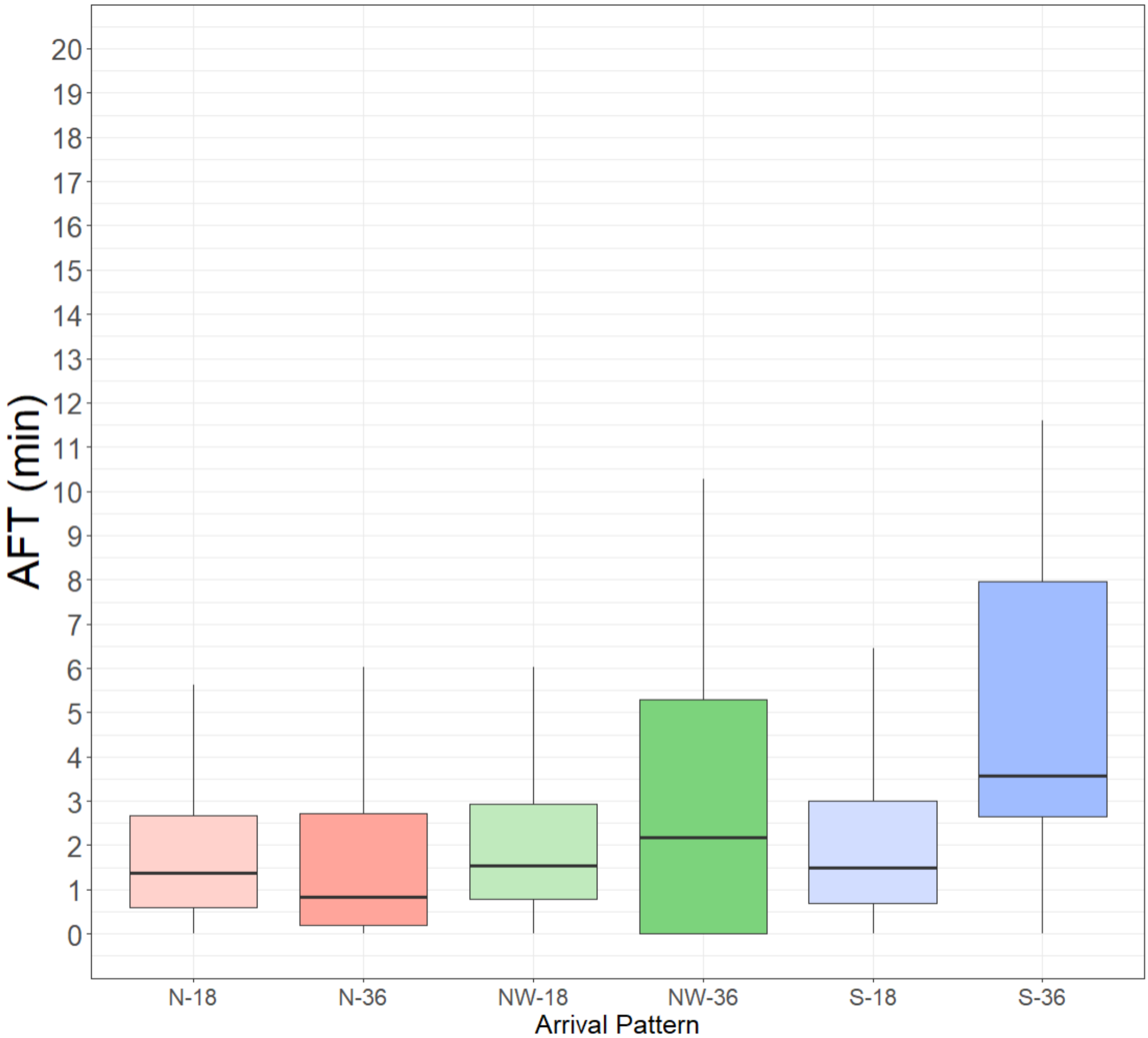

FIGURE 4.29 – Boxplots of additional flight time for SBRF arrival patterns.

4.1.8 SBSV

4.1.8.1 Standard Arrival Procedures

Figure 4.30 shows the standard arrival procedures at SBSV. This airport's arrival procedures connect five arrival regions with the runways 10/28, mainly using one arrival gate, except for South region, which has multiple arrival gates. The coding scheme is similar to those before, with the combination of arrival gate (North-N; Northeast-NE; Northwest-NW; West-W; and South-S), arrival gate (for the South region) and runway configuration.

FIGURE 4.30 – SBSV arrival procedures.

4.1.8.2 Analysis of Terminal Airspace Utilization

Figure 4.31 shows the distribution of flight operations by arrival pattern. Similarly to SBRF, the results reveal a very uneven distribution of air traffic across arrival procedures. The dominant traffic flow pattern for SBSV corresponds to arrivals from the South gate to runway 10. It is observed a high concentration of arrivals through the South (S) gate, which accounts for 66.0% of the operations. The Northeast (NE) gate represents the second major flow, accounting for 14.7% of the operations. Finally, 10.5% of the flights arrive through the West (W) gate, 8% use the North (N) gate and only 0.7% use the Northwest gate (NW). We also observed that runway 10 is used more than 97% of the time.

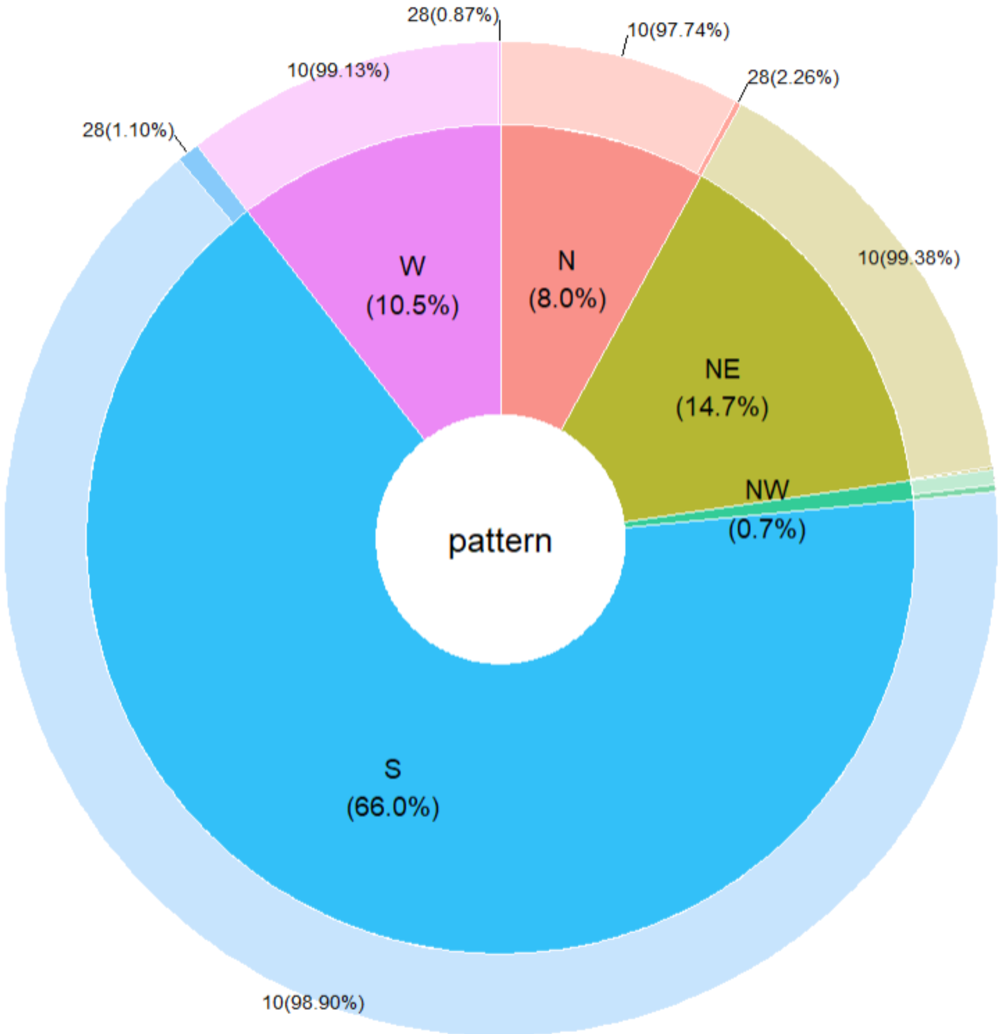

FIGURE 4.31 – Distribution of flight operations by arrival pattern at SBSV.

4.1.8.3 Analysis of Trajectory Conformance

Figure 4.32 shows the distributions of flight trajectory conformance by arrival pattern. SBSV showed the highest level of variability in trajectory conformance across arrival patterns, with one pattern (NW-28) showing very low adherence to standard procedures with normalized conformance values higher than 0.8. On the other hand, the dominant arrival pattern (S-10) presented the lowest level of variability and low normalized conformance values, suggesting high adherence of the actual trajectories to standard procedures for this flow.

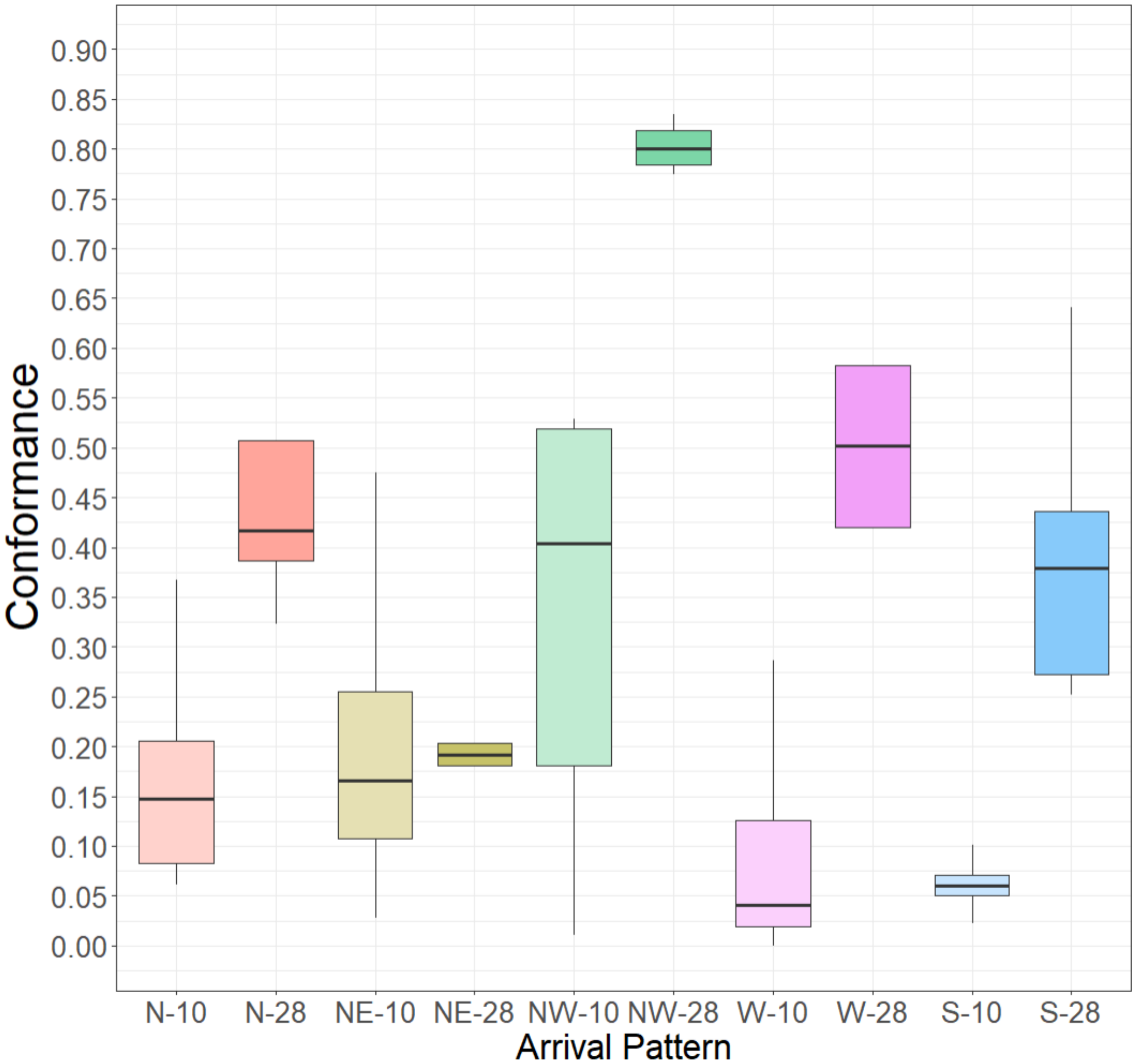

FIGURE 4.32 – Boxplots of trajectory conformance for SBSV arrival patterns.

4.1.8.4 Analysis of Additional Flight Time

Figure 4.33 shows the distributions of additional flight time by arrival pattern. We observed significant variability in temporal efficiency for some procedures, such as NW-28 and S-28, while others virtually did not observe delays (NE-28 and W-28).

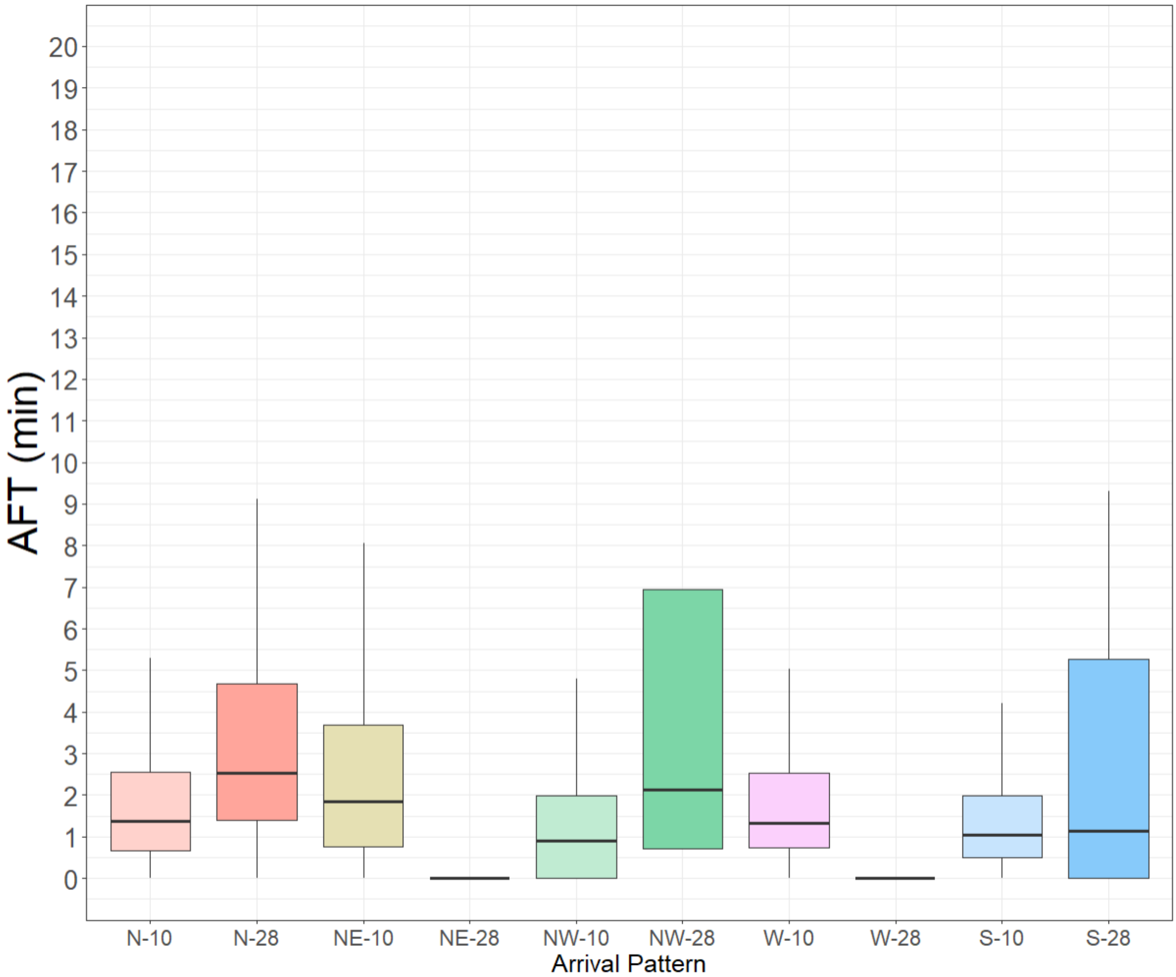

FIGURE 4.33 – Boxplots of additional flight time for SBSV arrival patterns.

4.1.9 SBPA

4.1.9.1 Standard Arrival Procedures

Figure 4.34 shows the standard arrival procedures at SBPA. This airport's arrival procedures connect six arrival regions with the runways 11/29, mainly using one arrival gate. The coding scheme follows the previous cases, with the combination of arrival region (North-N; Northeast-NE; Northwest-NW; West-W; Southwest-SW; South-S), arrival gate (for the Northwest region) and runway configuration.

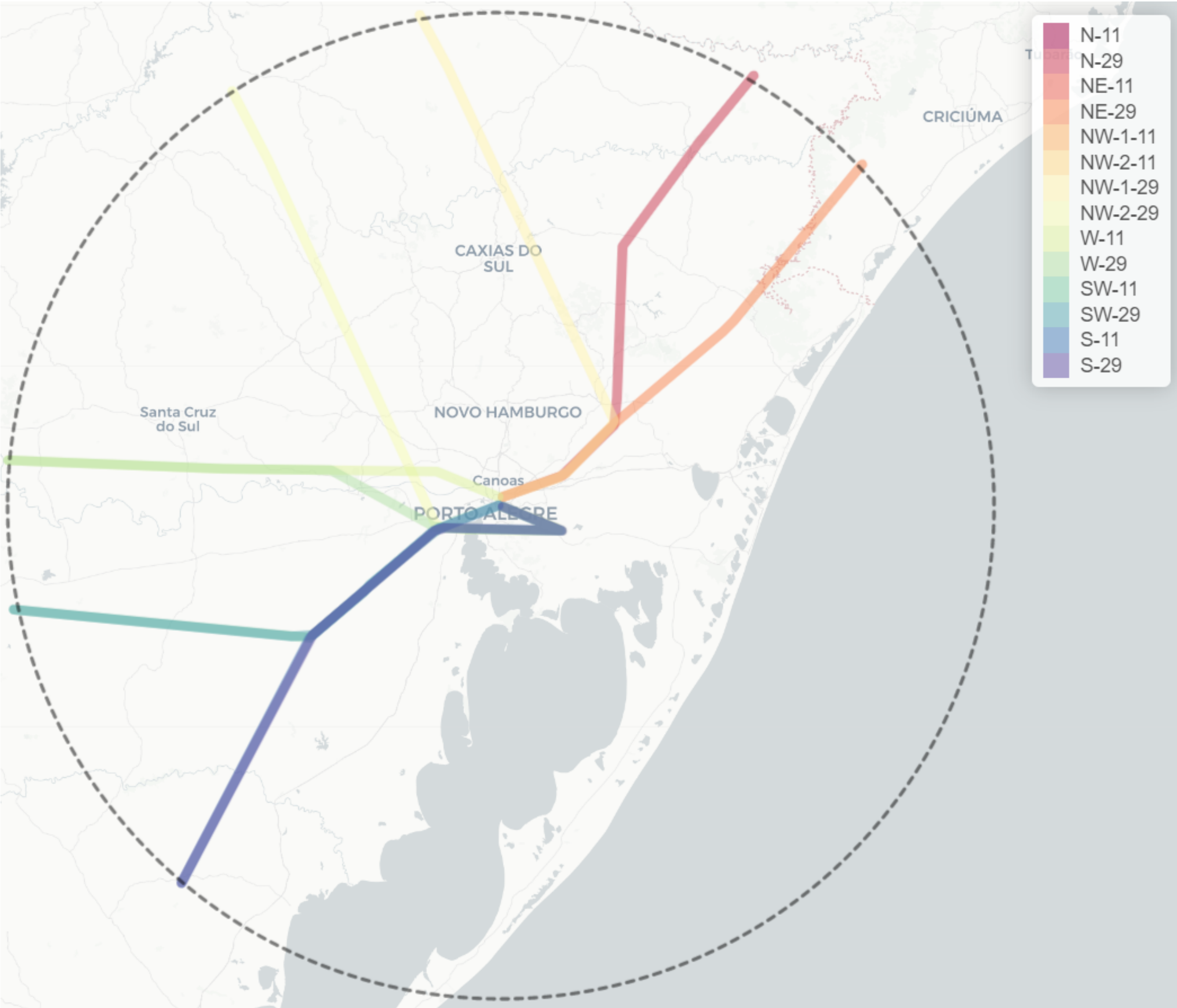

FIGURE 4.34 – SBPA arrival procedures.

4.1.9.2 Analysis of Terminal Airspace Utilization

Figure 4.35 shows the distribution of flight operations by arrival pattern. The results reveal a very uneven distribution of air traffic across arrival procedures. The dominant traffic flow pattern for SBPA corresponds to arrivals from the Northeast gate to runway 11. It is observed a high concentration of arrivals through the Northeast (NE) gate, which accounts for 65.8% of the operations. The North (N) gate represents the second major flow, accounting for 15.5% of the traffic. The Northwest (NW) gate represents the third major flow, with a share of 10.3%. Finally, 4.4% of the operations arrive through the South (S) gate, 3.4% use the West (W) gate and the remaining less than 1% use the SW (SW) gate.

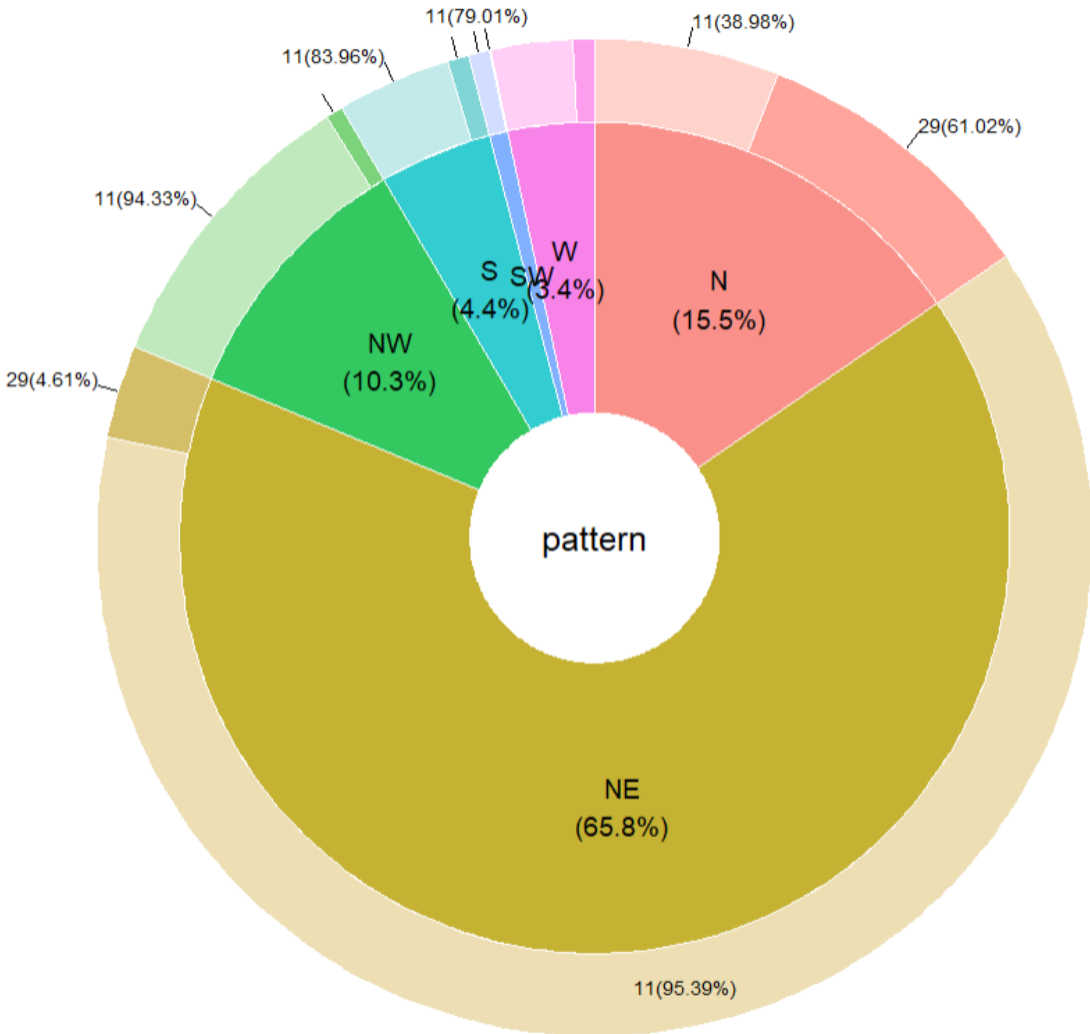

FIGURE 4.35 – Distribution of flight operations by arrival pattern at SBPA.

4.1.9.3 Analysis of Trajectory Conformance

Figure 4.36 shows the distributions of flight trajectory conformance by arrival pattern. In general, there is high variability in trajectory conformance across arrival patterns, with the Southwest patterns showing the lowest level of adherence to standard procedures. On the other hand, the most used procedure (NE-11) showed both low variability and low normalized conformance values, suggesting high adherence of the actual trajectories to standard procedures for the dominant traffic flow.

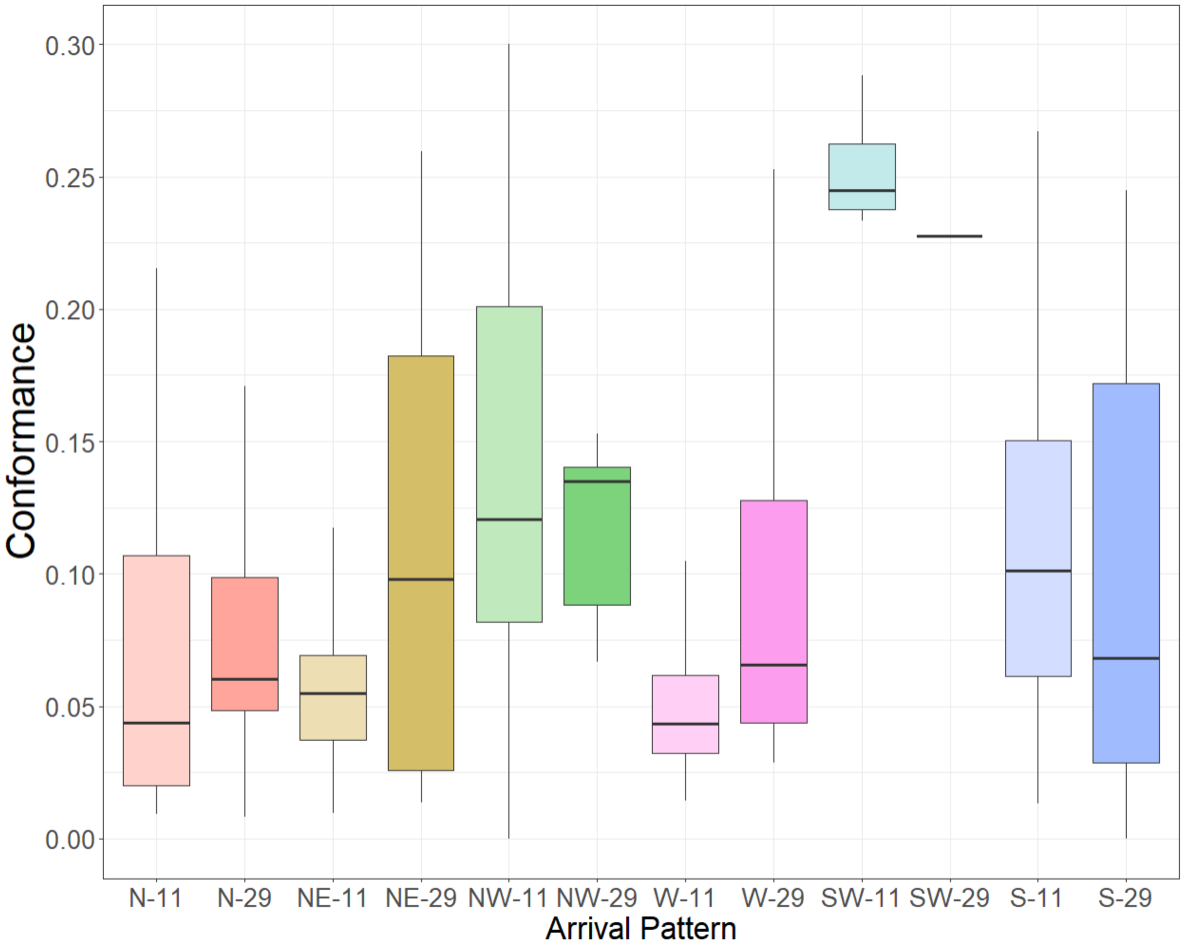

FIGURE 4.36 – Boxplots of trajectory conformance for SBPA arrival patterns.

4.1.9.4 Analysis of Additional Flight Time

Figure 4.37 shows the distributions of additional flight time by arrival pattern. We observed a high variability in temporal efficiency across arrival patterns and within some patterns. For instance, the median value of additional flight time was approximately 1 min for the dominant arrival pattern (NE-11), but reached almost 7 min for the SW-11 traffic pattern, with significant variability.

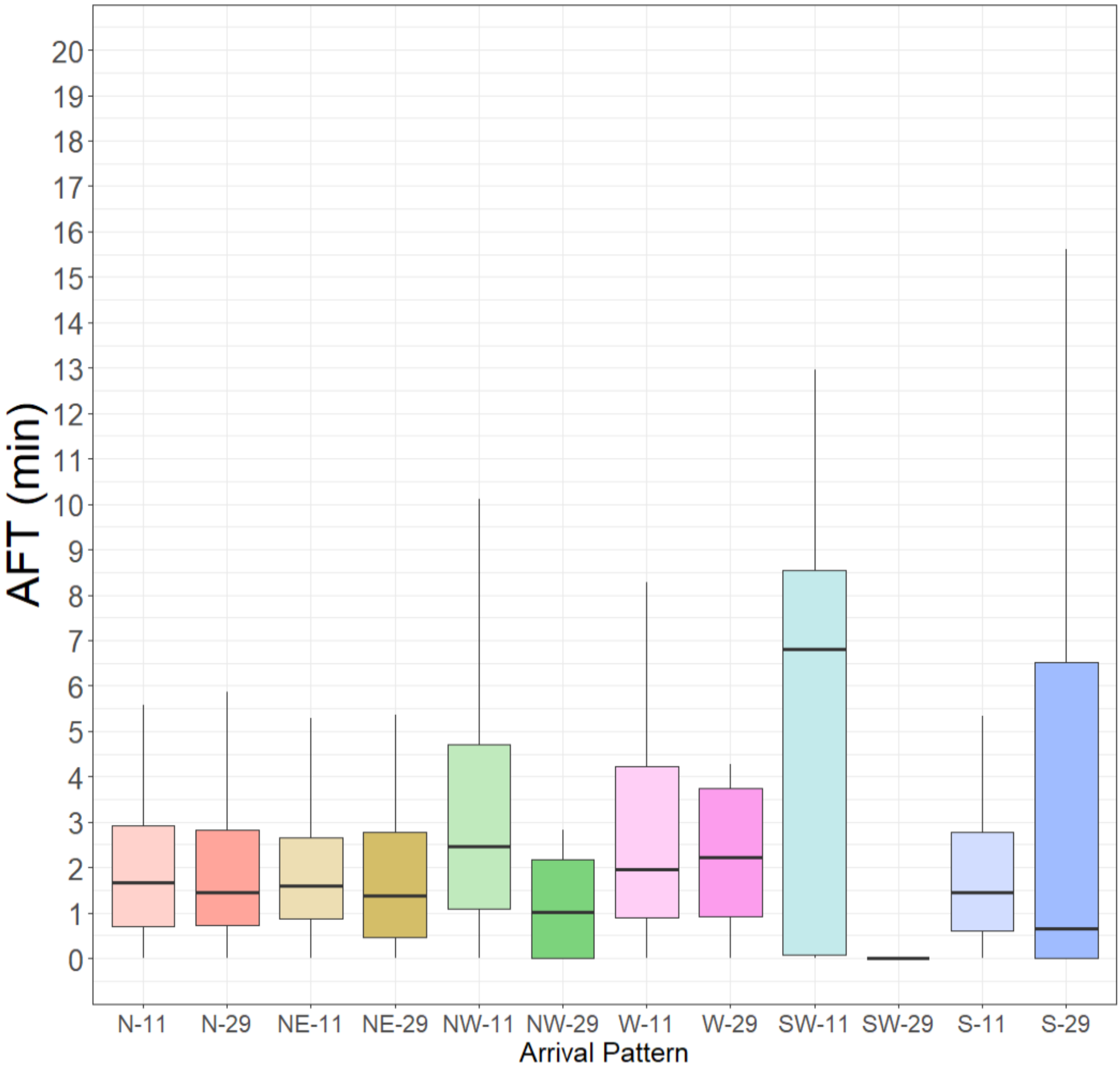

FIGURE 4.37 – Boxplots of additional flight time for SBPA arrival patterns.

4.1.10 SBCT

4.1.10.1 Standard Arrival Procedures

Figure 4.38 shows the standard arrival procedures at SBCT. This airport's arrival procedures connect five arrival regions with the runways 15/33, mainly using one arrival gate. The coding scheme follows the previous cases, with the combination of arrival region (North-N; Northwest-NW; West-W; South-S and East-E), arrival gate (for the West region) and runway configuration.

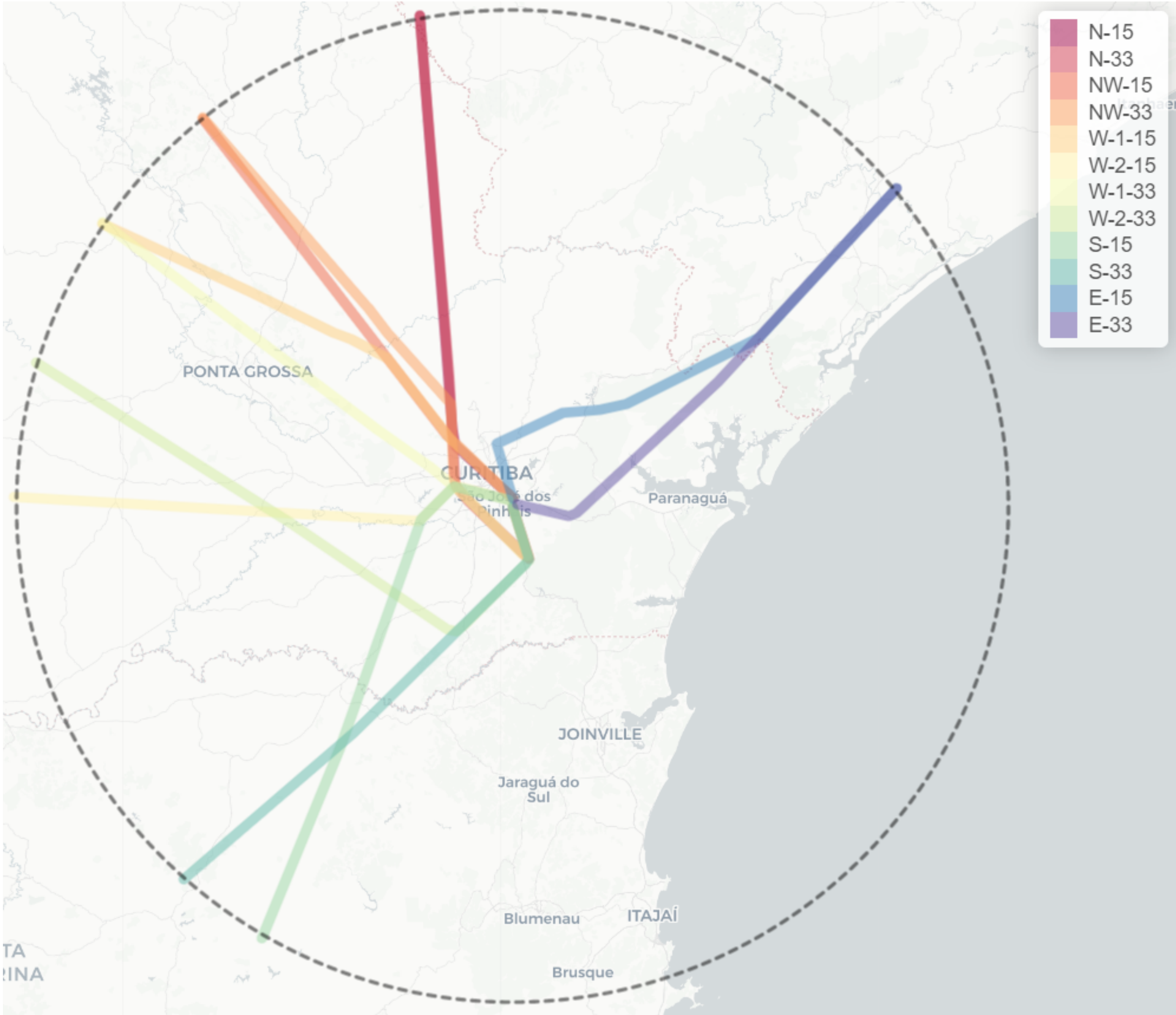

FIGURE 4.38 – SBCT arrival procedures.

4.1.10.2 Analysis of Terminal Airspace Utilization

Figure 4.39 shows the distribution of flight operations by arrival pattern. The results also reveal an uneven distribution of air traffic across arrival procedures at SBCT. The dominant traffic flow pattern corresponds to arrivals from the East gate to runway 15. It is observed a high concentration of arrivals through the East (E) gate, which accounts for 71.6% of the operations. The South (S) gate represents the second major flow, accounting for 9.7% of the operations. Finally, the Northwest (NW) gate accounts for 6.59% of the operations, 6.3% of the flights arrive through the North (N) gate and the remaining 5.8% use the West (W) gate. It is observed that runway 15 is the most frequently used, handling more than 65% of the arrival flights.

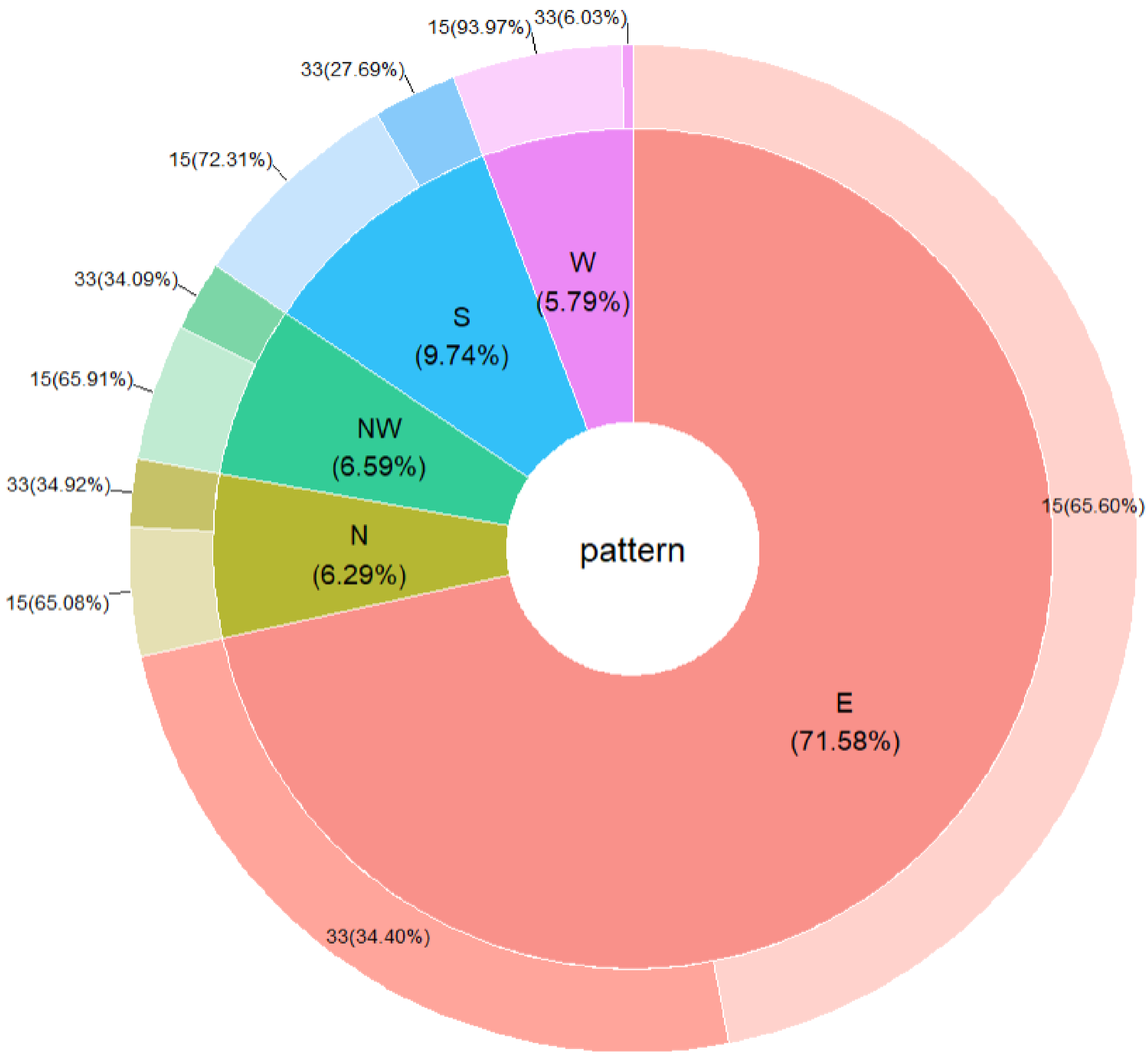

FIGURE 4.39 – Distribution of flight operations by arrival pattern at SBCT.

4.1.10.3 Analysis of Trajectory Conformance

Figure 4.40 shows the distributions of flight trajectory conformance by arrival pattern. In general, the median conformance values fluctuate less across arrival patterns when compared to other airports such as SBPA, indicating a more dependable level of trajectory conformance at SBCT. The arrival pattern N-15 showed the lowest normalized conformance values, suggesting better adherence of actual trajectories to standard procedures for this traffic flow.

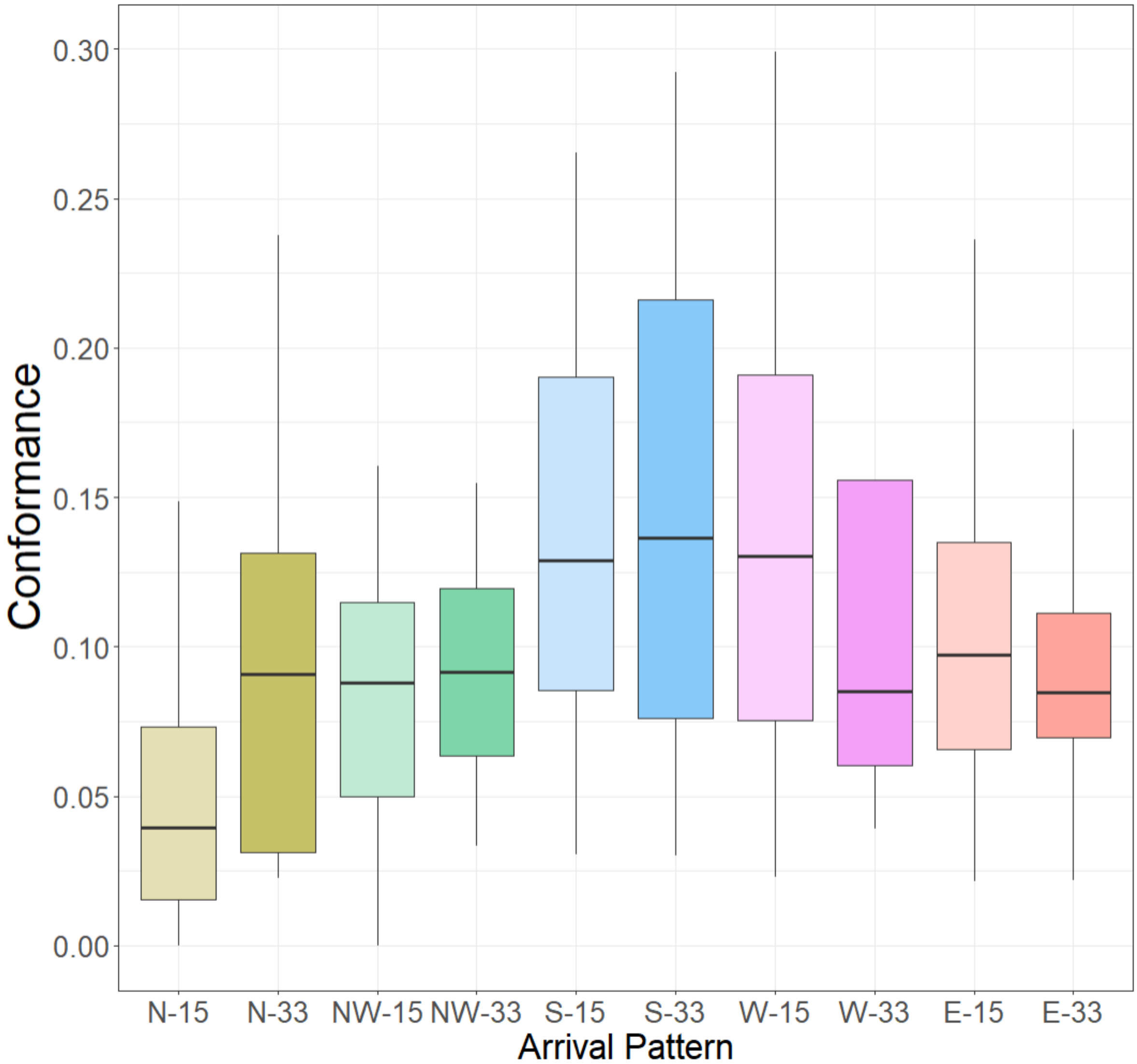

FIGURE 4.40 – Boxplots of trajectory conformance for SBCT arrival patterns.

4.1.10.4 Analysis of Additional Flight Time

Figure 4.41 shows the distributions of additional flight time by arrival pattern. We observed low variability in temporal efficiency across arrival patterns and within the same pattern. For instance, the median value of additional flight time ranged between 1 and 2 min for most of the arrival patterns. These results suggest an almost even distribution of delays in the terminal area.

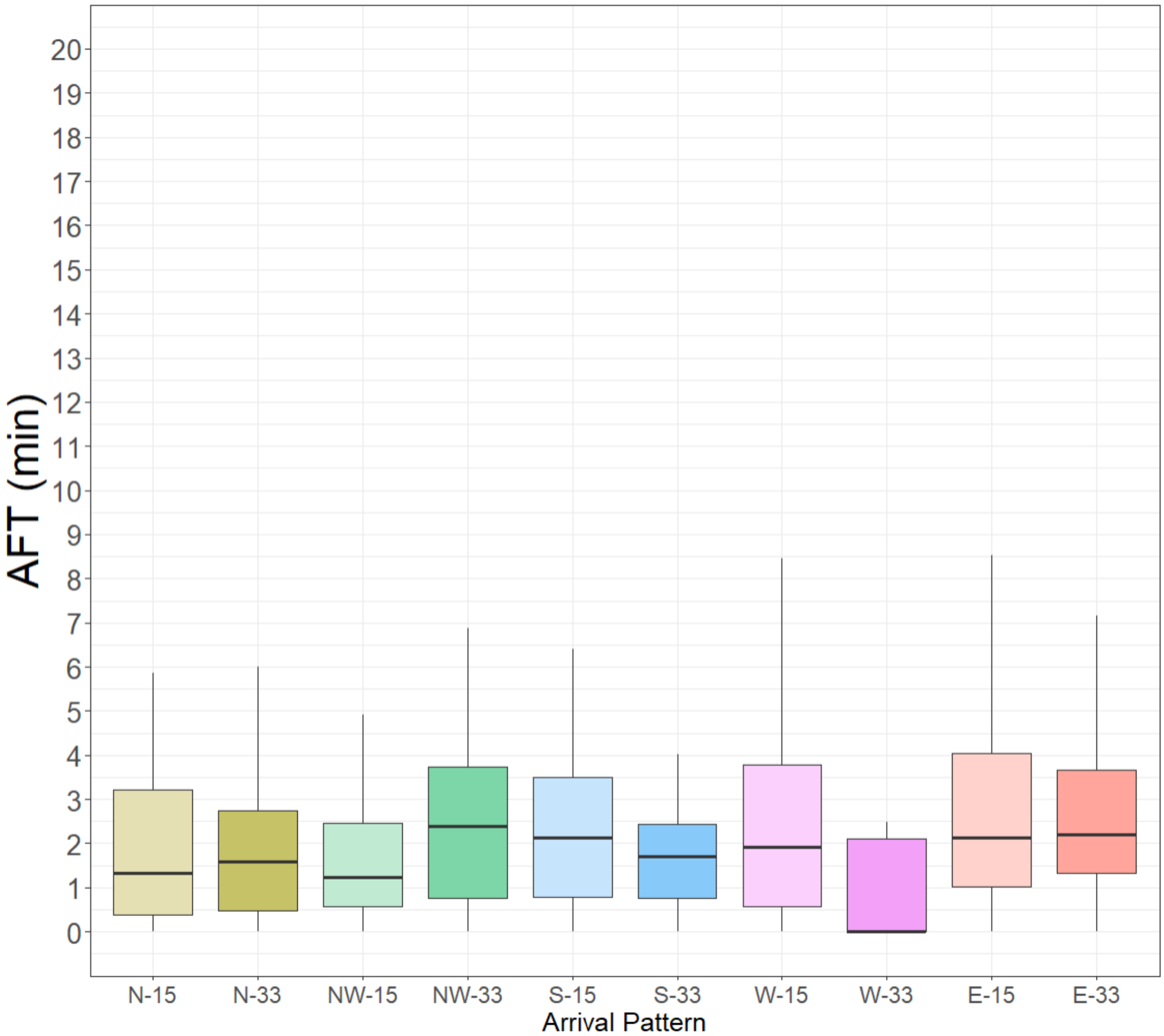

FIGURE 4.41 – Boxplots of additional flight time for SBCT arrival patterns.

4.2 Summary

This section summarizes and discusses the results of terminal airspace utilization and air traffic performance across the airports analyzed.

Table 4.2 shows the AU indicator for each airport. It is observed that most airports have values around 0.30. SBBR stood out with the lowest AU value, indicating a more balanced distribution of traffic across arrival procedures. By contrast, SBCT and SBPA presented the highest AU values of 0.53 and 0.47, respectively, indicating a high traffic concentration in one dominant procedure. This reveals an opportunity in those airports for a better distribution of flights, and with that, an increase in airspace capacity.

TABLE 4.2 – Utilization of the terminal airspace by arrival operations

Airport	*Airspace Utilization*
SBGR	0.34
SBSP	0.27
SBBR	0.08
SBKP	0.29
SBRJ	0.32
SBCF	0.22
SBRF	0.33
SBSV	0.23
SBPA	0.47
SBCT	0.53

Table 4.3 shows the most frequently used runway direction at each airport, with the corresponding percentage share of arrival operations. It is observed an unbalanced use of runway configurations at all airports. This is expected as the design of the airport layout and the definition of runway orientation considers the prevailing winds in the region where the airport is located in order to maximize the airport's usability and the operational efficiency and safety of aircraft during takeoff and landing. However, during low wind conditions, other factors such as the mix of arrival and departure operations or air traffic control preferences might influence the choice of runway configuration. The most balanced use of runways was observed at SBSP, with 60% of arrival operations using runway direction 17 and 40% using runway direction 35. On the other hand, SBSV exhibited the highest frequency of use for its dominant runway configuration, with runway direction 10 being utilized for arrivals 98% of the time.

TABLE 4.3 – Most frequently used runway direction and associated percentage share of arrival operations

Airport	*Runway Direction*	*Percentage*
SBGR	10	70%
SBSP	17	60%
SBBR	11	70%
SBKP	15	70%
SBRJ	20	90%
SBCF	17	75%
SBRF	18	90%
SBSV	10	98%
SBPA	11	80%
SBCT	15	65%

Table 4.4 presents the median level of the trajectory conformance indicator for each airport, globally, and for the most frequently used procedure. It is observed that the highest values of the TC indicator and, therefore, the lower levels of trajectory conformance, were mostly associated with the airports with the highest traffic volumes, such as the Sao Paulo airports (SBGR and SBSP) and SBBR. This agrees with the expectation, as ATC interventions for tactical sequencing, merging and spacing of arriving traffic are more likely to occur in dense terminal areas, causing trajectory deviations from standard procedures. However, we also observed a lower level of trajectory adherence to standard procedures at SBRF, which presented the highest median value of the TC indicator. Visual inspection of actual trajectories suggests that this might be associated with a higher number of shortcuts at this airport. For instance, Figure 4.42 shows the actual trajectories for the arrival procedure S-18 for one month of operations. It is noteworthy that the majority of flights deviate from the standard procedure, with their flight paths being shortened. However, further investigation is recommended in future studies.

The results shown in Table 4.4 also indicate that the most frequently used procedure at each airport presented a TC indicator value that is equal or lower than the global value, except for SBKP and SBPA. The highest difference was observed at SBBR. This might indicate prioritization of the dominant arrival flow during tactical air traffic control, leading to lower trajectory deviations from standard procedures. This was also observed at SBGR, as the PM use analysis revealed a lower frequency of use of the sequencing legs for the dominant North flow. On the other hand, the result may also suggest that the airspace structure is effectively utilized by ATC to accommodate higher traffic volumes safely.

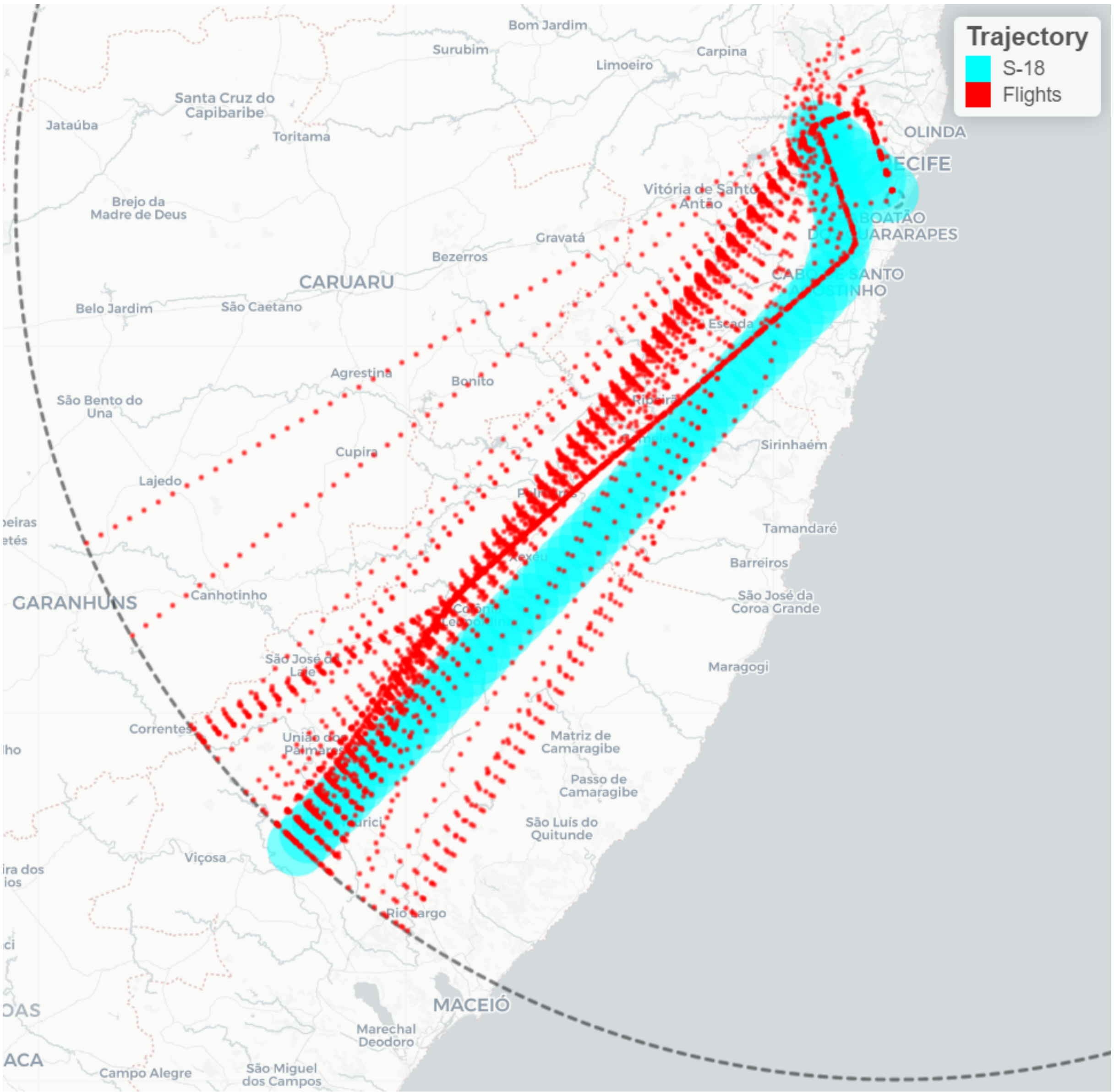

FIGURE 4.42 – Visualization of the S-18 arrival procedure at SBRF and the actual flight trajectories for one month of operations.

TABLE 4.4 – Median value of the trajectory conformance indicator.

Airport	*Most Frequently Used Procedure*	*Global*
SBGR	0.12	0.13
SBSP	0.11	0.14
SBBR	0.06	0.11
SBKP	0.08	0.06
SBRJ	0.03	0.06
SBCF	0.06	0.06
SBRF	0.14	0.16
SBSV	0.06	0.06
SBPA	0.06	0.05
SBCT	0.09	0.09

Finally, Table 4.5 presents the median level of temporal efficiency for each airport. SBGR, SBSP and SBKP showed the highest values of additional flight time. This highlights the density and complexity of the Sao Paulo terminal area and the resulting impact on air traffic performance. It is also interesting to note that SBRF presented one of the best temporal efficiencies, suggesting that its low conformance level is indeed more likely associated with trajectory deviations that do not elongate the flight path and generate delays.

TABLE 4.5 – Median value of the additional flight time indicator

Airport	*AFT (min)*
SBGR	3.7
SBSP	3.1
SBBR	1.3
SBKP	1.8
SBRJ	1.5
SBCF	1.4
SBRF	1.1
SBSV	0.9
SBPA	1.3
SBCT	1.6

5 Conclusion

The operational evaluation of existing airspace structures using large-scale historical data is an important step to deliver improvements in airspace design and management and, in turn, in air traffic performance. This is especially important in complex and dense airspace, such as terminal areas, which are more often subject to inefficiencies due to the high traffic density and the impact of stringent airport and airspace capacity constraints.

In this work, we performed a detailed characterization of arrival performance in terminal airspace for the top ten Brazilian airports. Based on actual aircraft tracking data and aeronautical information data, we first developed a trajectory classification approach to identify the use of arrival procedures and evaluate the actual use of the terminal airspace structure. Several performance indicators were developed to characterize airspace utilization and operational performance in terms of temporal efficiency and trajectory conformance.

Our findings revealed an unbalanced distribution of flights per arrival procedure for most of the airports. SBCT and SBPA stood out with the highest traffic concentration, whereas SBBR showed the most balanced use of the terminal airspace. With the novel trajectory conformance indicator, we were able to evaluate the level of adherence of actual trajectories to standard procedures. We observed that the lowest levels of trajectory conformance were mostly associated with the airports with the highest traffic volumes, such as the Sao Paulo airports (SBGR and SBSP) and SBBR. As expected, ATC interventions for tactical sequencing, merging and spacing of arriving traffic are more likely to occur in dense terminal areas, causing trajectory deviations from standard procedures. However, SBRF stood out with the highest median value of the indicator, revealing lower trajectory conformance at this airport. Visual inspection of actual trajectories suggests that this might be associated with a high frequency of shortcuts. Another interesting observation was the higher level of trajectory adherence for the most frequently used procedure, compared to other procedures, for most of the airports. This suggests that air traffic control might prioritize the dominant arrival flow during tactical operations while effectively using the airspace structure to safely handle higher traffic volumes.

Given the innovative Point Merge (PM) system design at SBGR, which was implemented in the most recent Sao Paulo terminal airspace redesign (TMA-SP Neo), we created new indicators to specifically evaluate the PM utilization and provide a more detailed operational evaluation for this airport. Our findings revealed an unbalanced distribution of flights per arrival gate and type of procedure, with almost half of the flights arriving from the north direction, predominantly using non-PM direct procedures. The novel PM structure was observed to be utilized by a reasonable share of the flights. More than 50% of the flights arriving from the south and northwest were found to use the outer sequencing leg of the main PM structure while 34% of the flights in the dominant north flow (N-10) used the inner sequencing leg. These results suggested air traffic control preferences regarding the arrival sequencing process with the PM, revealing a potential opportunity for improvement toward achieving a more equitable distribution of delays across arrival patterns. This is also backed by the observed high variability in additional flight time across arrival procedures. Finally, the PM arc utilization indicator revealed that a significant portion of 45.8% of the flights in the inner sequencing arc traversed more than 75% of its length, indicating a high use of the delay absorption capacity provided by the PM system during high-traffic periods, which justifies the implementation at SBGR.

This work provided several insights into the actual operational performance of various Brazilian terminal areas, yet several avenues remain for future exploration. Firstly, enhancing the trajectory conformance analysis by incorporating more granular indicators that distinguish between different segments of standard procedures could yield deeper insights into the nature of flight trajectory deviations. Causal models of air traffic performance might also be developed to identify the key factors influencing trajectory conformance and efficiency in terminal areas. Finally, correlating specific characteristics of the airspace structure with performance indicators might be explored towards the development of novel data-driven airspace design tools.

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<tr><td colspan="4">11. RESUMO:
Advancing Air Traffic Management with the implementation of novel airspace structures, systems and procedures is crucial to enhancing the economic and environmental performance of aviation. This requires detailed operational evaluations of different airspace design and management solutions through advanced data analysis. This work analyzes the terminal airspace operations for the major Brazilian airports using large-scale historical aircraft tracking data and aeronautical information data. A trajectory classification method is first developed to identify the actual use of standard operational procedures by arrival traffic. Several performance indicators are then proposed to evaluate the actual utilization of the terminal airspace structure and to quantify trajectory efficiency and conformance. The results reveal an uneven distribution of traffic across arrival procedures for most airports and a high variability in performance across airports and their procedures. Overall, we observe that the most frequently used procedures are generally associated with higher levels of trajectory conformance, while busier airports show less adherent trajectories. Specific indicators are created to analyze the novel Point Merge airspace design at Sao Paulo/Guarulhos International Airport. The results show a significant but unbalanced utilization of the Point Merge sequencing legs for delay absorption during tactical operations. The findings also highlight air traffic control preferences and opportunities for further improvements in delay management.</td></tr>
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