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Optimizing Airport Runway Capacity and Sustainability through the Introduction of Rapid Exit Taxiways: A Case Study

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Abstract: This contribution arises from the need to respond to the increased air demand of an airport with a sustainable approach that minimizes the land consumption of new runways and reduces the fuel burn and emissions associated with aircraft. A new methodology is presented for designing Rapid Exit Taxiways (RETs), which is applied in improving the runway capacity of Costa Smeralda Airport following both the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) guidelines. The optimal scenario resulted from a combination of these guidelines. Using this new approach, it is demonstrated that, through both the introduction of RETs and their positioning along the runway, the hourly capacity of the runway can effectively be improved, consequently enhancing the airport capacity and reducing the runway occupancy time and thus fuel burn and emissions. Moreover, the presence of RETs increases the infrastructure resilience, since airplanes can clear the runway faster in case of flooding in risk areas.

Keywords: sustainable and resilient development of airports; rapid exit taxiways; runway occupancy time; runway capacity

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1. Introduction

Airport infrastructures are very important nodes of the transportation network that play a crucial role in economic, social, and cultural development at regional, national, and international levels, as they promote accessibility to services and market connectivity. According to the Central Intelligence Agency [1], there are 41,820 airports worldwide, and around six million people fly somewhere everyday—nearly 0.1% of the world population.

A EUROSTAT Air transport statistics report reveals that, in 2018, 1106 million people in the EU travelled by air [2]. Domestic passenger traffic has steadily risen to exceed pre-pandemic levels. Air traffic in Europe is estimated to reach between 16 and 20 million flights by 2040, a potential scenario based on regulated and free growth, being, respectively, +53% and +84% of the current traffic [3]. Therefore, to address the growing demand and support the development of selected territories, airport managers need to enhance airport infrastructure toward increasing capacity and accommodating this rising traffic. Moreover, these enhancements must now be undertaken within a sustainable and resilient approach.

In this context, the objective of this research is to propose a solution to respond to increased air demand by applying a new methodology for designing RETs, using Costa Smeralda Airport in Olbia (Sardinia, Italy) as a case study. This study also aims to verify whether the solution ensures an increase in runway capacity and improves the sustainability and resilience of the airport infrastructure.

Following this introduction, the remainder of the paper is organized as follows. Section 2 is a review delving into the literature on methods for assessing and improving airport capacity. Section 3 describes Costa Smeralda Airport and its criticalities. The Rapid Exit Taxiways (RETs) are designed based on two guidelines, applied, and subjected to comparison. The results are reported and discussed in Section 4. Finally, Section 5 concludes this study, with recommendations for new avenues of research.

2. Literature Review

In the literature, numerous definitions of airport capacity are found: the International Civil Aviation Organization (ICAO) defines capacity as the number of movements per unit time that can be accepted during different weather conditions [4], whereas the Federal Aviation Administration (FAA) states that capacity is the measure of the maximum number of aircraft operations that can be accommodated by the airport or its components within one hour [5].

Various methods of assessing airport capacity have been proposed in the literature. Stamatopoulos et al. [6] studied a decision support system, the MANTEA Airfield Capacity and Delays (MACAD) model, which integrates macroscopic airside models to provide estimates of the capacity associated with every element of the airfield. It is easy to use and thus a good tool to support strategic decision-making. Zou et al. [7] presented a model for simulating airport capacity using ARENA software (version 14.00.0), whereas Di Mascio et al. [8] developed an analytical method for the estimation of airport capacity. Although the first two models provide a good approximation of capacity, a large amount of information is required; in some cases, such information is not readily available (e.g., aerodrome operational characteristics, traffic control system characteristics of local aircraft, and airside operational features). The analytical model based on Microsoft Excel is simpler but has a lower precision.

The most immediate solution for improving airport capacity is to increase the number of runways or the size of the airport. However, this is not always possible because of the complexity of the work involved and the long times required for construction and design, in addition to the substantial financial and territorial resources that are needed. Irvine et al. [9] studied increasing capacity using a Monte Carlo simulation applied to London airports and following the construction of a new airport hub in the Thames Estuary. They demonstrated that the construction of a new runway, without restrictions, leads to an increase of ~21% in the capacity for movement during rush hour.

Other strategies for increasing capacity concern the reduction of the runway occupancy time of aircraft, Airport Slot Allocation (ASA), and planning interventions. Skorupski and Wierzbicki [10] and Pavlin et al. [11] state that one of the key elements for reducing runway occupancy time is the active role of the driver and the braking technique used during the landing roll. ASA is generally used in congested airports as a short-term measure that allows the dynamic allocation of airport resources. Thus, Katsigiannis and Zografos [12] proposed a modeling framework that considers the preferences of the airlines and integration under constraints. Moreover, they suggested the advanced Tri-Objective Slot Allocation Model (TOSAM) [13], which considers the total and maximum duration of the project and equity based on demand, introducing a multi-level and multi-objective algorithm. Another method involves the development of strategic initiatives that airlines and civil aviation authorities could undertake on different time horizons, from strategic planning to real-time interventions [14].

However, the first and best option is still to increase runway capacity using a sustainable approach that does not necessarily require the expansion of airport infrastructure.

The runway capacity is directly dependent on two factors: the separation of the wake vortices and the runway occupancy time. By studying wake vortices and through the consequent separation of the aircraft, superior flight safety can be ensured [15], in addition to an improvement in the runway capacity. Butler and Poole [16] proposed the use of the Next Generation Air Transportation System (NextGen) at San Francisco International and the three main airports in New York. NextGen is a next generation air traffic control system of the FAA that can be used to increase airport runway capacity without expanding the airport's geographical boundaries. More recently, Chu and Zhou [17] studied the effects of the NextGen implementation by comparing aviation performance measures (departure delay, taxiing time, flight time, and arrival delay) for each flight at airports that adopted NextGen vs. airports where NextGen technologies have never been adopted. Their findings reveal that implementing NextGen resulted in reduced air travel times and decreased delays.

Pan et al. [18] studied the capacity of Chengdu Shuangliu airport using MATLAB (version R2021a), focusing on the American Wake Turbulence RE-CATegorisation (RECAT) (or Wake RECAT) proposed by the FAA, while Holzäpfel et al. [19] used the Monte Carlo simulations to demonstrate the potential of the wake vortex prediction system (WSVS) for improving aircraft separation. The separation of wake vortices depends, in turn, on the sequence of arrivals and departures, the air traffic mix, and meteorological conditions.

To the best of our knowledge, there are no reports on studies evaluating the capacity increase associated with the presence of RETs, as well as their influence on runway occupancy time (ROT). We attempt to address this gap through the study and design of RETs as part of a strategy to improve runway capacity using a sustainable approach that avoids land consumption due to new runway construction and reduces aircraft fuel burn and emissions. In this case study, RETs were designed, and their locations along the runway were optimized following both the International Civil Aviation Organization (ICAO) [20,21] and the Federal Aviation Administration (FAA) [22] guidelines. We assessed whether their introduction at Costa Smeralda Airport (Sardinia, Italy) could improve the runway capacity during rush hour, thereby optimizing the operational capacity of the entire airport. Using AirTOP software (version 3.1), we evaluated the capacity of the runway before and after the operation of the planned RETs to ascertain whether the interventions result in concrete improvements in capacity, as expected. The focus was on the location and type of runway exits because ROT is directly dependent on these parameters. Costa Smeralda Airport is characterized by high seasonality and constantly increasing traffic; therefore, solutions that allow an increase in the number of operations are of particular importance.

3. Materials and Methods

3.1. Study Area: Costa Smeralda Airport

Costa Smeralda Airport in Olbia is one of three airports in Sardinia, Italy (see Figures 1–3), connecting the island with the main national and European airports.

Figure 1. Location of the Costa Smeralda Airport—Olbia (Google Earth).

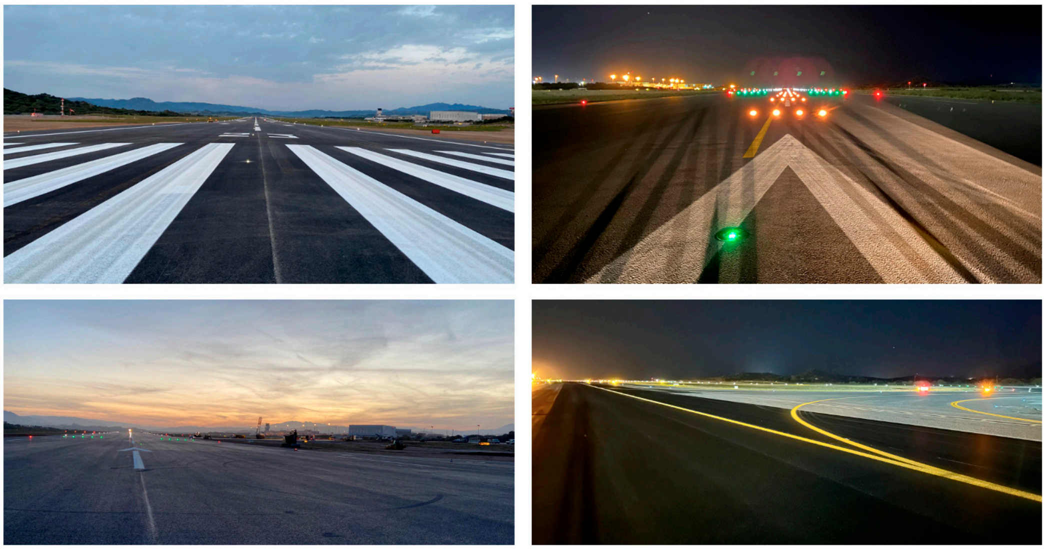


Figure 2. The Costa Smeralda Airport runway.

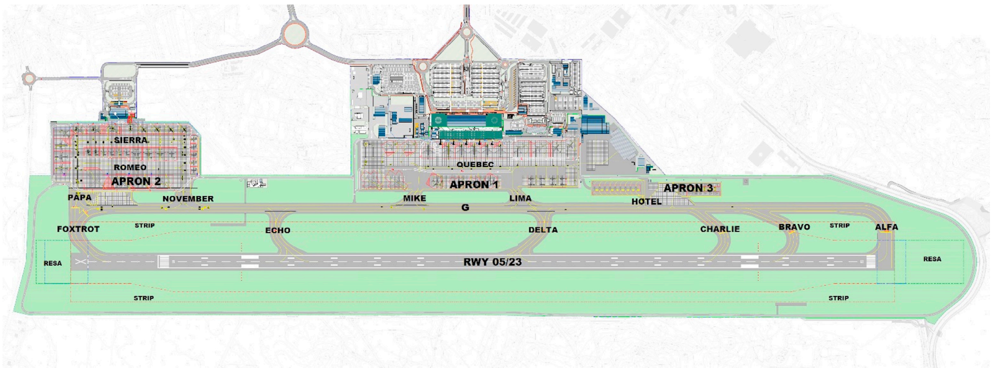


Figure 3. Layout of Costa Smeralda Airport.

The airport is located entirely in the municipality of Olbia, a few kilometers from the town center, in the northeastern area of Sardinia. The airport is located within an area of significant tourist, cultural, and commercial interest; therefore, it is important to ensure the reliability of air traffic in northern Sardinia. Thus, Costa Smeralda Airport is a highly seasonal airport, with constantly increasing traffic [23], as shown in Figure 4.

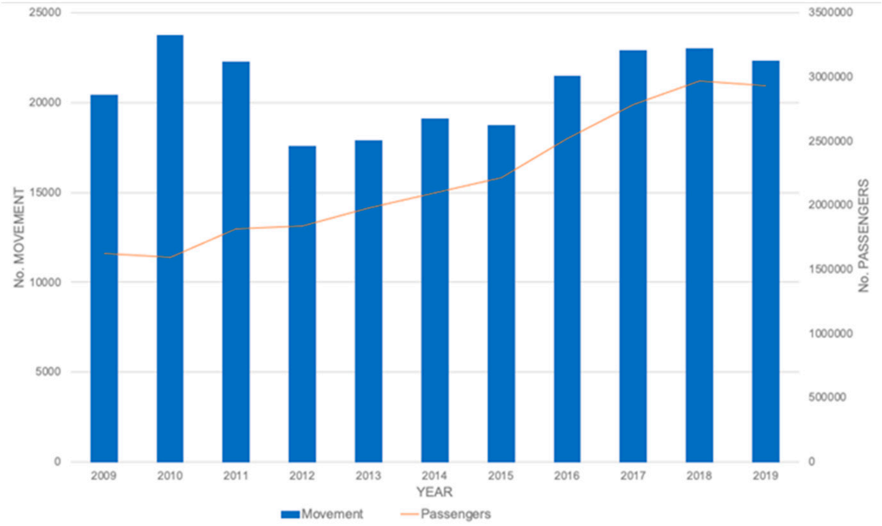


Figure 4. Number of movements from 2009 to 2019 [23].

The airside part consists of a single runway, a parallel taxiway, and six taxiways for exiting the runway, none of which support high-speed operations. Because of this configuration, operational criticalities arise during the high-traffic season, especially considering the volume of both commercial and general aviation traffic. To avoid operational limitations that could occur due to these circumstances, actions toward improving airport capacity are required. Limitations in the infrastructure of an airport during peak periods inevitably have repercussions for the social and economic fabric of the geographical reference area.

Hydraulic criticalities are present in the airport area, as highlighted in the regional and municipality sector studies following the flood on 18 November 2013. There are two main elements of hydraulic criticality in this airport area:

- The runway, the strip, and portions of the taxiways are situated in areas prone to flooding from the Padrongianus River, an event that occurs with low probability but high return times;
- Running below the airport area in the southwest sector is the Colcò buried channel, a left tributary of the Padrongianus River. The channel and the areas north of the airport experience significant flooding due to the backflow effect of the river (see Figure 5).

Figure 5. Critical areas subject to flooding (highlighted with green arrows and marks) and zoning, representing hydraulic hazards.

The exceptional flood event of 2013 produced significant damage to the runway (see Figure 6) and aprons, as well as to the airport security systems and service infrastructure. In order to guarantee the resilience of the infrastructure, the following interventions have been carried out:

- An increase in the runway slope;
- The construction of an embankment system to contain flooding from the Padrongianus River along the southeastern and southwestern sectors;
- Bank defense works in the northeastern sector;
- The hydraulic disconnection of the Colcò channel from the Padrongianus River through the construction of an anti-regurgitation floodway integrated into the embankment system;
- The application of the principle of hydraulic invariance to the Colcò channel basin, namely through construction of a controlled lamination basin in the area northwest of the airport;
- The reinforcement of the drainage network, with simultaneous disconnection from the river system;
- The construction of drainage trenches integrated with the disposal network.

Changes to the map of critical areas after these interventions are depicted in Figure 7.

Figure 6. Runway damage after flooding in 2013.

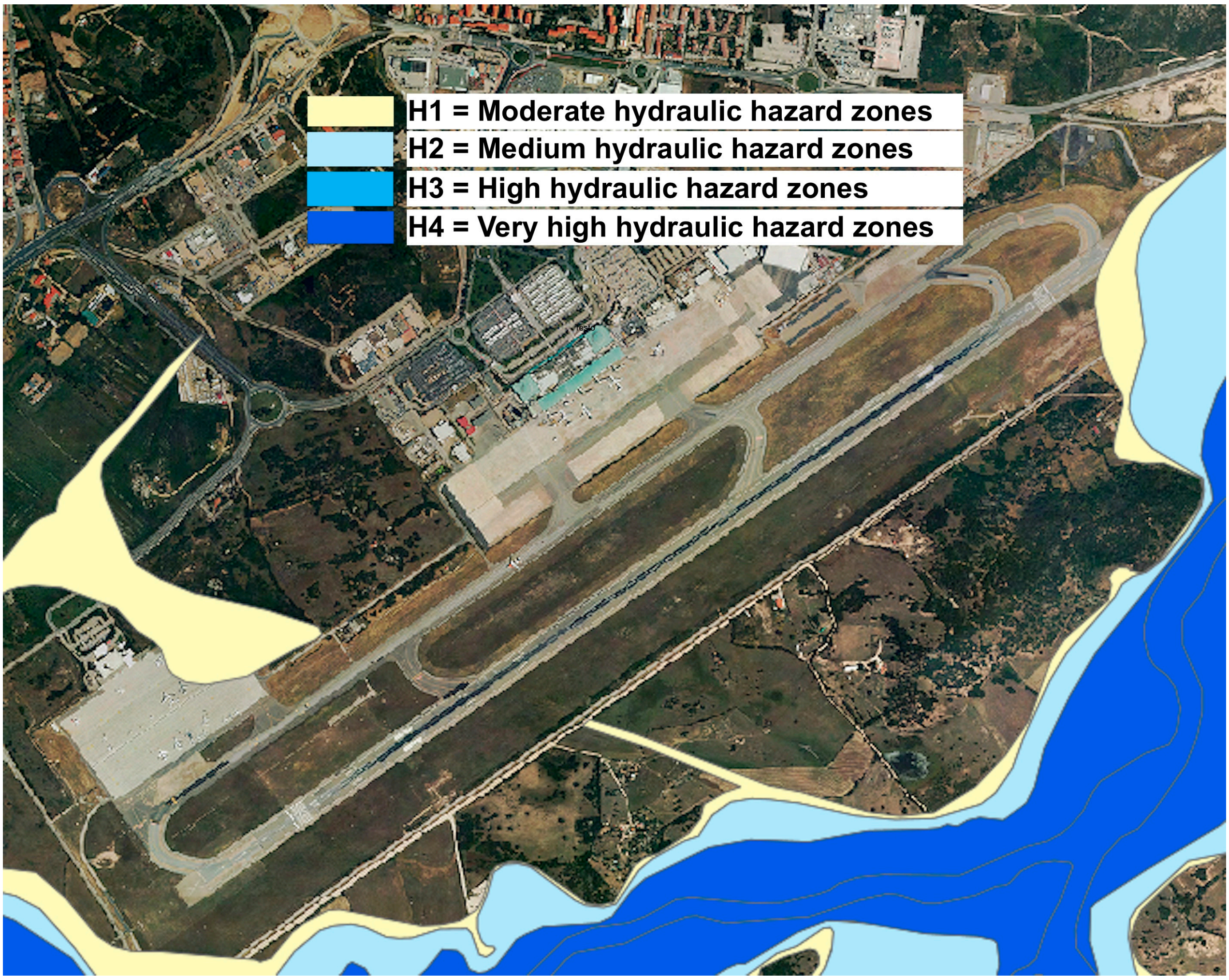


Figure 7. Critical areas subject to flooding rev in 2020 [24].

In this multifaceted context, finding a solution to cope with increased air demand while meeting sustainability and resilience requirements has been a major challenge for airport operators.

The economic growth and development resulting from the construction of infrastructure inevitably produces changes in the physical ecosystem because of the use and alteration of non-renewable resources such as soil, air, water, flora and fauna, fossil fuels, etc. Therefore, in view of sustainable development, the exploitation of a resource must be controlled to ensure that it is not depleted before acceptable substitutes are available.

Research on airport sustainability is actually increasing, despite the fact that the interest of most authors is focused on global greenhouse gas emissions from airfield pavements and energy management strategies for airport buildings [25–34]. Less attention is given to other issues, such as water conservation [35–39], climate change resilience and weather resilience [40–43], and waste management [44–46].

The Airport Cooperative Research Program (ACRP) [47], an industry-driven, applied research program aimed at developing practical solutions to airport challenges, defines environmental sustainability across five categories: energy and atmosphere, comfort and health, water and wastewater, site and habitat, and materials and resources. At present, however, researchers recognize that airport sustainability encompasses multiple environmental impacts. In the literature, some works focus on only one of these categories, whereas others attempt to identify indicators for multidimensional assessment that do not always cover all five categories. Therefore, a unanimous consensus on the definition of environmental sustainability of an airport is still far away.

Sustainable and resilient transport aims to move people and commodities in a safe, comfort, economical, efficient manner while preserving environmental resources and adapting to climate change-related and other emergency conditions, such as adverse weather events [48–50].

This requires that airport infrastructures be planned, designed, and managed while maximizing efficiency and emphasizing cost-cutting, even beyond environmental initiatives.

3.2. Methodology: RET Project

The International Air Transport Association (IATA) highlights that design decisions involving airports can have an enduring impact on their environmental and operational performance. Thus, it suggests some sustainable strategies to consider for maximizing the use of existing resources and using technology to improve the efficiency of airport processes, and thus reducing the environmental impact and enhancing sustainable building standards. Further, the IATA states that an efficient airfield layout can optimize the operational capacity and performance of an airport and reduce aircraft fuel consumption and emissions. An efficient layout can be obtained by minimizing the taxi distances from the gate or stand to taxiways and runways or through the use of runway holding bays and bypassing taxiways to facilitate aircraft flow and sequencing [51].

Therefore, a decision was made to design one or more RETs because this represents an intervention that does not require expanding the size of the airport. As stated by O'Flynn S. [52], this operation helps reduce ROT, which is one of the most critical factors influencing airside capacity.

To pursue the safety objective of RETs and consequently facilitate the rapid and safe exit of the aircraft from the runway [53], it is necessary to carefully design this infrastructure in such a way that it is optimally positioned along the runway. The ICAO [21] and FAA [22] define RETs as traffic routes connected to the runway via an acute angle, generally equal to 30°, which can accommodate aircraft at speeds of approximately 45/50 knots. Standardizing the design of these connections is essential for facilitating easier and safer landing maneuvers by pilots at any airport in the world. The two methodologies for designing RETs, proposed by ICAO [20,21] and the FAA [22], are described below.

3.2.1. International Civil Aviation Organization (ICAO) RET Design Guidelines [20,21]

RET design parameters are provided in Annex 14, Volume I of Aerodrome Design and Operations of ICAO [20]. The RETs are grouped according to the runway, with code numbers 1–4. Before developing the design, it was necessary to assess if such an intervention could lead to a benefit in terms of capacity. Such predictions were made with reference to the number of movements during rush hour: if these exceeded 25 mov/h, then such an intervention would ensure a certain improvement in airport capacity. The airport in question is a seasonal layover; thus, in the summer months, the number of movements exceeds the indicative minimum number of mov/h for the introduction of RETs and justifies the planning of this intervention.

The ICAO defines the following different steps to perform a correct design [21]:

1. Determination of the number of RETs to be inserted along the runway.

This number is identified in relation to the type of aircraft and the number of aircraft that engage at the airport during rush hour. So, it was necessary to analyze the fleet mix of aircraft landing in Costa Smeralda Airport. Indeed, the lighter the aircraft, the easier it is to exit from the intermediate exits (RETs) along the runway. Conversely, heavier aircraft require more space for landing, braking, and exiting the runway. Data provided by the airport management company revealed that the most frequent type of aircraft belong to category C of the ICAO classification (see Figure 8).

We decided to insert two RETs: one for landings taking place along RunWaY (RWY) 05 and one for those taking place along RWY 23. In fact, in terms of statistical distribution, the two directions of the runway are in equal use (50%) for each runway head. Therefore, in this study of RETs, these two directions of landing must be considered to ensure an effective increase in capacity under all conditions.

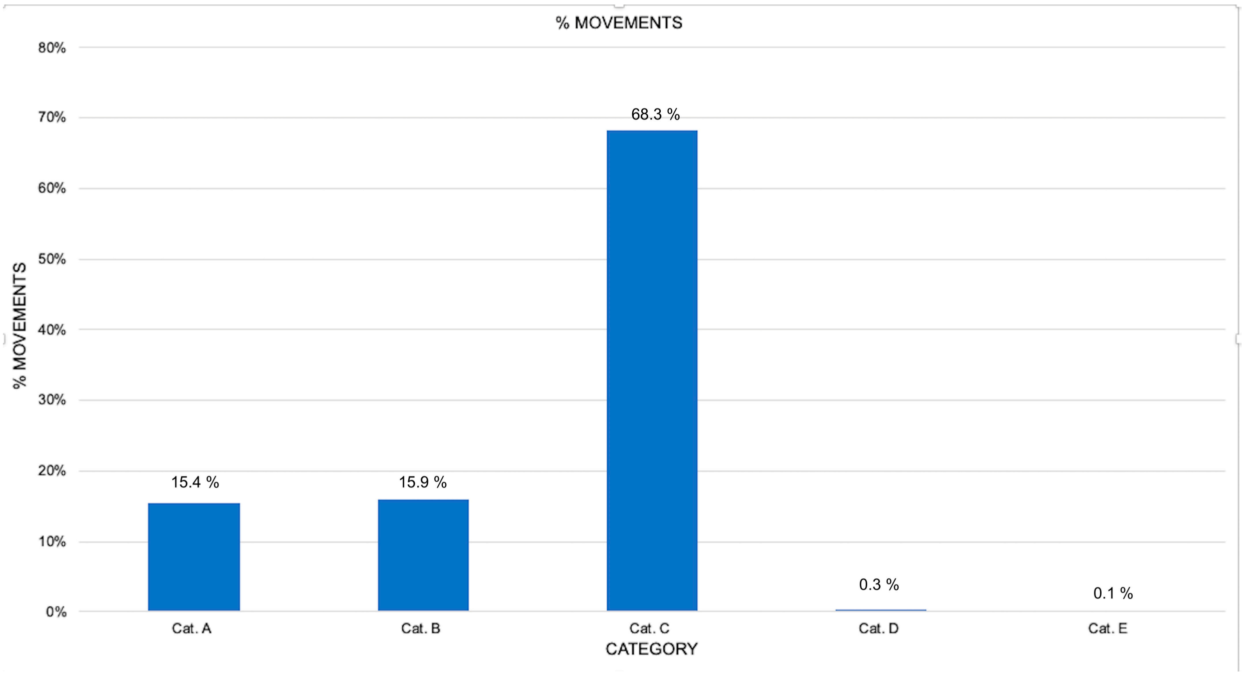


Figure 8. Percentage of movements by aircraft category 2019.

2. Assessment of RET position along the runway.

These estimations are generally made according to the different needs of each airport. To define the location of the RET, after first identifying the operating conditions of the airport, we established a representative fleet mix for the scenario in which the exit is intended to serve and verified that the distance between the runway and the taxiway was sufficient to allow the introduction of this new infrastructure. The three-segment method was used, which consists of the sum of three segments, shown in Figure 9, which depend on different factors, such as the aircraft category, the slope of the touchdown zone, wind conditions, the threshold crossing speed, and the speed turn-off and deceleration rates, and can be analytically quantified using the equations in Table 1.

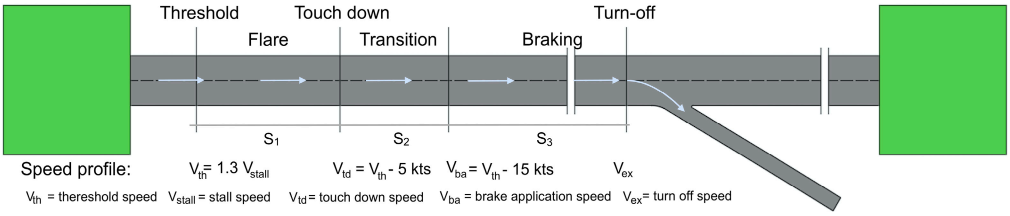


Figure 9. Three segment method.

Table 1. Equations for calculation of the three segments.

Segment	Aircraft Category	Length
S1	A or B	450 m +50 m every −0.25% of slope +50 m every 5 knots of wind in favor
	C or D	250 m +30 m every −0.25% of slope +30 m every 5 knots of wind in favor
S2	all categories	$S_2 = 5 \times (V_{th} - 10)$
S3	all categories	$S_3 = [(V_{th} - 15)^2 - V_{ex}{}^2]/8 \times a$ [1]

[1] V_{th} = threshold speed; V_{ex} = tourn-off speed; a = rate of deceleration.

The calculations carried out for the airport in the first approximation helped us determine the Optimal Turning Point (OTP) values, as shown in Table 2, for each type of aircraft (the Airbus A320 family and the Boeing B737 family) and for all wind conditions typical of the territory (0, 5.4, 10.8, and 16.2 kt).

Table 2. Values of OTP.

Wind Condition [kt]	Type of Aircraft	OTP [m]
0	Airbus A320 Family	2061
	Boeing B737 Family	2037
5.4	Airbus A320 Family	1933
	Boeing B737 Family	1910
10.8	Airbus A320 Family	1810
	Boeing B737 Family	1788
16.2	Airbus A320 Family	1692
	Boeing B737 Family	1670

Subsequently, to consider the dispersion occurring at the touchdown point, in the transition interval, and in the braking distance, the Optimal Turning Segment (OTS) was evaluated by summing 100 m before and 200 m after the OTPs calculated. The optimal locations of RETs were determined in relation to the OTP and OTS parameters: the OTS with the highest percentage of aircraft served was selected, and the percentage of aircraft for which the OTP is a part within the OTS was then added. The OTPs that have a non-negligible percentage were at 1788 m and 1910 m, and they are highlighted in Figure 10.

The geometry of the RETs was defined according to the actual space in the airport complex. The design followed the ICAO guidelines [21] for runway categories 3 or 4, since the Costa Smeralda Airport runway is a category 4 runway. The design conformed to the following main criteria:

- The angle of intersection between the RET and runway is equal to 30°.
- The radius of the deviation curve and its tangent are equal to 550 m and 147 m, respectively; this ensures an aircraft exit speed of 50 kt in wet conditions.
- The straight section following the curve should not be less than 75 m, which allows the outgoing aircraft to stop completely, away from any taxiway.

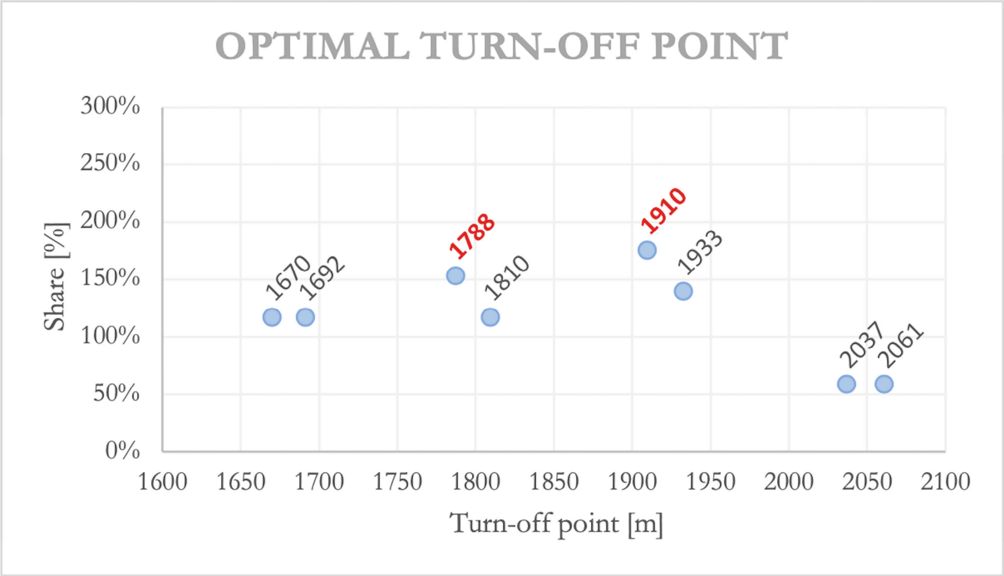


Figure 10. Indication of the outputs, with prevailing OTPs (in red).

Shown in Figures 11 and 12 are the geometry of the RETs and their location on the runway, respectively.

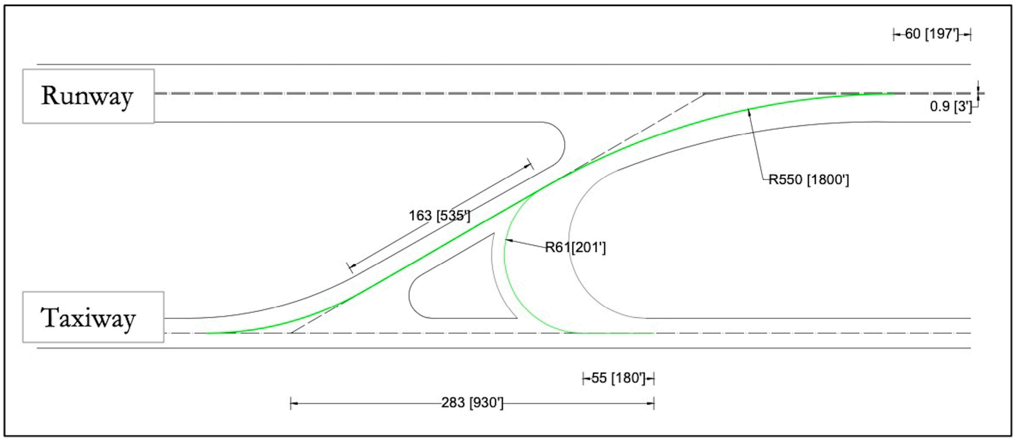


Figure 11. RET geometry.

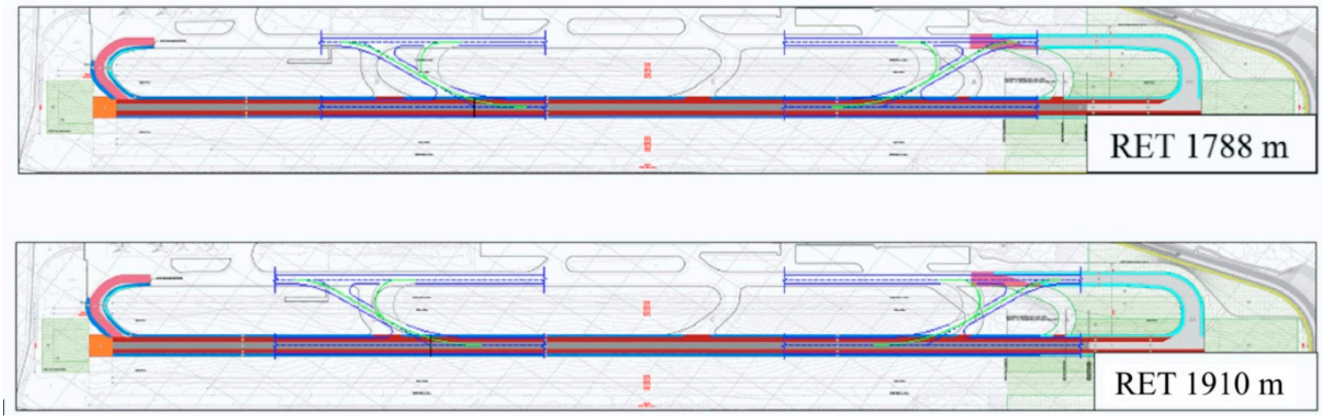


Figure 12. Layout of RET placement at the airport.

3.2.2. Federal Aviation Administration (FAA) RET Design Guidelines [22]

Software REDIM-V3 is the alternative to the ICAO regulations for determining the location of RETs in the Olbia airport complex. It was developed by the FAA and involves the Monte Carlo simulation, which allows us to realistically recreate the operations of aircraft. In the studies of Koščák et al. [54], Trani et al. [55], Trani et al. [56], and Trani et al. [57], the impact of optimal RET positioning along the runway is assessed. The results of these studies were helpful for creating an iterative model that allows estimating the ROT of aircraft. To determine the optimal locations for the RETs and to evaluate the ROT and the percentage of RET use for each aircraft in the fleet mix, the following input data are necessary:

- Runway length;
- Runway width;
- Altitude above sea level;
- Humidity conditions;
- Fleet mix of the airport;
- Whether there are any exit strips present along the runway.

We performed a series of simulations for each of the two different runways, 05 and 23, and for two fleet mixes: one comprising all aircraft in the airport, including those with low employment rates, and one that contained only aircraft with a high percentage of occupation. The simulation results show that the position of the RET along the runway does not change when varying the two fleet mixes; this is because the new releases include more category C aircraft, which are present at the airport for longer times, while other types of aircraft could use the new exits or continue to use the existing exits. However, there is an obvious difference in the location of the new infrastructure identified for the two runways (see Table 3 and Figure 13).

Table 3. REDIM results for the RET positions.

RWY	Exit	Point of Curvature Location [m]
05	Delta	1241
	RET 05	1431
	Charlie	1943
	Bravo	2179
	Alfa	2496
23	RET23	1650
	Echo	2025
	Foxtrot	2715

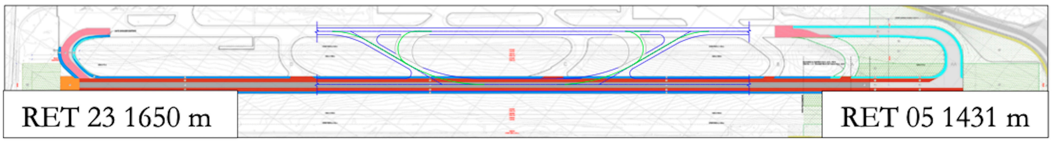


Figure 13. Positions of the RETs in the airport layout.

3.2.3. Comparison

The relevant data to verify whether the introduction of RETs led to an improvement in the capacity of the runway are represented by the ROT of aircraft, which is closely related to the location of the new taxiway exit. Furthermore, the ROT, which is dependent on multiple factors, was obtained using REDIM-V3 software, which allows obtaining precise values for executing a series of evaluations. In fact, from the obtained results, as shown in Figures 14 and 15, we found the following:

- For RWY 05, most aircraft currently use the taxiway Charlie to exit the runway, for which an average of 63 s is required to completely clear the runway. The introduction of a RET allows a large number of aircraft to use such an output, thus reducing the runway occupancy time by 5 s when a RET is placed at 1910 m from the threshold, 9 s when the RET is positioned at 1788 m from the threshold, and 12 s when the RET is placed at 1431 m from the threshold.

- For RWY 23, based on the current output configuration, the taxiway mainly used by aircraft is Echo, with a ROT of 67 s. Similarly to RWY 05, the introducing of a RET results in the ROT being reduced to 8 s when the RET is positioned at 1910 m, 12 s when the RET is positioned at 1788 m, and 17 s when the RET is positioned at 1650 m.

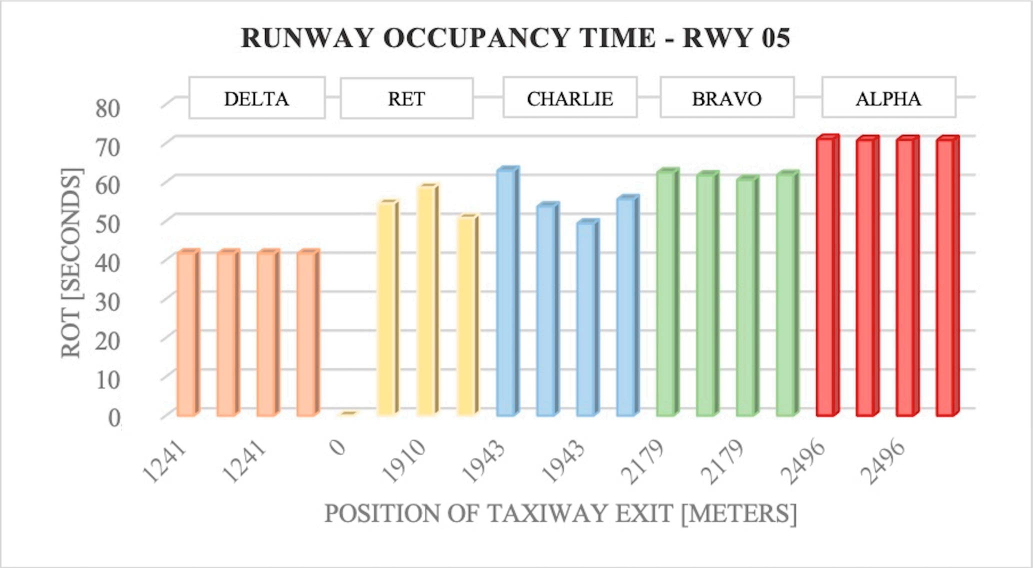


Figure 14. ROT for Runway 05.

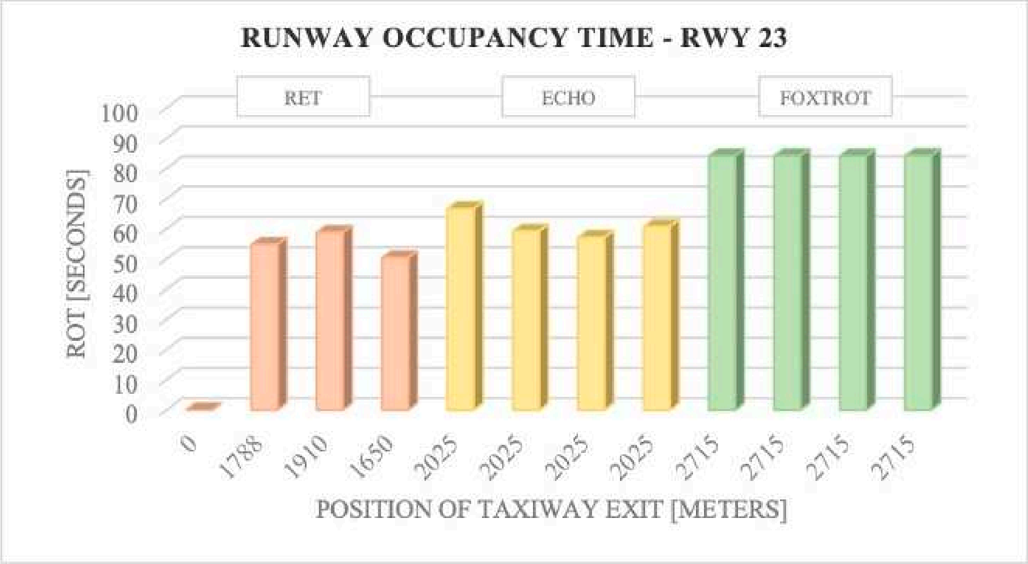


Figure 15. ROT for Runway 23.

Notably, the introduction of RETs results in benefits in terms of ROT; therefore, considering that ROT is closely linked to the runway capacity, we conclude that this result is unequivocal evidence for the improvement of runway capacity.

4. Result and Discussion: Assessment of Runway Capacity

Once the value of the ROT was determined, the runway capacity was evaluated. It was estimated using the configuration of the current exits and various configurations of

RETs, based on the new designs. Specifically, we measured capacity improvement in terms of ROT reduction. In addition, we verified which of the configurations obtained using either the ICAO regulations or REDIM software provides the greatest benefits in terms of capacity. In the case study, simulations were performed using software AirTOP. The elaborations provided a clear overview regarding the situation of the airport, especially in the 3 h of the year with the greatest number of movements, for the investigated scenarios. The model is based on the physical and technical characteristics of the airport, including the layout, location, and orientation of the runway. Subsequently, the following minimum operating rules were defined to generalize the study results:

- Runway Dependencies

1. Departure after departure. Lift off if minimum separation is achieved (3 nautical miles (NM)): a departure should be separated by 3 NM from the following departure.
2. Departure before arrival. Start take-off before the next arrival has captured the runway (capture distance of 1.8 NM). The airplane may be cleared for take-off if the time it takes for line-up and take-off is less than the time that the incoming aircraft takes from 1.8 NM to the threshold. Otherwise, the take-off will be delayed until the aircraft has landed.
3. Departure after arrival. Start take-off after the arrival has vacated the runway: the departure will be authorized for take-off as soon as the previous arrival has evacuated the runway.
4. Arrival after arrival. Start take-off after the arrival has vacated the runway. Two consecutive arrivals must be separated by a distance of greater than 3 NM, with the minimum distance varying according to the size of the airplanes upon arrival.

- Ground Traffic Flow to Analyze Runway Capacity

1. Departures will use the only pitch available according to the direction of the analyzed runway.
2. Arrivals will clear the runway at the first available exit to reach the pitch indicated for arrivals.

- Aircraft performance: each aircraft will use a specific taxiway to clear the runway in relation to its characteristics (touchdown speed, nominal deceleration, and maximum output speed) and the characteristics of the output taxiway (position and typology).
- Traffic sample used for simulation.

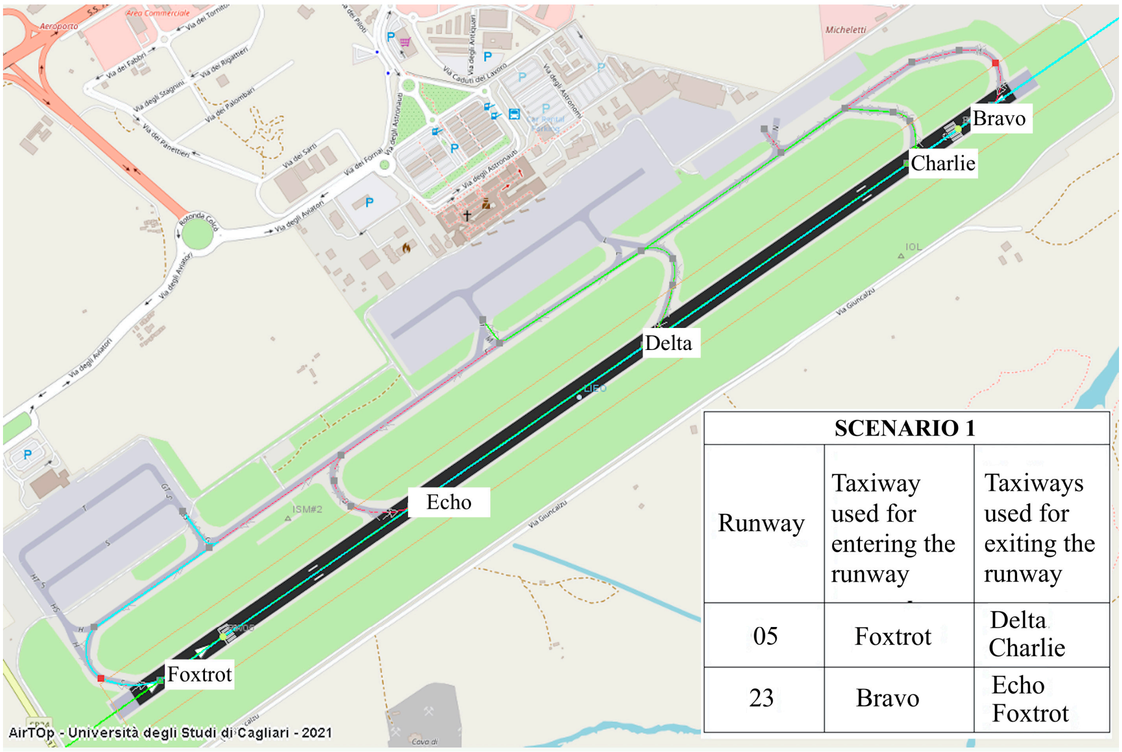
Figures 16–18 show details of the three scenarios that were constructed and analyzed. For each scenario, we assumed the taxiways used for entering and exiting the runway.

The values of runway capacity and thus the benefits that RET brings within the airport complex were obtained by subjecting the runway to the maximum traffic that it can handle without ever exceeding the limit of 10 min of delay.

Regarding the case of hourly movements, two runways, 05 and 23, are considered, similarly to the evaluation of ROT.

The results of the various simulations show that the value of the current runway capacity is 47 movements per hour for RWY 05 and 45 movements per hour for RWY 23. However, the presence of RETs increases these values because the new infrastructure allows, as previously demonstrated, a reduction in the ROT.

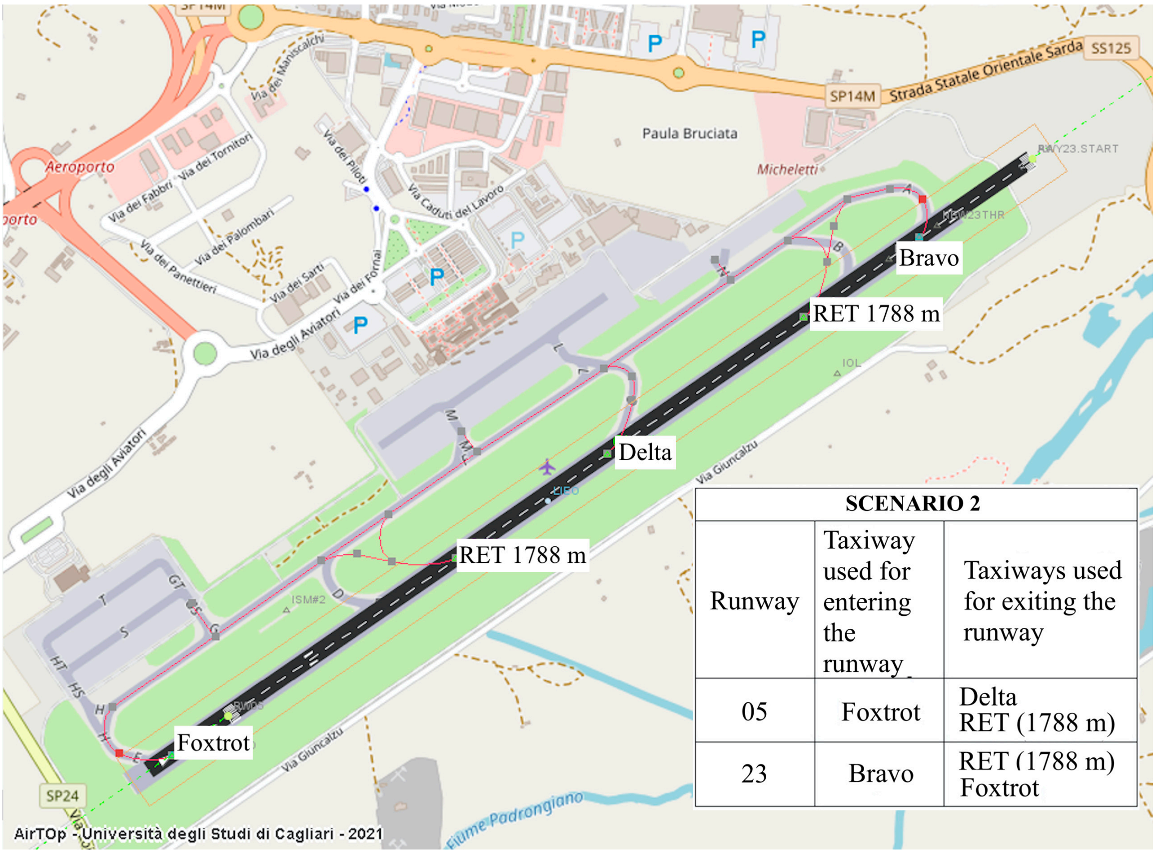
For RWY 05, as shown in Figure 19, the observed capacity increase is 6 mov/h with the RET positioned at 1788 m and 3 mov/h when the RET is positioned at 1431 m. For RWY 23, as shown in Figure 20, an improvement in capacity of 1 mov/h was obtained for the RET positioned at 1788 m and 8 mov/h for the RET positioned at 1650 m.



SCENARIO 1

Runway	Taxiway used for entering the runway	Taxiways used for exiting the runway
05	Foxtrot	Delta Charlie
23	Bravo	Echo Foxtrot

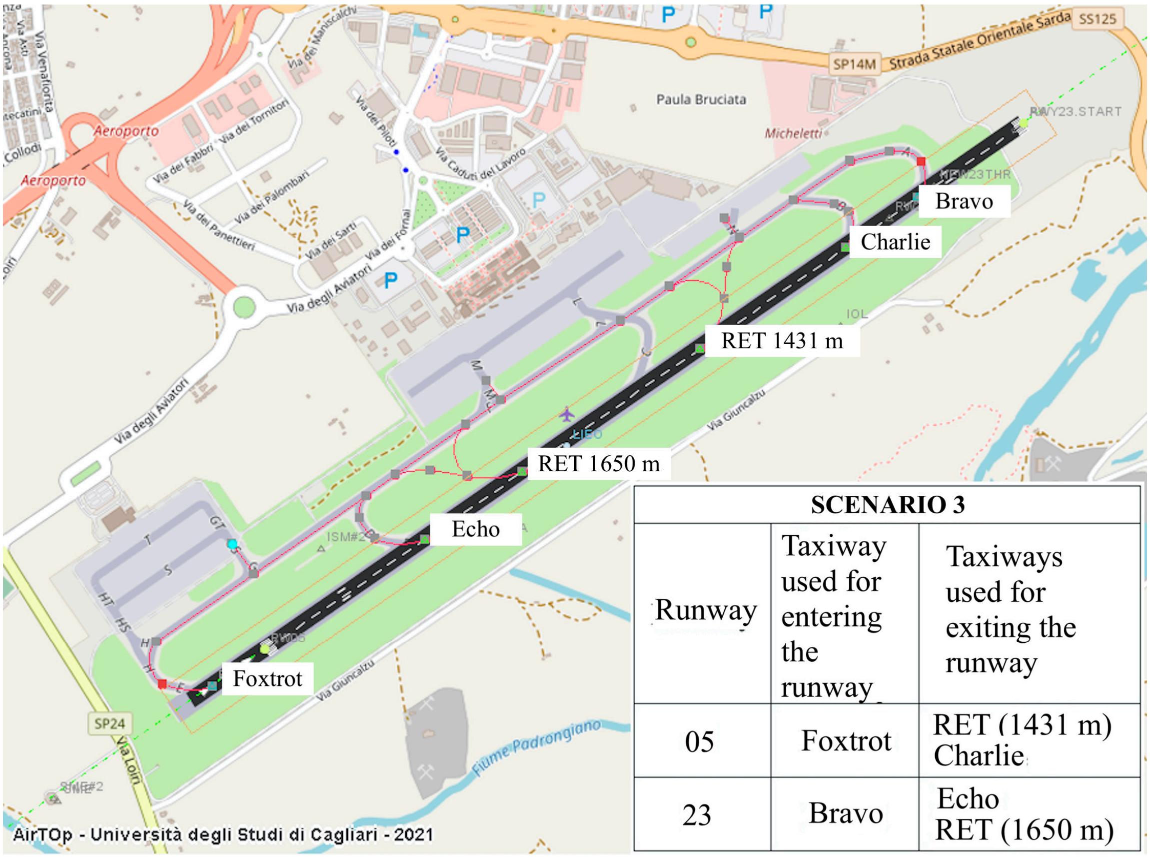
Figure 16. Scenario 1.



SCENARIO 2

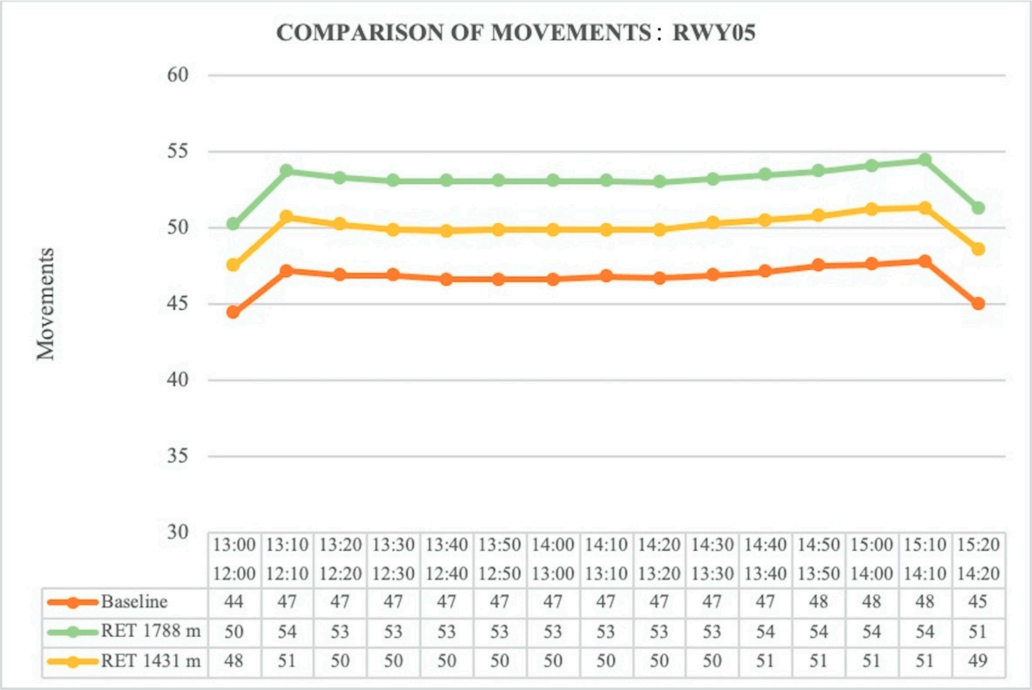
Runway	Taxiway used for entering the runway	Taxiways used for exiting the runway
05	Foxtrot	Delta RET (1788 m)
23	Bravo	RET (1788 m) Foxtrot

Figure 17. Scenario 2.



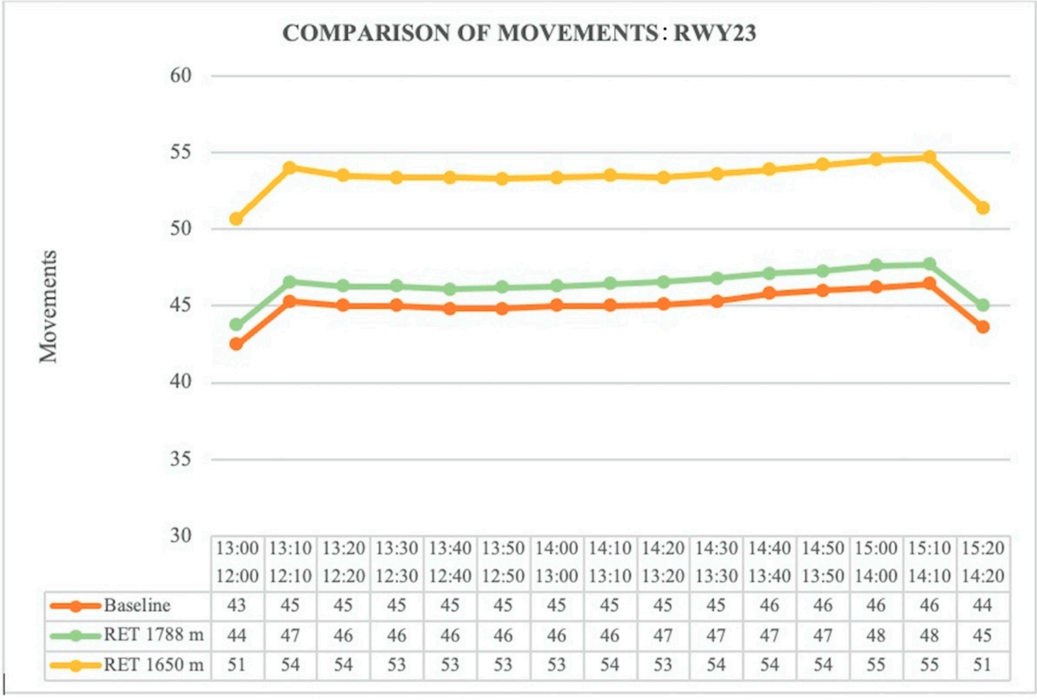
SCENARIO 3		
Runway	Taxiway used for entering the runway	Taxiways used for exiting the runway
05	Foxtrot	RET (1431 m) Charlie
23	Bravo	Echo RET (1650 m)

Figure 18. Scenario 3.



	13:00 12:00	13:10 12:10	13:20 12:20	13:30 12:30	13:40 12:40	13:50 12:50	14:00 13:00	14:10 13:10	14:20 13:20	14:30 13:30	14:40 13:40	14:50 13:50	15:00 14:00	15:10 14:10	15:20 14:20
Baseline	44	47	47	47	47	47	47	47	47	47	47	48	48	48	45
RET 1788 m	50	54	53	53	53	53	53	53	53	53	54	54	54	54	51
RET 1431 m	48	51	50	50	50	50	50	50	50	50	51	51	51	51	49

Figure 19. Comparison of movements for RWY 05.



	13:00 12:00	13:10 12:10	13:20 12:20	13:30 12:30	13:40 12:40	13:50 12:50	14:00 13:00	14:10 13:10	14:20 13:20	14:30 13:30	14:40 13:40	14:50 13:50	15:00 14:00	15:10 14:10	15:20 14:20
Baseline	43	45	45	45	45	45	45	45	45	45	46	46	46	46	44
RET 1788 m	44	47	46	46	46	46	46	46	47	47	47	47	48	48	45
RET 1650 m	51	54	54	53	53	53	53	54	53	54	54	54	55	55	51

Figure 20. Comparison of movements for RWY 23.

The results obtained from the simulations performed through AirTOP show how the greatest improvement of the runway capacity of Costa Smeralda Airport cannot be obtained through a single design strategy but, rather, a mix of the two designed solutions (ICAO and FAA). In fact, the highest improvement for RWY 05 is achieved by placing the RET at 1788 m from the threshold, which is the distance obtained via the ICAO regulations. For RWY 23, the highest capacity increment is obtained by placing the RET at 1650 m from the threshold, which is the distance obtained using REDIM software (FAA). The Pareto diagram (see Figure 21) shows how the number of maximum movements (arrivals and departures) is obtained from the combination of the two designed solutions.

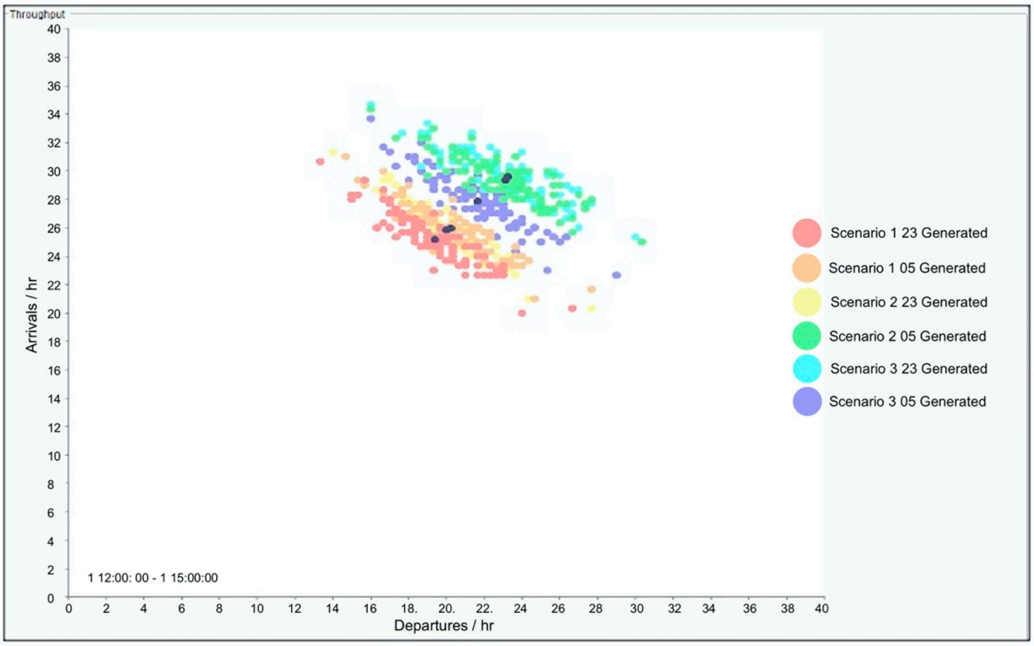


Figure 21. Pareto diagram.

5. Conclusions

With the constant growth in air traffic, the airport managers must develop solutions to optimize the use of the available infrastructure to increase capacity, while focusing on a sustainable and resilient approach. This is especially important for typically seasonal airports or those that have built their business models within a narrow operating band. Airport capacity is a fundamental parameter for the assessment of airport performance. Often, the runway is the critical piece of infrastructure influencing airport capacity, especially for airports with only one runway. The criteria for assessment of capacity vary and depend on the operating conditions, physical characteristics, objectives, and available resources of each individual airport.

In this context, we proposed a solution to respond to increased air demand by applying a new methodology for designing RETs, using Costa Smeralda Airport in Olbia (Sardinia, Italy) as a case study. This airport is highly seasonal and has constantly increasing traffic. The innovation in this study is the application of both ICAO and FAA guidelines in designing RETs and verifying whether their introduction ensures an increase in runway capacity.

After determining the locations for RETs along the runway, this study focused on quantifying the reduction of ROT, which is closely linked to the capacity of the runway. The results show that the introduction of RETs reduces ROT by up to 12 s and 17 s, respectively, for RWY 05 and RWY 23.

Once the ROT values were determined, the runway capacity was evaluated according to the configuration of the current exits and various configurations of RETs based on the new designs. The findings indicate that the best scenario for maximizing capacity results from combining the ICAO and FAA guidelines. For RWY 05, the highest improvement of 6 mov/h is achieved by placing the RET at 1788 m from the threshold, which is the distance obtained through the ICAO regulations. For RWY 23, the highest capacity increment of 8 mov/h is obtained by placing the RET at 1650 m from the threshold, which is the distance obtained through REDIM software (FAA).

The results from using this new approach show that, through both the introduction of RETs and optimizing their position along the runway, the hourly capacity of the runway can effectively be improved, thereby avoiding the need for complex airport expansion. The adopted solution responds to increased air demand while complying with sustainable strategies because it preserves land use and reduces aircraft fuel burn and emissions [58,59]). Indeed, it can be generally noted that there is a correlation between ROT and fuel consumption: minimizing the time aircraft spend idling and taxiing can lead to a reduction in fuel consumption and emissions. It could be very interesting to quantify the reduction in fuel consumption and emissions in relation to a reduction in ROT. However, this is not straightforward, since fuel consumption in airplanes is influenced by numerous factors, such as aircraft type, technology, and design; age at flight; fuel properties; take-off time; the number of crew and passengers; wind speed; etc. [60].

Moreover, it can be observed that the presence of the RETs increases the resilience of Costa Smeralda Airport, which is prone to flooding. The reduced ROT indicates that the runway can be cleared faster in case of flooding.

Although the runway capacity is the fundamental value that indicates the overall capacity of an airport, it is also important to determine, in equivalent detail, the capacity of the elements that constitute the airside, such as the aprons and taxiways. The total capacity is therefore reflected by the capacity of the least efficient component. Therefore, future studies on increasing capacity should consider and characterize the influence of the operating conditions at the boundary, such as the orographic components surrounding the airport, the take-off and approach procedures, and any other elements that may contribute to the determination of airport capacity.

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Conflicts of Interest: The authors Francesca Maltinti, Mauro Coni, and Michela Flore declare no conflicts of interest. Franco Pigozzi is an employee of GEASAR, the company that manages Olbia Costa Smeralda Airport.

References

1. CIA. Available online: https://www.cia.gov/the-world-factbook/countries/world/#transportation (accessed on 28 March 2023).
2. EUROSTAT Challenges of Growth 2018. European Aviation in 2040. Available online: https://www.sipotra.it/wp-content/uploads/2019/12/Air-transport-statistics.pdf (accessed on 30 March 2023).
3. Challenges of Growth 2018. European Aviation in 2040. Available online: https://www.eurocontrol.int/publication/challenges-growth-2018 (accessed on 4 April 2024).
4. International Civil Aviation Organization. *Manual on Global Performance of the Air Navigation System*; Doc. 9883; International Civil Aviation Organization: Montreal, QC, Canada, 2009.
5. Federal Aviation Administration. *Airport Capacity and Delay*; (AC 150 /5060-5); Federal Aviation Administration: Washington, DC, USA, 1983.
6. Stamatopoulos, M.A.; Zografos, K.G.; Odoni, A.R. A decision support system for airport strategic planning. *Transp. Res. Part C* **2004**, *12*, 91–117. [CrossRef]
7. Zou, X.; Cheng, P.; Cheng, N. A simulation model for airport runway capacity estimation. In Proceedings of the 17th International IEEE Conference on Intelligent Transportation Systems (ITSC), Qingdao, China, 8–11 October 2014; pp. 2669–2674. [CrossRef]
8. Di Mascio, P.D.; Rappoli, G.; Moretti, L. Analytical method for Calculating sustainable airport capacity. *Sustainability* **2020**, *12*, 9239. [CrossRef]
9. Irvine, D.; Budd, L.C.; Pitfield, D.E. A Monte-Carlo approach to estimating the effects of selected airport capacity options in London. *J. Air Transp. Manag.* **2014**, *42*, 1–9. [CrossRef]
10. Skorupski, J.; Wierzbicki, H. Airport capacity increase via the use of braking profiles. *Transp. Res. Part C* **2017**, *80*, 467–484. [CrossRef]
11. Pavlin, S.; Žužić, M.; Pavičić, S. Runway occupancy time as element of runway capacity. *Promet-Traffic Transp.* **2006**, *18*, 293–299.
12. Katsigiannis, F.A.; Zografos, K.G. Optimising airport slot allocation considering flight-scheduling flexibility and total airport capacity constraints. *Transp. Res. Part B* **2021**, *146*, 50–87. [CrossRef]
13. Katsigiannis, F.A.; Zografos, K.G.; Fairbrother, J. Modelling and solving the airport slot-scheduling problem with multi-objective, multi-level considerations. *Transp. Res. Part C* **2021**, *124*, 102914. [CrossRef]
14. Barnhart, C.; Fearing, D.; Odoni, A.; Vaze, V. Demand and capacity management in air transportation. *EURO J. Transp. Logist.* **2012**, *1*, 135–155. [CrossRef]
15. Vyshinsky, V.V. Flight safety, aircraft vortex wake and airport operation capacity. *Air Space Eur.* **2001**, *3*, 206–208. [CrossRef]
16. Butler, V.; Poole, R.W.J. *Increasing Airport Capacity without Increasing Airport Size*; Reason Foundation: Los Angeles, CA, USA, 2008.
17. Chu, Z.; Zhou, Y.C. The effect of adopting the Next Generation Air Transportation System (NextGen) on air travel performance. *Reg. Sci. Urban Econ.* **2023**, *102*, 103918. [CrossRef]
18. Pan, W.; Zhang, H.; Yin, H.; Wu, T.; Yin, Z. Study on capacity improvement of close range dual runway of Shuangliu airport under new wake classification standard (RECAT). In Proceedings of the IOP Conference Series: Earth and Environmental Science, Xi'an, China, 18–19 December 2020; p. 693. [CrossRef]
19. Holzäpfel, F.; Strauss, L.; Schwarz, C. Assessment of dynamic pairwise wake vortex separations for approach and landing at Vienna airport. *Aerosp. Sci. Technol.* **2021**, *112*, 106618. [CrossRef]

20. International Civil Aviation Organization. *Aerodrome Design and Operations*; Annex 14, I; International Civil Aviation Organization: Montreal, QC, Canada, 2018.
21. International Civil Aviation Organization. *Aerodrome Design Manual*; Doc. 9157. Taxiways, Aprons and Holding Bays, 2; International Civil Aviation Organization: Montreal, QC, Canada, 2020.
22. Federal Aviation Administration. *Airport Design*; (AC 150/5300-13); Federal Aviation Administration: Washington, DC, USA, 1989.
23. Ente Nazionale per l'Aviazione Civile [Italian Civil Aviation Authority]. *Dati di Traffico Degli Scali Italiani [Traffic Data of Italian Airports], 2009–2019*. Available online: https://www.enac.gov.it/aeroporti/infrastrutture-aeroportuali/dati-di-traffico (accessed on 12 March 2021).
24. SardegnaGeoportale. Available online: https://www.sardegnageoportale.it/ (accessed on 23 March 2023).
25. ACRP, FAA, McKee, Dresser Camp, & Synergy Consulting Services. *Handbook for Considering Practical Greenhouse Gas Emission Reduction Strategies for Airports Report 56*; Transportation Research Board: Washington, DC, USA, 2011.
26. Monsalud, A.; Ho, D.; Rakas, J. Greenhouse gas emissions mitigation strategies within the airport sustainability evaluation process. *Sustain. Cities Soc.* **2015**, *14*, 414–424. [CrossRef]
27. Baxter, G.; Srisaeng, P.; Wild, G. Sustainable airport energy management: The case of Kansai International Airport. *Int. J. Traffic Transp. Eng.* **2018**, *8*, 334–358.
28. Baxter, G.; Srisaeng, P.; Wild, G. An assessment of airport sustainability, part 2—Energy management at Copenhagen Airport. *Resources* **2018**, *7*, 32. [CrossRef]
29. Ozdemir, G.; Filibeli, A. Basic principles of CO_2 emission calculations at airports: A case study from Turkey. *Int. J. Glob. Warm.* **2014**, *6*, 315–324. [CrossRef]
30. Kılkıs, B. Energy consumption and CO2 emission responsibilities of terminal buildings: A case study for the future Istanbul International Airport. *Energy Build.* **2014**, *76*, 109–118. [CrossRef]
31. Postorino, M.N.; Mantecchini, L. A transport carbon footprint methodology to assess airport carbon emissions. *J. Air Transp. Manag.* **2014**, *37*, 76–86. [CrossRef]
32. Greer, F.; Rakas, J.; Arpad Horvath, A. Airports and environmental sustainability: A comprehensive review. *Environ. Res. Lett.* **2020**, *15*, 103007. [CrossRef]
33. Bahman, N. Airport sustainability through life cycle assessments: A systematic literature review. *Sustain. Dev.* **2023**, *31*, 1268–1277. [CrossRef]
34. Mancinelli, E.; Canestrari, F.; Graziani, A.; Rizza, U.; Passerini, G. Sustainable Performances of Small to Medium-Sized Airports in the Adriatic Region. *Sustainability* **2021**, *13*, 13156. [CrossRef]
35. De Castro Carvalho, I.; Calijuri, M.L.; Assemany, P.P.; Silva, M.D.F.M.E.; Neto, R.F.M.; da Fonseca Santiago, A.; de Souza, M.H.B. Sustainable airport environments: A review of water conservation practices in airports. *Resour. Conserv. Recycl.* **2013**, *74*, 27–36. [CrossRef]
36. Baxter, G.; Srisaeng, P.; Wild, G. An assessment of airport sustainability: Part 3—Water management at Copenhagen Airport. *Resources* **2019**, *8*, 135. [CrossRef]
37. Somerville, A.; Baxter, G.S.; Richardson, S.; Wild, G. Sustainable water management at major Australian regional airports: The case of Mildura Airport. *Aviation* **2015**, *19*, 83–89. [CrossRef]
38. Ribeiro, E.N.; de Sousa, W.C.; de Julio, M.; Irrazabal, W.U.; Nolasco, M.A. Airports and environment: Proposal of wastewater reclamation at Sao Paulo International Airport. *Clean-Soil Air Water* **2013**, *41*, 627–634. [CrossRef]
39. Couto, E.D.A.; Calijuri, M.L.; Assemany, P.P.; da Fonseca Santiago, A.; Lopes, L.S. Greywater treatment in airports using anaerobic filter followed by UV disinfection: An efficient and low cost alternative. *J. Clean. Prod.* **2015**, *106*, 372–379. [CrossRef]
40. Burbidge, R. Adapting European airports to a changing climate. *Transp. Res. Procedia* **2016**, *14*, 14–23. [CrossRef]
41. Poo, M.C.P.; Yang, Z.; Dimitriu, D.; Qu, Z. Review on seaport and airport adaptation to climate change: A case on sea level rise and flooding. *Mar. Technol. Soc. J.* **2018**, *52*, 23–33. [CrossRef]
42. Coffel, E.D.; Thompson, T.R.; Horton, R.M. The impacts of rising temperatures on aircraft takeoff performance. *Clim. Change* **2017**, *144*, 381–388. [CrossRef]
43. Lui, G.N.; Hon, K.K.; Liem, R.P. Weather impact quantification on airport arrival on-time performance through a Bayesian statistics modeling approach. *Transp. Res. Part C Emerg. Technol.* **2022**, *143*, 103811. [CrossRef]
44. Turner, M.E. *Airport Waste Management and Recycling Practices*; National Academies of Sciences, Engineering, and Medicine Press: Washington, DC, USA, 2018. [CrossRef]
45. Baxter, G.; Srisaeng, P.; Wild, G. An assessment of airport sustainability, part 1—Waste management at Copenhagen Airport. *Resources* **2018**, *7*, 21. [CrossRef]
46. Lam, C.M.; Yu, I.K.M.; Medel, F.; Tsang, D.C.W.; Hsu, S.C.; Poon, C.S. Life-cycle cost-benefit analysis on sustainable food waste management: The case of Hong Kong International Airport. *J. Clean. Prod.* **2018**, *187*, 751–762. [CrossRef]
47. TRB's Airport Cooperative Research Program (ACRP). *Report 147: Climate Change Adaptation Planning: Risk Assessment for Airport*; Transportation Research Board: Washington, DC, USA, 2015.
48. United Nations (UN). *Mobilizing Sustainable Transport for Development, Analysis and Policy Recommendations*; Outlook Report, High-Level Advisory Group on Sustainable Transport; United Nations (UN): New York, NY, USA, 2018; Available online: https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=2375&menu=35 (accessed on 26 September 2023).

49. Dimitriou, D.; Voskaki, A. Regional airports 'environmental management: Key messages from the evaluation of ten European airports. *Int. J. Sustain. Dev. Plan.* **2010**, *5*, 149–161. [CrossRef]
50. Dimitriou, D.; Karagkouni, A. Assortment of Airports' Sustainability Strategy: A Comprehensiveness Analysis Framework. *Sustainability* **2022**, *14*, 4217. [CrossRef]
51. International Air Transport Association (IATA). Airport Environmental Sustainability—Nov 2022. Available online: https://www.iata.org/contentassets/d1d4d535bf1c4ba695f43e9beff8294f/airport-environmental-sustainability-policy.pdf (accessed on 12 December 2022).
52. O'Flynn, S. *Airport Capacity Assessment Methodology*; The European Organisation for the Safety of Air Navigation: Brussels, Belgium, 2016.
53. European Union Aviation Safety Agency. A.S. Agency. *Easy Access Rules for Aerodromes*; (Regulation (EU) No 139/2014); EUR-Lex: Brusselles, Belgium, 2019.
54. Koščák, P.; Kolesár, J.; Ferenc, J. Increasing the capacity of the runway. In Proceedings of the X International New Trends in Aviation Development Conference, Košice, Slovachia, 13–14 September 2012.
55. Trani, A.; Hobeika, A.; Sherali, H.; Kim, B.; Sadam, C. *Runway Exit Designs for Capacity Improvement Demonstrations—Phase I*; National Technical Information Service: Springfield, WV, USA, 1990.
56. Trani, A.; Hobeika, A.; Kim, B.; Nunna, V.; Zhong, C. *Runway Exit Designs for Capacity Improvement Demonstrations—Phase II*; National Technical Information Service: Springfield, WV, USA, 1992.
57. Trani, A.; Cao, J.; Terrago-Trani, M. Limited Study of Flight Simulation Evaluation of High-Speed Runway Exits. *Transp. Res. Rec. J. Transp. Res. Board* **1999**, *1662*, 82–89. [CrossRef]
58. Di Mascio, P.; Corazza, M.V.; Rosa, N.R.; Moretti, L. Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports. *Sustainability* **2022**, *14*, 9692. [CrossRef]
59. Corazza, M.V.; Di Mascio, P.; Esposito, G. Airports as Sensitive Areas to Mitigate Air Pollution: Evidence from a Case Study in Rome. *Environments* **2022**, *9*, 108. [CrossRef]
60. Hassan, T.H.; Sobaih, A.E.E.; Salem, A.E. Factors Affecting the Rate of Fuel Consumption in Aircrafts. *Sustainability* **2021**, *13*, 8066. [CrossRef]