Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

Programa de Doctorado en Economía y Empresa

TESIS DOCTORAL

Algoritmos para la secuenciación de operaciones de aterrizaje en aeropuertos con restricciones ambientales

Algorithms for scheduling landing operations in airports with environmental restrictions

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RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

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RESUMEN (en español)

Una de los mayores obstáculos para la construcción de nuevos aeropuertos y la expansión de la capacidad de la pista son las preocupaciones ambientales, especialmente el ruido. El objetivo principal de esta Tesis es el estudio de las propuestas para la reducción del impacto del ruido del transporte aéreo y la implementación de nuevos modelos y algoritmos de programación que muestren las capacidades de mejora en este campo.

En la revision de la literatura existe una laguna de los trabajos previos que tratan de recopilar y analizar las aproximaciones para reducir el impacto del ruido del transporte aéreo. Así la realizacion de una revisión extensa de la literatura se convirtió en uno de los objetivos principales de la Tesis. Se encontró que las políticas de regulación o los cambios en los procedimientos de operación son una de las mejoras más habitualmente implementadas para minorar el impacto del ruido. También se realizan muchos esfuerzos para modelar, monitorizar y desarrollar herramientas de simulación para la estimación del ruido. Sin embargo, existe aún un amplio campo de investigación en algoritmos de optimización que ayuden a los controladores a programar las operaciones del aeropuerto sin descuidar las restricciones de ruido ni disminuir el ratio aceptable de salidas y llegadas.

Dado que la naturaleza dinámica de los aeropuertos exige el desarrollo de algoritmos de programación que puedan ser replanificados cuando ocurren nuevos eventos de tráfico, otro de los objetivos principales de esta investigación es diseñar un algoritmo que se pueda usar en un entorno real, lo que implica que los resultados deben mostrase en línea, teniendo en cuenta las restricciones de las operaciones reales de control del tráfico aéreo. Se ha desarrollado un algoritmo que minimiza las desviaciones de los horarios programados de los vuelos de llegada y salida, bajo la separación de vórtice de estela y las restricciones de desplazamiento de posición restringida. El algoritmo desarrollado utilizando recocido simulado obtiene una mejora del 95% en los retrasos en menos de un segundo de cómputo para las instancias de prueba generadas. Con respecto a los entornos reales, muestra una mejora del 30% en los retrasos de tiempo durante una secuencia de tres horas en el aeropuerto de Londres Gatwick.

Por un lado, otra de las conclusiones de la revisión de la literature es que el ruido de los aviones es la causa principal de la oposición de la comunidad a las operaciones del aeropuerto, convirtiéndose en un problema crítico que afecta la sostenibilidad del crecimiento futuro del tráfico aéreo. Por otro lado, las operaciones de planificación que se centran exclusivamente en el impacto del ruido pueden dar como resultado un aumento del consumo de combustible o de los retrasos. Teniendo esto en cuenta, y también el algoritmo anterior, el objetivo final de esta Tesis fue desarrollar un modelo bi-objetivo adecuado para el aterrizaje de aeronaves, que encuentre una secuencia que minimice el impacto del ruido, el consumo total de combustible y las demoras, bajo la restricción de la separación de estela turbulenta y con la restricción de desplazamiento de posición. Los resultados de este modelo se comparan con las operaciones reales en un relevante aeropuerto europeo para evaluar el nivel potencial de mejoras. Al comparar con datos reales del aeropuerto Adolfo Suárez Madrid-Barajas, la investigación muestra mejoras potenciales de hasta un 4,5% de reducción del consumo total de combustible (sin aumentar los niveles de ruido) solo modificando la secuencia de llegadas, y hasta un 43% de la reducción del impacto del ruido sobre las poblaciones estudiadas (sin consumo extra de combustible).

Con esta Tesis queremos enfatizar y probar que existen alternativas para mejorar el impacto del ruido sin afectar la capacidad de los aeropuertos y sin ser necesario cambiar las regulaciones o los procedimientos operativos existentes.

RESUMEN (en Inglés)

One of the biggest barriers the building of new airports and expanding runway capacity is environmental concerns, especially noise. The major purpose of this Thesis is the study of previous approaches to air transport noise impact reduction and the implementation of new scheduling models and algorithms that show the capabilities of improvement in this field.

Since there were no previous studies in the literature that gather and analyze previous approaches to reduce air transport noise impact, doing an extensive literature review became one major goal of the Thesis. Regulation policies or changes in operation procedures were found to be one of the most popular improvements implemented for reducing impact noise. Lots of efforts are also done to model, monitor and develop simulation tools for noise estimation. However, there is a large field of research in optimization algorithms that help controllers schedule airport operations by considering noise restrictions in order not to decrease the acceptance ratio of departures and arrivals.

Since the dynamic nature of airports demands the development of scheduling algorithms that are amenable to replanning when new traffic events occur, another main objective of this research is to design an algorithm that can be used in a real environment, which implies that results must be delivered online, and that takes into account real restrictions in air traffic control operations. An algorithm that minimizes deviations from the scheduled times of arrival and departure flights, under wake vortex separation and Constrained Position Shifting restrictions has been developed. The algorithm developed using simulated annealing obtains a 95% improvement on time delays in less than one second of computation for the test instances generated. Regarding real environments, it shows an improvement of 30% in the time delays during a sequence of three hours at London Gatwick airport.

On the one hand, another of the review conclusions is that aircraft noise is the single major cause of community opposition to airport operations, becoming a critical issue that affects the sustainability of future air traffic growth. On the other hand, planning operations exclusively focusing on noise impact may result in an increase of fuel consumption or delays. Taking this into account and the previous algorithm, the final

major goal of this Thesis was to develop a suitable bi-objective model for landing aircraft, which finds a schedule that minimizes noise impact, total fuel consumption and delays, under wake vortex separation and Constrained Position Shifting restrictions. The results of this model are compared with real operations in a major European airport to assess the potential level of improvements. By comparing with real data from Adolfo Suárez Madrid-Barajas airport, the research shows potential improvements of up to 4.5% reduction of total fuel consumption (without increasing noise levels) only by modifying the sequence of arrivals, and up to 43% (without extra fuel consumption) of reduction in noise impact over the populations under study.

With this Thesis we want to emphasize and prove that there are alternatives to improve noise impact without impacting the capacity of airports and without being necessary to change regulations or operational procedures.

SR. PRESIDENTE DE LA COMISIÓN ACADÉMICA DEL PROGRAMA DE DOCTORADO EN ECONOMÍA Y EMPRESA

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Curso de inicio de los estudios de doctorado	**2013**

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Prólogo

Esta tesis se presenta como compendio de tres publicaciones en revistas de reconocido prestigio. La estructura del documento que se presenta sigue las directrices establecidas por la Universidad de Oviedo respecto al formato que debe seguir una Tesis presentada en esta institución.

Uno de los mayores obstáculos para la construcción de nuevos aeropuertos y el aumento de la capacidad (despegues y aterrizajes) de los existentes son los problemas ambientales, en particular, el ruido. El objetivo principal de esta Tesis es analizar qué se ha hecho hasta ahora en materia de reducción del impacto que genera el ruido procedente del transporte aéreo y la implementación de nuevos modelos y algoritmos de secuenciación que pongan de manifiesto la capacidad de mejora en este campo.

Puesto que no existían estudios previos en la literatura que recopilaran y analizaran los trabajos que se han hecho hasta el momento con el objetivo de reducir el impacto del ruido generado por el transporte aéreo, uno de los propósitos principales de esta Tesis ha sido hacer una revisión extensa de la literatura en esta materia. Las políticas de regulación o los cambios en los procedimientos operacionales del aeropuerto resultan ser una de las mejoras más populares implementadas para reducir el impacto del ruido. También se ha estudiado extensamente en la literatura existente el modelado, la monitorización y el desarrollo de herramientas de simulación para mejorar la estimación del ruido generado por los aviones. Sin embargo, existe un amplio campo de investigación en algoritmos de optimización que ayuden a los controladores a secuenciar los aviones en las operaciones de aterrizaje y despegue teniendo en cuenta restricciones de ruido, para así, no disminuir la tasa de aceptación de salidas y llegadas.

Dada la dinámica de los aeropuertos, es necesario desarrollar algoritmos de secuenciación que puedan ser replanificados en tiempo real. Por ello, otro de los objetivos de esta investigación es diseñar algoritmos que puedan ser utilizados en un entorno real, lo que implica que los resultados deben se generados de forma prácticamente inmediata, teniendo en cuenta además las restricciones reales impuestas por la operativa de control de tráfico aéreo. Se ha desarrollado un algoritmo que, utilizando Recocido Simulado, minimiza las desviaciones en los horarios de llegada y salida de los vuelos programados, bajo restricciones de separación causadas por la estela turbulenta y la limitación de cambio respecto a la posición inicial del avión en la secuencia programada.

Una de las conclusiones de la revisión de la literatura es que el ruido de los aviones es la causa principal de oposición entre las poblaciones colindantes a un aeropuerto al aumento de las operaciones en el mismo, convirtiéndose en un problema crítico que afecta la sostenibilidad del crecimiento del tráfico aéreo. Sin embargo, considerar únicamente el impacto del ruido en los criterios de secuenciación de aviones puede implicar un aumento del consumo de combustible, o más retrasos. Teniendo esto en cuenta y también los resultados del algoritmo anteriormente descrito, el objetivo final de esta Tesis fue desarrollar un modelo bi-objetivo adecuado para el aterrizaje de aeronaves, que encuentre una secuencia que minimice el impacto del ruido, el consumo total de combustible y los retrasos, bajo restricciones de estela turbulenta y la limitación de cambio respecto a la posición inicial del avión en la secuencia programada. Los resultados de este modelo se comparan con datos reales de una secuencia de llegadas del aeropuerto Adolfo Suárez Madrid-Barajas, uno de los más importantes en Europa.

Con esta Tesis se ha demostrado que existen alternativas para mejorar el impacto del ruido producido por las operaciones de aproximación y aterrizaje a un aeropuerto sin perjudicar la capacidad del mismo y sin ser necesario cambiar la regulación o los procedimientos operativos del aeropuerto.

Esta tesis está dividida en cuatro capítulos. En el primero se hace una introducción a la temática y la literatura utilizada para apoyar las investigaciones y desarrollos llevados a cabo, estableciendo el marco teórico de la investigación. El segundo capítulo define los objetivos de la Tesis, mientras que los resultados se describen en el tercero. Las conclusiones forman el cuarto capítulo, mientras en el quinto se presentan las referencias consultadas. Además, hay dos anexos en los que se incluyen las publicaciones que conforman la Tesis, y un informe con los factores de impacto de las revistas en las que se publicaron.

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1. **Introducción**

Según las estadísticas anuales compiladas por la ICAO (*International Civil Aviation Organization*), 4.100 millones de pasajeros viajaron en vuelos regulares en 2017. Asia y el Pacífico son las principales regiones al contar con el 34% del tráfico mundial, seguida de Europa con el 27% (ICAO, 2019).

Airbus's Global Market Forecast 2015-2034 destaca que, en la actualidad, 47 aeropuertos concentran más del 90% de los vuelos y casi un millón de pasajeros al día, y 39 de esos 47 experimentan altos niveles de congestión (Airbus, 2014). Se espera que la demanda de tráfico aéreo se duplique en Europa y EE.UU., y quizás se triplique en algunas regiones, en los próximos 15 años (Airbus, 2014). Y no sólo eso. Se estima que, en 2040, habrá una demanda de 1,5 millones de vuelos que no se pueda satisfacer, es decir, 160 millones de pasajeros que no puedan volar (Eurocontrol, 2018).

Uno de los desafíos que afronta la industria de la aviación, por tanto, es el crecimiento de la demanda de tráfico aéreo, que provoca una alta congestión de muchos aeropuertos, principalmente *hubs* (Flores-Fillol, 2010). Satisfacer el aumento de la demanda es un reto para todos los *stakeholders* de la industria. Las aerolíneas se esfuerzan por aumentar su eficiencia, con aviones de última tecnología y ocupando cada asiento disponible, alcanzando una carga media de un 80% por avión. La construcción de nuevos aeropuertos y la expansión de la capacidad de los existentes es otra alternativa limitada por las preocupaciones ambientales, como son la perturbación del ruido, las emisiones, la contaminación del agua o la destrucción del hábitat (Laurenzo, 2006).

Puesto que los aeropuertos y los controladores aéreos tienen recursos limitados, el tráfico aéreo debe planificarse cuidadosamente para satisfacer el mayor número posible de demanda (Artiouchine *et al.*, 2008). La gestión de tráfico aéreo contribuye a su seguridad, eficiencia, eficacia, rentabilidad y sostenibilidad ambiental. Mediante la gestión de tráfico aéreo, los diversos actores del sistema (compañías aéreas, organismos de gestión de tráfico aéreo, aeropuertos, instituciones públicas, sociedad) colaboran para conciliar las limitaciones de recursos del sistema con las prioridades económicas y ambientales (Bertsimas *et al*., 2011). La mejor alternativa, por tanto, para equilibrar la demanda y la capacidad de los aeropuertos con las restricciones medioambientales es hacer un uso más eficiente de la infraestructura actual por parte de la operativa de gestión de tráfico aéreo (ATM – *Air Traffic Management*).

Dentro de estas exigencias, uno de los mayores obstáculos para la construcción de nuevos aeropuertos y el aumento de su capacidad (despegues y aterrizajes) es la perturbación que genera el ruido en la calidad de vida de las comunidades cercanas (Ho-Huu *et al*., 2017; Arntzen y Simons, 2014; Visser *et al*., 2008). El ruido de las aeronaves es una perturbación producida por cualquier aeronave o sus componentes, durante el vuelo, el rodaje, el aterrizaje y el despegue. El ruido, descrito como sonido no deseado (Schmidt, 2005), tiene varios efectos adversos en los seres humanos, como pérdida de la audición, interferencias en el sueño, niveles elevados de estrés, ansiedad, depresión, hipertensión (Janssen *et al*., 2014; Salah, 2014; Ozkurt *et al*., 2014; Vogiatzis, 2012). De hecho, varios estudios muestran una correlación entre la exposición al ruido de los aviones y las enfermedades cardiovasculares o psicológicas (Postorino y Mantecchini, 2015).

Durante los últimos años, la expansión de las ciudades y la cercanía de nuevas zonas residenciales a los aeropuertos existentes implica un incremento en el número de personas afectadas por ruidos indeseables (Ganic *et al*., 2015a). El ruido de los aviones es un factor relevante en la oposición de la sociedad a las operaciones aeronáuticas y a la mejora de la capacidad de los aeropuertos, convirtiéndose en una barrera para la sostenibilidad del crecimiento del tráfico aéreo futuro (Arntzen y Simons, 2014; Visser *et al*., 2008).

En general, el ruido de la aeronave está influenciado por factores específicos, como las condiciones atmosféricas, la frecuencia de vuelos, el tipo de aeronave o la trayectoria del vuelo. Sari *et al*. (2014) identifican tres fuentes principales de este ruido: el producido por el motor de la aeronave, el ruido aerodinámico y el generado por otras fuentes mecánicas, mientras que Arntzen y Simons (2014) y Prats *et al*. (2009) las agrupan en dos categorías: el ruido del motor y el ruido del fuselaje, consecuencia de la fricción del aire con la aeronave.

En un mundo ideal, una aeronave despegaría, ascendería a su altitud de crucero óptima y, si fuera posible, mantendría la altitud de crucero antes de comenzar un descenso constante, con el motor inactivo hasta el aterrizaje. Sin embargo, en la realidad, las aeronaves deben coordinarse con los responsables de gestión de tráfico aéreo y, cuando hay retrasos por congestión, se obliga a las aeronaves a pasar más tiempo en altitudes más bajas y desviarse de su trayectoria prevista (Laurenzo, 2006). La combinación de bajas altitudes y motores activos conduce al aumento del impacto de ruido aerodinámico durante la fase de llegada del vuelo (Coppenbarger, 2007), incrementado por el despliegue del tren de aterrizaje a bajos niveles de altitud. Aunque se espera que los avances mecánicos permitan reducir el ruido de los motores de las aeronaves (principal causa de ruido durante los despegues), éstos no mejorarán la reducción del ruido durante los aterrizajes.

Además de estas medidas en la fuente, una segunda opción que se utiliza actualmente para reducir el impacto del ruido en el foco es el aislamiento acústico de los edificios (Ganic *et al*., 2015b). Sin embargo, a fin de conciliar las limitaciones de recursos del sistema con las prioridades económicas y ambientales, todos los *stackeholders* involucrados (gobiernos, fabricantes de aeronaves, ATM, sociedad, aeropuertos) deben colaborar aportando mejoras reductoras de este impacto al entorno (Bertsimas *et al*., 2011).

Una tercera alternativa presente en los aeropuertos con mayores problemáticas de ruido en las poblaciones colindantes, son todas las restricciones operativas impuestas por la gestión del tráfico aéreo (limitar los aterrizajes y despegues en horario nocturno, prohibir el uso de determinadas rutas de aproximación y despegue para no sobrevolar determinadas poblaciones, establecer tarifas de uso del aeropuerto según la categoría de ruido de las aeronaves, entre otras). Los controladores tienen, por tanto, una flexibilidad limitada para secuenciar las aeronaves ya que están sujetos a requisitos de seguridad, equidad y eficiencia. La seguridad se logra manteniendo la separación mínima establecida entre las aeronaves; la eficiencia es equivalente a lograr un alto rendimiento y/o un bajo retraso promedio; y la equidad se modela limitando la desviación de un orden nominal o minimizando la varianza en el retraso.

Teniendo en cuenta la literatura, Anagnostakis *et al*. (2001) distingue, del mismo modo, dos tipos de restricciones, clasificándolas en restricciones duras y blandas. Las limitaciones inviolables (restricciones duras) son las que afectan a la seguridad. Uno de los factores que añade más limitaciones de esta índole en la frecuencia de despegues y aterrizajes es la estela turbulenta. Sus efectos son generalmente proporcionales al peso de la aeronave y cuanto más ligeros son los aviones que suceden a un avión pesado, más sufren sus efectos, por lo que se exige una mayor separación de la aeronave anterior (Artiouchine *et al*., 2008). Los tiempos de separación requeridos entre las aeronaves sucesivas dependen entonces del tipo de los dos aviones involucrados. El orden en que la aeronave aterriza juega, por tanto, un papel importante en la capacidad del aeropuerto (Bäuerle *et al*., 2007).

Las restricciones blandas, aquellas que pueden ser ignoradas sin afectar a la seguridad, deben respetarse en la medida de lo posible para no dañar la calidad de la solución, reduciendo así la eficiencia y equidad de la secuencia planificada. Un ejemplo son los horarios programados (o *slots*). Cada avión tiene asignada una hora programada de salida o llegada. En la programación de la secuencia, los vuelos tienen un horario óptimo de salida o llegada que responde a la demanda, las flotas disponibles y las rutas, entre otros factores. Sin embargo, los límites en la capacidad de los aeropuertos se traducen en que algunos vuelos no pueden operar a la hora prevista. Por lo tanto, es válido modificar los horarios de algunos vuelos con respecto a sus horarios óptimos (Cao y Kanafani, 2000).

El desafío radica en lograr simultáneamente seguridad, eficiencia y equidad, que a menudo son objetivos contrapuestos, y hacerlo en un tiempo razonable (Anagnostakis *et al*., 2001). Por tanto, es preciso desarrollar algoritmos de secuenciación que puedan ser replanificados en tiempo real (Mukherjee y Hansen, 2009) tras la aparición de nuevos eventos, como el cambio de sector aéreo controlado o la actualización de los datos del vuelo (Balakrishnan y Chandran, 2010).

Sin embargo, los retrasos suelen ser impredecibles y hacen que sea casi imposible secuenciar los aviones con precisión y anticipación (Artiouchine *et al*., 2008). De hecho, la secuencia inicial debe replanificarse cuando los aviones están lo suficientemente cerca del aeropuerto, es decir, cuando se aproximan a *TRACON* (*Terminal Radar Approach Control*) -a 5 y 50 millas de distancia del aeropuerto- o en tierra (ya que los retrasos en tierra cuestan la mitad que en el aire, Inniss y Ball, 2004). Por lo tanto, los retrasos causados por la congestión se materializan en tierra, donde las aeronaves deben esperar antes de acceder a una pista de despegue, o durante el vuelo, donde se desvían de su trayectoria prevista a la espera de poder aterrizar. Estos retrasos por congestión pueden gestionarse a nivel estratégico (mediante la expansión de las pistas o aplicando estándares de separación más cortos), a nivel pre-táctico (dividiendo flujos y sectores) o a nivel táctico (mediante la re-secuenciación de los vuelos) (Gwiggner y Nagaoka, 2014).

Lieder *et al*. (2015) mencionan que no se han propuesto métodos eficientes en la literatura para los problemas de aterrizaje que sean capaces de resolver grandes instancias de datos en tiempo real. Los enfoques más comunes para la resolución de este tipo de problemas son la programación dinámica (Dear, 1976), algoritmos de ramificación y poda (*B&B – Branch & Bound*) (Abela *et al*., 1993); *Mixed-Integer Programming* (Beasley *et al*., 2000) y soluciones heurísticas (Pinol y Beasley, 2006). Sin embargo, estas implementaciones producen soluciones “buenas” en tiempos de computación cortos (pero no en tiempo real) y no son adecuados para grandes problemas y, por lo tanto, no son útiles para aplicar en entornos reales.

En esta Tesis, se diseñan algoritmos que puedan ser utilizados en un entorno real, lo que implica que los resultados deben de estar disponibles de forma prácticamente inmediata, teniendo en cuenta además las restricciones reales impuestas por la operativa de control de tráfico aéreo, como son las restricciones mínimas horizontales oficiales de separación entre aeronaves, los requisitos ambientales, y el criterio de equidad que se conseguirá mediante el *Constraint Position Shifting* (CPS) que limita el número máximo de posiciones en las que se puede alterar la posición de un vuelo con respecto a la secuencia prevista inicialmente.

2. **Objetivos**

El objetivo principal de esta Tesis es analizar qué se ha hecho hasta ahora en materia de reducción del impacto que genera el ruido procedente del transporte aéreo y la implementación de nuevos modelos y algoritmos de secuenciación que pongan de manifiesto la capacidad de mejora en este campo permitiendo la toma de decisiones en tiempo real. Para lograr este objetivo general, se desglosa el mismo en varios objetivos específicos:

- Realizar una revisión bibliográfica en profundidad para analizar los estudios previos que tratan de reducir el impacto ambiental del ruido generado por el tráfico aéreo.

- Desarrollar un algoritmo para secuenciar los vuelos bajo restricciones operativas reales que proporcione resultados en tiempo real y mejore la capacidad de la pista.

- Desarrollar un modelo para aterrizajes que minimice el impacto del ruido, el consumo total de combustible y los retrasos.

2.1. Estudios previos sobre el impacto del ruido en aeropuertos

Una la revisión de la literatura previa existente es útil para proporcionar una perspectiva histórica del área de investigación bajo estudio, así como un punto de referencia para comparar los resultados con otros hallazgos (Creswell, 2013). En este caso, se ha aplicado una revisión sistemática de la literatura (*SLR – Systematic Literature Review*) (Denyer y Tranfield, 2009) la cual consta de cinco pasos. La primera etapa es la definición del contexto. Esto corresponde al estudio de cómo la reducción de ruido impacta en la capacidad de los aeropuertos desde el punto de vista de las operaciones aeronáuticas.

Los dos siguientes pasos son la ubicación de los estudios y su selección y evaluación. En este caso, la búsqueda bibliográfica se realizó a través de la base de datos Scopus. También se consideraron documentos de conferencias y documentación de organismos internacionales (como ICAO, SESAR, FAA) ya que el tema de investigación es de gran alcance, y los informes oficiales pueden agregar información de interés al estudio. Con respecto al horizonte temporal, aunque no se ha limitado, todos los documentos encontrados se concentran entre 1998 y 2016. Las palabras clave utilizadas para la búsqueda fueron: {"airport capacity" OR "scheduling" OR "procedures" OR "optimization"} AND {"noise reduction" OR "aircraft noise"}. Después de un primer escrutinio, algunos de los documentos recopilados se descartaron porque no se ajustaban exactamente al tema del estudio de revisión, dejando un resto de 131 documentos o documentación oficial. Se encontraron una gran cantidad de documentos relacionados con la influencia del ruido en la salud o el aislamiento acústico que se descartaron, ya que estos temas no están relacionados con la capacidad los aeropuertos, objeto de la investigación.

Los últimos dos pasos de la metodología son el análisis y la síntesis de los documentos, lo cual se cubre en el apartado 3.1. de resultados.

2.2. Algoritmo de secuenciación *online* bajo operativa real

Esta Tesis aborda entre sus principales objetivos el hecho de que la secuenciación de vuelos precise algoritmos que arrojen resultados de forma suficientemente rápida para que puedan ayudar a los controladores de tráfico aéreo a tomar decisiones en tiempo real. Estos algoritmos deben poder procesar entonces grandes cantidades de datos en periodos de tiempo muy cortos.

Según la revisión de la literatura existente se han desarrollado algoritmos exactos y heurísticos para resolver problemas de secuenciación. Dada la complejidad del problema a resolver, los métodos exactos no funcionan con los requisitos deseados para las instancias de tamaño elevado (Salehipour *et al*., 2013). Los investigadores recurren por ello a algoritmos heurísticos como solución. Aunque estos últimos no garantizan soluciones óptimas, la resolución de problemas en períodos cortos de tiempo los hace muy atractivos. Al buscar un algoritmo metaheurístico rápido, el recocido simulado (*SA – Simulated Annealing*) es en muchas ocasiones la alternativa elegida, dado su buen rendimiento y simplicidad (Bertsimas y Tsitsiklis, 1993; Salehipour *et al*., 2013).

Por ello, en la presente investigación se ha estudiado el diseño de un algoritmo de SA que calcule la hora de aterrizaje que minimiza la demora total respecto a la hora de aterrizaje estimada (ELDT), sujeto a restricciones de separación impuestas por la estela turbulenta y el CPS. El CPS se basa en la especificación de un parámetro que limita el número máximo de posiciones (hacia adelante o hacia atrás) en las que se puede alterar su posición con respecto a la secuencia inicial de llegada (*First Come-First Served*) (Balakrishnan y Chandran, 2010). Cabe destacar que para CPS = 0, el orden de la secuencia es el FCFS. Dear (1976) observó que el CPS aumenta la tasa de rendimiento de la pista, trata a las aeronaves individuales de manera equitativa y se ajusta bien a las capacidades de computación ya que la actualización de la solución evita la re-secuenciación "global", entre otras características.

En concreto, esta parte de la investigación se enfoca a aeropuertos con una sola pista y operaciones mixtas (al tener una única pista, esta sirve tanto para aterrizajes como para despegues) por ser los de mayor complejidad en su resolución. Este objetivo permite no solo reducir los retrasos, sino también maximizar la capacidad de la pista, minorando los problemas de congestión en los aeropuertos. Siguiendo la clasificación de Gwiggner y Nagaoka (2014) mencionada previamente en el capítulo 1, esta investigación se ubica en el nivel táctico.

El algoritmo implementado se evaluará para instancias con diferente número de aviones, categorías de estela turbulenta variadas y números alternativos de CPS.

Además, se realizará una comparación con otros algoritmos usando una serie pública de datos y con datos reales del aeropuerto de Gatwick, para así probar el comportamiento del algoritmo en una situación real.

2.3. Minimización bi-objetivo para aterrizajes

El tercer objetivo específico de esta Tesis es elaborar un modelo que no sólo calcule los tiempos de aterrizaje (como es el caso del segundo objetivo) sino también seleccione la pista de aterrizaje más adecuada con la ambición de minimizar el ruido para la población circundante al aeropuerto, el consumo de combustible, y la demora total de los vuelos considerados. Para minimizar los retrasos y el consumo de combustible, se ha considerado nuevamente el CPS en el desarrollo de este modelo. Estudios previos (D'Ariano *et al*., 2012; Tavakkoli-Moghaddam *et al*., 2012; Bennell *et al*., 2013; Samà *et al*., 2014) han tratado la secuenciación considerando por separado como restricciones el ruido, el consumo de combustible, el WTC (*Wake Turbulence Category*) o el CPS, pero no como parte de la misma función objetivo. Abordar estas restricciones conjuntamente es el reto de esta parte de la investigación. Además, el modelo propuesto también se ha diseñado para que cumpla con el principal objetivo de la Tesis: poder utilizarse en operaciones reales e implementarse en software real, teniendo, por tanto, baja carga computacional.

El modelo desarrollado aquí, como se ha dicho, no solo pretende optimizar la capacidad de la pista como en el algoritmo anteriormente expuesto en el apartado 2.2., sino también optimizar el consumo de combustible de los vuelos considerados. Una de las decisiones que debe tomar el modelo es elegir la pista de aterrizaje que minimice el impacto del ruido de la ruta de aproximación final para la población circundante sin proponer ningún cambio en las rutas de aproximación existentes ni en los procedimientos operativos del aeropuerto. Para lograrlo, se define un modelo lineal para hacer frente a la naturaleza bi-objetivo del problema planteado (minimizar el impacto de ruido total y minimizar el consumo total de combustible), y se emplea el método de ε-*constraints* para construir la frontera de Pareto.

Para garantizar la eficiencia del modelo propuesto, se probó su funcionamiento usando datos reales del aeropuerto Adolfo Suárez Madrid-Barajas, el aeropuerto más grande de España y el quinto en la UE en términos de pasajeros (AENA, 2018), midiendo la mejora potencial en el coste por la eficiencia en el consumo de combustible logrado y la reducción del nivel de ruido, con el impacto social positivo que esto supone.

3. Resultados

En este capítulo, se aborda la descripción de resultados para cada uno de los objetivos anteriormente planteados.

3.1. Estudios previos sobre el impacto del ruido en aeropuertos

La revisión y análisis de los estudios previos realizada y sintetizada en el apartado 2.1. dio lugar a establecer la siguiente clasificación en diferentes áreas de estudio que se habían abordado hasta la fecha vinculadas con la problemática del ruido en el sector del tráfico aéreo: regulación, monitorización – modelado – simulación, procedimientos operacionales y algoritmos de optimización.

- Regulación

  A nivel mundial, la ICAO es responsable de desarrollar estándares para limitar las emisiones de ruido producidas por las aeronaves civiles.

  A nivel de la UE, existe una guía clara proporcionada por la Directiva de la UE 2002/30 para el establecimiento de normas y procedimientos para la introducción de restricciones operativas relacionadas con el ruido en los aeropuertos. La Comunidad Europea adoptó el Reglamento (UE) No. 598/2014 sobre los procedimientos para la introducción de exigencias operativas relacionadas con el mismo impacto ambiental. Dado que las restricciones también afectan a las compañías aéreas de países no pertenecientes a la UE, el Reglamento cumple con los principios internacionales sobre la gestión del ruido.

En EE.UU., la Administración Federal de Aviación (FAA – *Federal Aviation Administration*) tiene la autoridad y la responsabilidad de controlar el ruido de las aeronaves (FAA, 2016). Los aeropuertos son los principales responsables de la planificación e implementación de acciones diseñadas para reducir el efecto del ruido en los residentes de áreas circundantes. Tales acciones incluyen procedimientos de reducción del nivel de ruido y restricciones en el uso del aeropuerto, entre otras.

Pero no sólo existen políticas legislativas. Girvin (2009), en su revisión, compara y contrasta las directrices legales de ruido de la aviación y las medidas de reducción del ruido en todo el mundo. En su estudio, pone de manifiesto que las aeronaves pagan recargos a los aeropuertos por ruido generado por operación, o en función de los límites de ruido por aeronave o cuotas de ruido. Los cargos por ruido a menudo se utilizan con tarifas, según la categoría de registro de ruido de la aeronave o los niveles de certificación (Genescà *et al*., 2013). Generalmente, el impuesto sobre el ruido aumenta algunas veces con el peso de las aeronaves, ya que las aeronaves más pesadas también tienden a ser más ruidosas. La aplicación de descuentos para aeronaves más silenciosas y recargos por ruido para aeronaves más ruidosas es un incentivo para que las aerolíneas usen más aeronaves silenciosas (Morrell y Lu, 2000). Hsu y Lin (2005) destacan que, desde la perspectiva del aeropuerto, cuanto más ocupado esté, mayor será la tarifa por ruido que se cobrará por aterrizaje, para compensar el daño ambiental a las comunidades circundantes por el impacto producido.

En algunos países, se definen las áreas de protección contra el ruido. Estas son zonas urbanas que no se deben sobrevolar debido a políticas para la minimización del ruido. La distancia que se debe mantener desde estas áreas protegidas depende no sólo del tipo de aeronave sino también de las condiciones atmosféricas (ya que el viento tiene una enorme influencia en la propagación del ruido) (Schilke y Feuerle, 2013).

- Monitorización - Modelado – Simulación

También se ha encontrado en la revisión de la literatura que existe una importante relación entre las herramientas de monitorización, modelado y simulación del ruido en aeropuertos. La monitorización se realiza en un entorno de tiempo real para medir el impacto del ruido. El modelado sirve para propósitos de planificación y necesita las medidas de la monitorización para validar los modelos desarrollados. La simulación precisa tanto de la monitorización como del modelado para ayudar en la toma de decisiones para el diseño de procedimientos operativos y la evaluación de nuevas tecnologías (Figura 1).

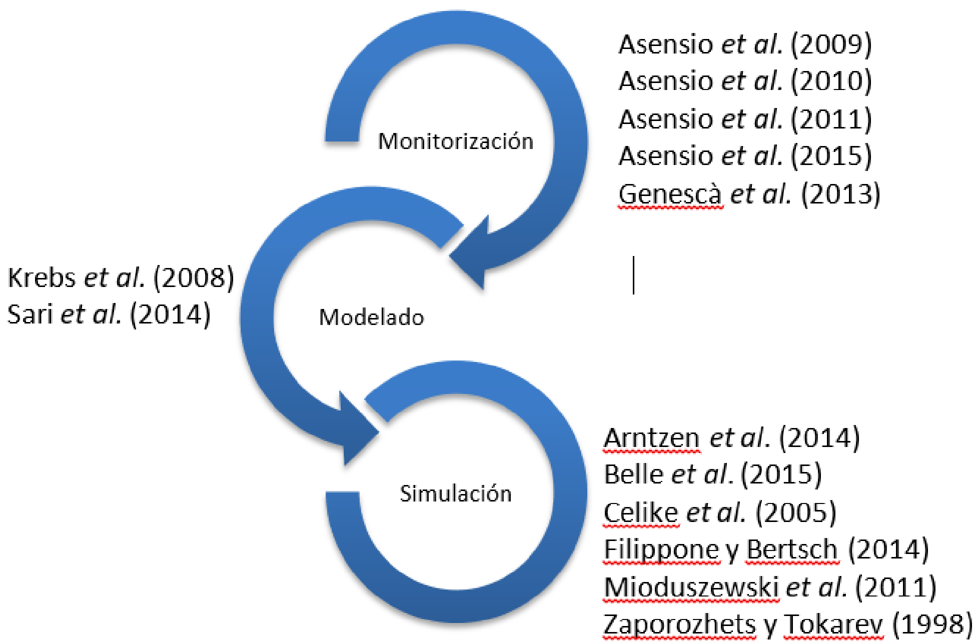

Figura 1. Relación entre Monitorización - Modelado – Simulación

Como se mencionó anteriormente, el impacto social del ruido en los aeropuertos ha provocado el desarrollo de una estricta legislación a nivel mundial. Este marco legal se basa en la monitorización del ruido, que generalmente combina información derivada de medidores de nivel de ruido y radares (Tarabini *et al*., 2014). Por esta razón, la monitorización del ruido se considera el mecanismo más relevante tanto para la planificación como para la gestión del ruido en los aeropuertos (Asensio *et al.*, 2010 y 2011). Permite medir a lo largo del tiempo el nivel de sonido, identificar eventos significativos y clasificar dichos eventos producidos por aeronaves. Varios estudios previos en la literatura tratan del problema de la monitorización. Cabe destacar que Asensio *et al*. (2010) diseñaron un sistema que puede detectar sonidos de aeronaves en tiempo real, de modo que su integración con una unidad de monitorización pueda mejorar las tasas de detección de aeronaves durante las mediciones, o Genescà *et al*. (2013) que proponen el uso de un conjunto de 12 micrófonos para medir el ruido directo de la aeronave, evitando el efecto de los reflejos del suelo y el ruido de fondo urbano en la medida de lo posible.

El siguiente paso después de una correcta monitorización del ruido es la validación de los modelos desarrollados. El modelado de ruido se utiliza para pronosticar el ruido actual o futuro de la aeronave en los aeropuertos y para producir mapas de ruido (Genescà, 2016; Sari *et al*., 2014). En todo el mundo se utilizan diferentes modelos, distintos métodos de cálculo, estructuras diferenciadas de datos y parámetros alternativos que se deben ajustar para representar la situación real.

Finalmente, se requieren métodos de simulación rápidos pero precisos. Filippone y Bertsch (2014) los definen como mejores prácticas y metodologías de predicción científica. Las herramientas de mejores prácticas generalmente se basan en modelos totalmente empíricos derivados de las mediciones del ruido de fondo. Las metodologías de predicción científica del ruido de las aeronaves desempeñan un papel importante en el proceso de formulación de políticas y las regulaciones resultantes. Estas últimas generalmente se basan en contornos de ruido (una línea en un mapa que representa niveles iguales de exposición al ruido) expresados en métricas promediadas anualmente. La evaluación del contorno del ruido de las aeronaves es un procedimiento complejo debido a los diferentes esquemas de rutas, procedimientos, aeronaves y tipos de motores que operan alrededor de un aeropuerto (Zaporozhets y Tokarev, 1998).

- Procedimientos operacionales

Los procedimientos operativos de reducción de ruido que se utilizan en la actualidad cubren las fases de despegue y aproximación. El término *Continuous Descent Approach* (CDA) se adoptó para abarcar las diferentes técnicas que se aplican para maximizar la eficiencia operativa y al mismo tiempo abordar los requisitos y limitaciones del espacio aéreo local durante la aproximación de la aeronave al aeropuerto. Estas operaciones se denominan de diversas maneras: *Continuous Descent Arrivals* (Jackson *et al*., 2009), *Optimized Profile Descents* (McConnachie *et al*., 2015; Hughes *et al*., 2012), *Tailored Arrivals* (Pinkerton, 2013; Elmer *et al*., 2008), *3D Path Arrival Management* (Tong *et al*., 2007) y *Continuous Descent Operations* (Thompson *et al*., 2013; Robinson y Kamgarpour, 2010).

CDA permite que las aeronaves se acerquen a áreas moderadamente densas, eliminando los segmentos de altitud de nivel y sus transitorios asociados a baja altitud, al tiempo que siguen trayectorias de descenso casi inactivas que ahorran combustible y reducen emisiones y el ruido (Ren *et al*., 2011; Weitz *et al*., 2005). Sin embargo, estos procedimientos no se usan de manera generalizada porque la implementación efectiva es difícil ya que las aeronaves requieren equipos especiales y pueden tener un impacto negativo en el rendimiento aéreo y la carga de trabajo del controlador (Jackson, 2009; Reynolds *et al*., 2005). La gestión del tráfico aéreo carece en muchos casos de la automatización en tierra requerida para proporcionar servicios de aseguramiento de separación durante las operaciones de CDA. Por lo tanto, el CDA se utiliza actualmente solo en escenarios de poco tráfico (Kuenz *et al*., 2007; Tong *et al*., 2007).

Boeing Database (2016) proporciona una base de datos de restricciones reales de ruido y emisiones de 654 aeropuertos en todo el mundo. Después de analizar esta información, se ha encontrado que 517 aeropuertos tienen procedimientos de reducción de ruido, pero solo 72 aeropuertos tienen procedimientos CDA implementados o en una etapa de desarrollo de prueba. Los otros tienen procedimientos que se refieren a las trayectorias de llegada y/o salida, así como las técnicas de vuelo recomendadas o el uso preferido de ciertas pistas.

- Algoritmos de optimización

Como se ha mencionado, el principal obstáculo para la implementación de los procedimientos operacionales de reducción de ruido es la incapacidad de los controladores de tráfico aéreo para mantener manualmente la secuencia y la separación de seguridad precisa requerida para obtener las máximas tasas de despegue y aterrizaje en condiciones de tráfico intenso. Por lo tanto, la introducción de automatización que prediga el impacto del ruido de las aeronaves, y utilice esta información para ayudar al controlador en la toma de decisiones, es fundamental para la aplicación exitosa de los procedimientos de reducción del ruido (Clarke, 2003).

Sin embargo, no hay una gran cantidad de literatura referente a la optimización de secuenciación que tenga en cuenta el ruido. En la Figura 2 se presentan los principales estudios encontrados, clasificados por las etapas de vuelo en las que son aplicables: despegue, ascenso, crucero, descenso, aproximación y aterrizaje.

La mayoría de las investigaciones previas sobre herramientas de optimización se refieren a la optimización de la trayectoria de vuelo (Visser, 2005; Salah y Abdallah, 2012; Salah, 2013), la cual tiene en cuenta eludir áreas construidas, detalles topográficos, exigencias de seguridad y requisitos de gestión de tráfico aéreo (Filippone, 2014).

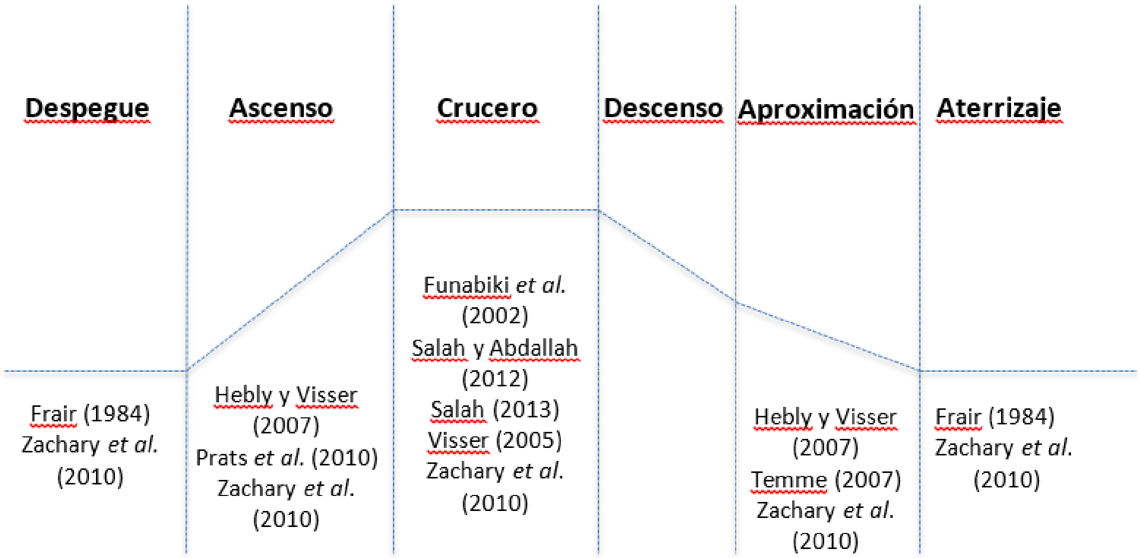

Figura 2. Algoritmos de optimización en función de la etapa de vuelo.

Sin embargo, es posible encontrar un estudio que data de 1984 sobre optimización del ruido en aeropuertos relativo a secuenciación de vuelos. Frair (1984) formula un modelo matemático de optimización cuyo objetivo es minimizar la molestia causada por las aeronaves que llegan y salen de un aeropuerto determinado, obteniendo el 40% de reducciones en los impactos del ruido.

Temme (2007) define un método para ayudar al controlador de tráfico aéreo a elegir rutas que reduzcan el ruido en tiempo real. Hebly y Visser (2007) presentan un sistema de soporte de decisiones para los controladores de tráfico aéreo que permite guiar el tráfico de llegada y salida cerca de los aeropuertos de una manera segura y eficiente, minimizando al mismo tiempo los efectos ambientales negativos. Formulan el problema como un modelo *Mixed Integer Linear Programming* con CPS.

Prats *et al*. (2010) definen un modelo de programación no lineal para la optimización de las salidas que se resuelve mediante el uso de una técnica de optimización lexicográfica multi-objetivo. Este enfoque permite el establecimiento de un orden jerárquico entre todas las diferentes ubicaciones sensibles al ruido. Sin embargo, el principal inconveniente de este planteamiento es la limitación en el número de ubicaciones sensibles al ruido que deben considerarse debido al crecimiento exponencial en el coste computacional.

Un estudio interesante y completo es el realizado por Zachary *et al*. (2010). Proponen un algoritmo de optimización que explora la mejor selección de posibilidades de vuelo ofrecidas para minimizar el ruido y/o las emisiones al seleccionar las trayectorias, los horarios y los procedimientos operativos disponibles de la aeronave, a través de una programación de enteros no lineales.

Hacer un uso de la infraestructura actual más eficiente es una parte esencial de la solución. Se ha publicado una cantidad importante de investigaciones para optimizar la programación de vuelos en aeropuertos. En este sentido, Bennel *et al*. (2013) revisan las técnicas y herramientas de investigación operativa y ciencia de la gestión que se utilizan para programar los aterrizajes y despegues de aeronaves con el fin de optimizar la programación de la pista del aeropuerto. Las principales técnicas de solución incluyen programación dinámica, derivación y enlace, heurísticas y metaheurísticas. Las restricciones de ruido casi no están presentes cuando se desarrollan estos algoritmos. Se ha encontrado una sola perspectiva interesante para incluir el ruido en la optimización de la programación. Sölveling *et al*. (2011) estudiaron la optimización de la programación de la pista en función de los impactos ambientales (CO_2 y ruido), y descubrieron que podría generar importantes ahorros para todas las partes implicadas (sociedad, aeropuertos y aerolíneas). Hay, entonces, un gran campo de investigación que aún no se ha desarrollado en términos de algoritmos de optimización que tengan en cuenta el ruido como una restricción u objetivo de la investigación.

3.2. Algoritmo de secuenciación *online* bajo operativa real

Para satisfacer el segundo objetivo de investigar las posibilidades de secuenciar bajo restricciones reales con resultados online, se ha diseñado un algoritmo de *Simulated Annealing* o Recocido Simulado. La Figura 3 ilustra el pseudocódigo del algoritmo SA desarrollado, donde S_{act} es la solución actual (real) y S_{cand} es la solución candidata, que se comparará con S_{act}. Los parámetros usados para el desarrollo del algoritmo son:

T_o Temperatura inicial

α Ratio de descenso de la temperatura

T_f Temperatura final

L Número de veces que el algoritmo trata de encontrar una nueva solución antes de decrementar la temperatura

```
INPUT (To, α, Tf , L)
T ← To
Sact ← Generate_initial_solution
WHILE T ≥ Tf DO
          BEGIN
           FOR  cont ← 1 TO L(T) DO
                           BEGIN
                           Scand ← Select_solution_N(Sact)
                           δ ← cost(Scand) – cost (Sact)
                           IF (U(0,1) < e^(-δ/T)) OR (δ <0)
                           THEN Sact ← Scand
                          END
           T ← α(T)
           END
{OUTPUT: best Sact visited}
```

Figura 3. Algoritmo SA

Las variables usadas por el modelo son:

N Número total de vuelos en la secuencia

WTC_i Categoría de estela turbulenta del vuelo i (ligera, media, pesada)

WVS_{ij} Separación mínima entre los vuelos i,j según sus categorías de estela turbulenta

p_i Vuelo en posición i en la solución propuesta por el algoritmo

v_i Posición del vuelo i en la solución propuesta por el algoritmo

e_i Hora de aterrizaje estimada del vuelo i

t_i Hora de aterrizaje objetivo del vuelo i, calculada teniendo en cuenta las horas planificadas del vuelo y las restricciones de separación según la estela turbulenta

δ Diferencia entre el coste de la solución S_{cand} y la S_{act}

c_i Coste de penalización por unidad temporal de retraso del vuelo i

Puesto que se considera un aeropuerto con una pista de operaciones mixtas, no es posible asumir el triángulo de desigualdad (Bennell *et al.,* 2013; Chandran y Balakrishnan, 2007), por lo que las horas objetivo de aterrizaje se calculan para cada vuelo i como:

$$t_i = \max\{e_i; t_j + WVS_{ji}\} \ \forall j = 1, \ldots, i-1 \qquad (1)$$

La función objetivo se define como:

$$\min C_\sigma = \min (\Sigma_{i=1..N} (|t_i - e_i|*c_i) \qquad (2)$$

Los resultados se han evaluado según su porcentaje de mejora:

$$\% \text{ mejora} = 100 \times (C_{FCFS} - C_{sol}) / C_{FCFS} \qquad (3)$$

donde C_{FCFS} y C_{sol} son los costes de la solución FCFS y la solución encontrada por el algoritmo, calculados según la ecuación (2).

Una vez que se ha definido el algoritmo SA, se ha diseñado el conjunto de pruebas que permitirá validar el comportamiento del mismo. La idea es generar un gran número de instancias aleatorias para las cuales se conoce el resultado óptimo y compararlas con las soluciones encontradas por el algoritmo. Se han identificado tres factores en la revisión de la literatura previa que podrían influir en los resultados obtenidos, lo cuales se han introducido en el procedimiento de generación de instancias para cuantificar cómo de importantes son:

- **F1.** Categoría de estela turbulenta de los vuelos de la secuencia (WTC). Se han considerado dos situaciones diferentes: una en la que todos los vuelos tienen como WTC = Media (F1.1.) y otra donde todos los vuelos tendrán asignada una categoría de estela turbulenta aleatoria (F1.2.) entre las 3 categorías consideradas (Pesada, Media y Ligera). Esto permite analizar si considerar vuelos con la misma categoría de estela turbulenta (es decir, todos deben satisfacer la misma separación entre ellos, de modo que se satisfaga la desigualdad del triángulo) es relevante o no para el rendimiento del algoritmo.

- **F2.** Cambio de posición. Se han elegido cinco niveles para CPS = {1; 2; 3; 4; 5}, teniendo en cuenta que los controladores siempre desean mantener la secuencia lo más similar posible a la secuencia FCFS recibida.

- **F3.** Número de vuelos. Con el fin de tener una secuencia de aviones de tamaño realista en un aeropuerto con una sola pista, se consideran secuencias de 50 (F3.1), 100 (F3. 2), 150 (F3.3) y 200 (F3.4) vuelos. Aunque no es realista que un aeropuerto considere una secuencia tan grande en una pista de operaciones mixtas (la capacidad de rendimiento máxima para una mezcla de flota homogénea en una sola pista es de 60 vuelos por hora -Sherry, 2009-), esto permitirá comprobar la capacidad del algoritmo para gestionar instancias extremadamente grandes.

Una vez identificados los factores a tener en cuenta, es necesario generar un conjunto de instancias para las cuales se conoce la solución óptima. Esto significa generar instancias de diferente número de vuelos (F3) con un coste 0 que cumplan con las restricciones de WTC (F1). Estas instancias se varían de forma aleatoria respetando los cinco niveles de CPS considerados (F2). Las instancias generadas son las consideradas como secuencias de entrada FCFS para el algoritmo. Se han generado 50 repeticiones para cada una de las combinaciones $2\times5\times4$ de factores considerados, dando un total de 40×50=2.000 instancias.

Como puede observarse en la Figura 4, para 828 de las 2.000 instancias generadas (41,4% del total), el algoritmo fue capaz de encontrar la solución óptima (es decir, coste cero). Para un 98,6% de instancias, el algoritmo encontró una solución con un 95% de mejora en el coste total de la secuencia.

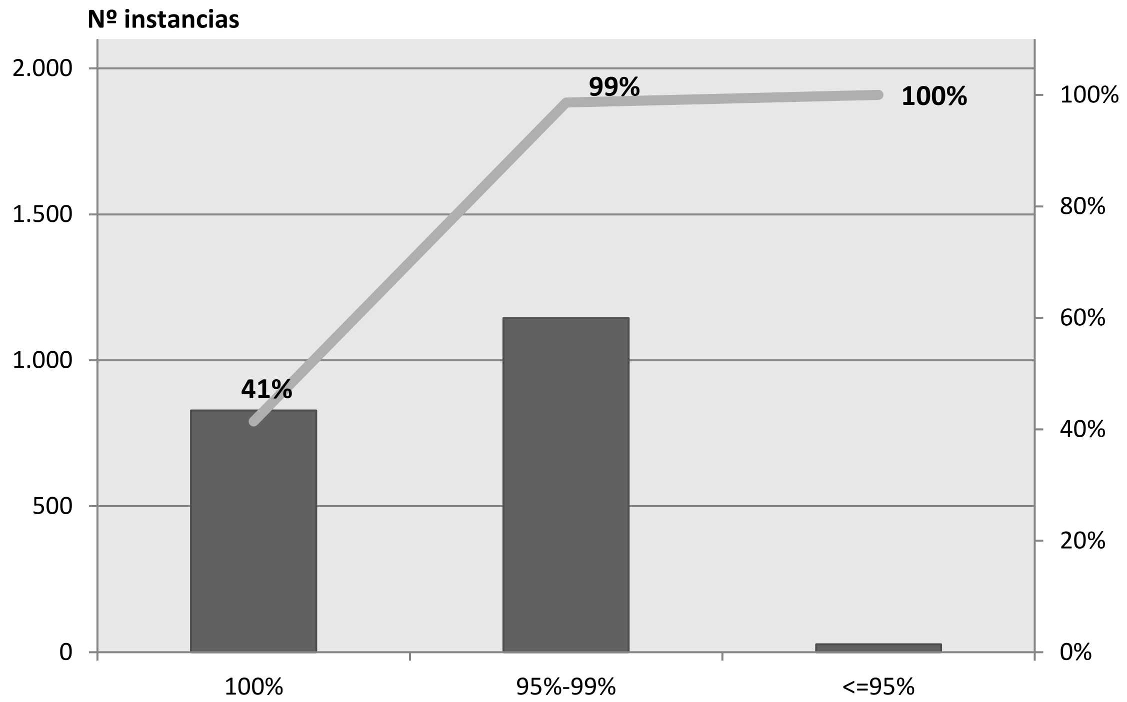

Figura 4. Diagrama de Pareto para representar la mejora obtenida para las 2.000 instancias generadas.

Se realizó la prueba de Kruskal-Wallis para medir la importancia de los diferentes factores considerados en la generación de instancias. Los resultados muestran que F3 (es decir, el número de vuelos) no es significativo (p = 0,214) en la explicación de la mejora, al contrario de lo que ocurre con F1 (p = 0,001) y F2 (p = 0,000). Esto significa que la eficiencia del algoritmo no depende del número de aeronaves de la secuencia considerada. Como se muestra en la Tabla 1, el factor F1.2 (diferentes tipos de aeronaves) y el factor F2.1 (CPS = 1) son los más difíciles de manejar para el algoritmo SA desarrollado. Estos resultados son razonables, ya que el factor F1.2 implica una mayor complejidad, ya que la desigualdad del triángulo se cumple, y cuando CPS = 1, el número de posibles reasignaciones de las aeronaves en la secuencia para encontrar su mejor posición es menor. Por otro lado, y como podría esperarse, los mejores resultados se obtienen para valores altos de CPS (F2) y solo un tipo de aeronave (F1.1). La Tabla 1 también muestra el GAP promedio y el límite inferior tal como se define en Pinol y

Beasley (2006). Los valores de los GAPs obtenidos muestran que el algoritmo es capaz de encontrar la solución óptima en todos los casos. Los valores de límite inferior señalan que en el peor de los casos se obtiene un 90% de mejora en algunos casos.

Tabla 1. Resultados descriptivos de mejora (%) respecto a F1, F2 y F3. El porcentaje de GAP refleja la diferencia en porcentaje entre la solución óptima y la mejor solución.

Factores	**Niveles**	**Media**	**GAP medio (%)**	**Límite inferior**	**Desviación estándar**	**Intervalo confianza 95%**	
						Límite inferior	**Límite inferior**
F1	1	99,877	0	90,36	0,329	99,857	99,897
	2	98,789	0	92,23	1,032	98,725	98,854
F2	1	98,733	0	90,36	1,580	98,573	98,892
	2	99,373	0	90,36	0,791	99,295	99,451
	3	99,564	0	97,81	0,511	99,513	99,614
	4	99,537	0	95,51	0,520	99,486	99,588
	5	99,460	0	94,29	0,607	99,401	99,520
F3	50	99,369	0	90,77	0,952	99,284	99,453
	100	99,320	0	92,63	0,916	99,239	99,401
	150	99,363	0	92,20	0,879	99,285	99,441
	200	99,309	0	90,36	0,994	99,222	99,397

Como se mencionó previamente, el tiempo de computación es de gran relevancia en esta investigación. La Figura 5 muestra que resultados buenos se obtienen en menos de un segundo. Como podría esperarse, los resultados mejoran a medida que el algoritmo realiza más interacciones. Como puede verse también en la Figura 5, en la iteración 15.000, los resultados alcanzaron mejoras promedio del 80% en solo 0,15 segundos, mientras que la mejora promedio del 100% (es decir, el coste cero) se alcanza en 0,25 segundos (en la iteración 30.000).

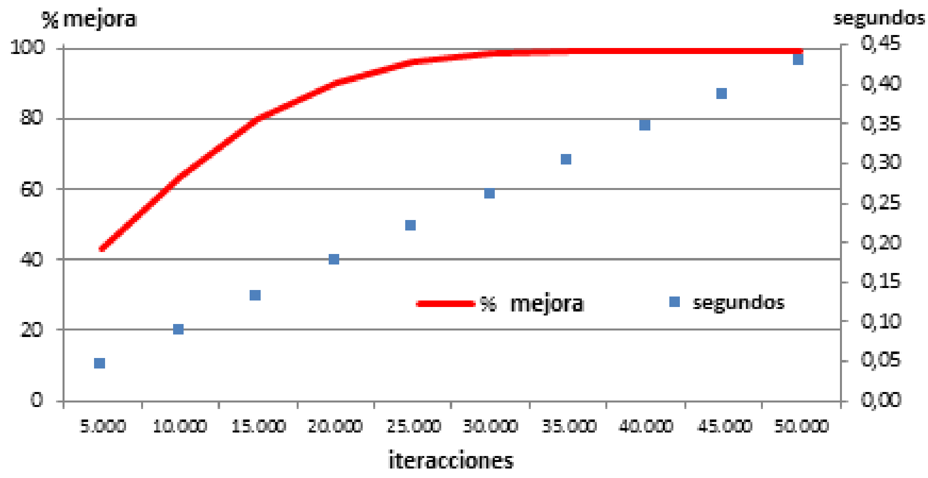

Figura 5. Evolución del porcentaje de mejora y el tiempo de computación medio en segundos para las 2.000 instancias generadas.

Además de validar el comportamiento del algoritmo con las instancias generadas ad-hoc para este problema, se ha querido también considerar conjuntos de instancias disponibles públicamente. Para ello, se han tenido en cuenta 11 archivos de datos de aterrizaje de aeronaves de la Biblioteca OR (Beasley, 1990) y los resultados se han comparado con los obtenidos por Pinol y Beasley (2006) y Salehipour *et al*. (2013). La Figura 6 muestra una comparación entre el porcentaje de mejora de este algoritmo y el resultado óptimo. Los resultados obtenidos por estos dos autores son ligeramente mejores que el enfoque de SA ya que sus algoritmos permiten que los vuelos aterricen antes de su tiempo estimado, mientras que el enfoque considerado en este estudio no considera esta posibilidad, persiguiendo reflejar con la mayor fidelidad posible el modo de funcionamiento habitual de las operaciones aeroportuarias. A pesar de eso, el porcentaje de mejora no es muy diferente en la mayoría de los casos. La Figura 6 también refleja la diferencia en el tiempo de procesamiento, considerando el tiempo de procesamiento de Pinol y Beasley (2006) y Salehipour *et al*. (2013) el menor de sus respectivos algoritmos. Debe destacarse la ventaja con respecto a los tiempos de cómputo del algoritmo SA, alcanzando así el objetivo de obtener soporte en línea. Por lo tanto, el algoritmo SA puede obtener mejoras competitivas en el coste de la secuencia y en la mayoría de los casos en menos de un segundo.

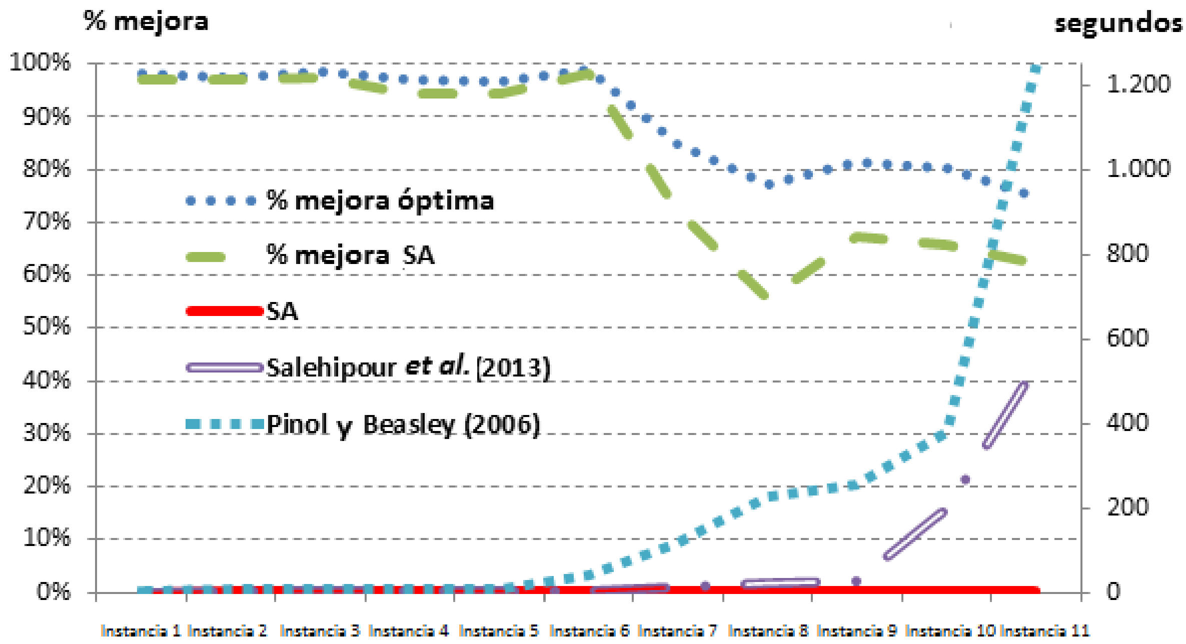

Figura 6. Comparación de algoritmos que han usado la Biblioteca OR de instancias públicas.

Una vez que se ha establecido la validez del enfoque propuesto utilizando tanto el banco de pruebas generado ad-hoc como otro ampliamente usado en la literatura previa, es interesante ver cuál es el comportamiento del algoritmo cuando se usan datos reales. Para este propósito, se eligió el aeropuerto de Gatwick, el segundo aeropuerto más grande del Reino Unido y el aeropuerto comercial de pista única más transitado del mundo (Gatwickairport, 2015).

La información de los vuelos se recopiló para el día 7 de septiembre de 2015 de 6:00 am a 9:00 am (FlightRadar24, 2018). La separación de tiempo mínima en función del WTC de cada vuelo considerado se basa en Malaek y Naderi (2008). Puesto que CPS es un parámetro teórico, se ha testeado el algoritmo con 49 valores diferentes (de 1 a 49) para ver cómo este parámetro puede influir en los resultados en un caso real y, por lo tanto, tratar de determinar el valor óptimo de CPS. El valor de los parámetros de SA utilizado fue el mismo que en los experimentos de banco de pruebas.

La Figura 7 muestra la evolución del porcentaje de mejora dependiendo del CPS después de ejecutar el algoritmo SA. Se puede ver que la mejora aumenta a 30% para el CPS 10 y disminuye cuando el valor de CPS es superior a 25. Al implementar este algoritmo en entornos reales, sería necesario definir el valor del parámetro CPS con los controladores para obtener el mejor rendimiento del algoritmo que respete sus requisitos de minimizar la alteración de la posición de los planes de vuelo dentro de la secuencia inicial.

Con respecto a su implementación potencial, el algoritmo puede ofrecer las soluciones en menos de 1 segundo, lo que es un tiempo de cálculo razonable para ser utilizado en entornos reales, donde los controladores están acostumbrados a obtener soluciones en línea.

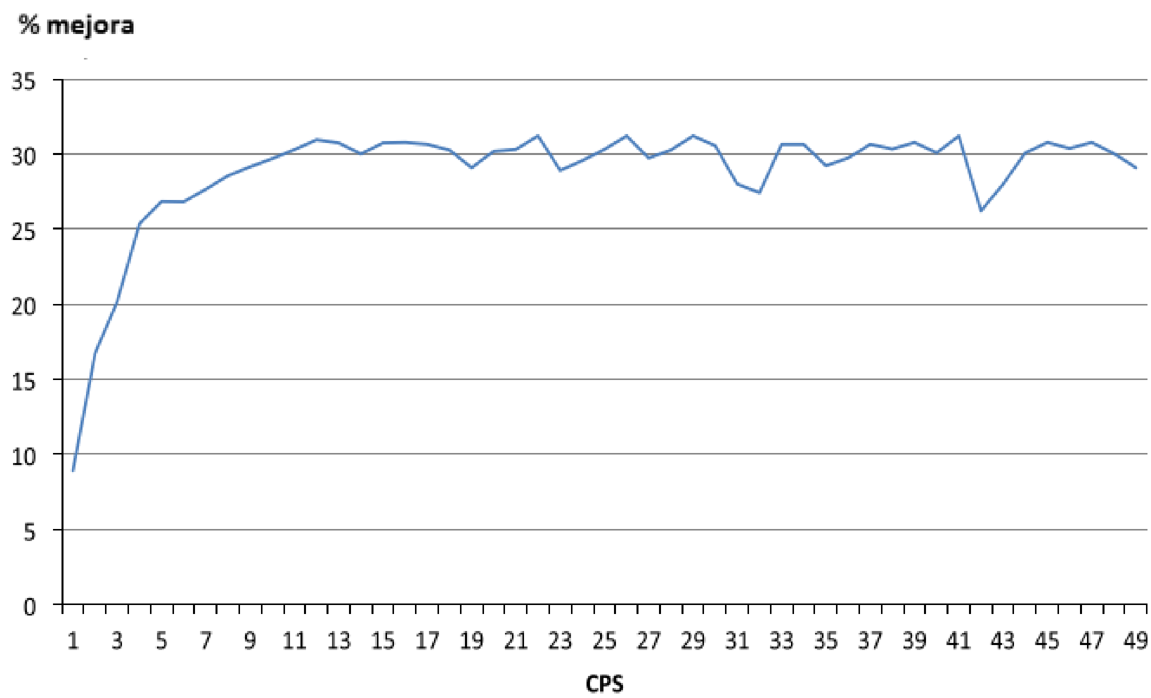

Figura 7. Evolución del % de mejora del aeropuerto de Gatwick para valores reales y diferentes valores de CPS

3.3. Minimización bi-objetivo para aterrizajes

Para satisfacer el tercer objetivo de desarrollar un modelo para aterrizajes que minimice el impacto del ruido, el consumo total de combustible, y los retrasos, fue necesario en primer lugar seleccionar una métrica para medir el impacto de ruido del avión en el aterrizaje. Se ha considerado la métrica *LOUDPeople*, LP (Christian y Sparrow, 2013). Esta métrica evita que se pueda tomar la decisión de asignar un nivel de ruido inaceptablemente alto a una pequeña población para reducir el impacto del ruido total:

$$LP = \sum_i Población_i * 2^{\left(\frac{SEL_i - 100}{10}\right)} \qquad (4)$$

$$SEL = L_{eq} + 10 * log_{10}(T) \qquad (5)$$

donde *i* representa cada ciudad situada en los alrededores del aeropuerto; SEL_i es el nivel de exposición al ruido (en dB) normalizado a un segundo en la ciudad *i*; T es la duración en segundos del periodo de tiempo en el que se mide el ruido, y L_{eq} es el nivel de ruido equivalente medido en cada cuidad. Nótese que cuando T=1 (el caso del presente estudio), SEL = L_{eq}.

Una vez definido cómo medir el impacto del ruido, se desarrolló un modelo lineal que fuera capaz de gestionar la naturaleza del problema bi-objetivo. Los datos considerados son:

N	Número total de vuelos en la secuencia
R	Número de rutas de aproximación del aeropuerto bajo estudio
HS_i	Hora programada de despegue del vuelo *i*.
$flight\_time_{i,r}$	Tiempo de vuelo mínimo del vuelo *i* cuando utilizar la ruta *r*.
K_i	Consumo de combustible del vuelo *i* por segundo
LP_{ir}	Impacto de ruido del vuelo *i* siguiendo la ruta r en una población
CPS	*Constrained Position Shifting*

$WTC_{i,j}$ Separación entre el vuelo *i* y el j según su categoría de estela turbulenta

M Número grande

Las variables de decisión consideradas para definir una secuencia factible son:

$$\rho_{i,r} \begin{cases} 1 \text{ si el plan de vuelo } i \text{ se aproxima usando la ruta r} \\ 0 \text{ en cualquier otro caso} \end{cases}$$

t_i Hora de aterrizaje del vuelo *i* según el modelo

d_i Retraso forzado del vuelo *i* antes de aterrizar para asegurar la separación mínima de seguridad entre 2 vuelos consecutivos (en minutos)

$$\tau_{i,j} \begin{cases} 1 \text{ si el vuelo } i \text{ aterriza antes que el } j\ (t_j > t_i) \\ 0 \text{ en cualquier otro caso} \end{cases}$$

Las funciones objetivo son:

- Minimizar el consume total de combustible:

$$min\ \sum_i (t_i - HS_i) \times K_i \qquad (6)$$

- Minimizar el impacto total de ruido:

$$min\ \sum_i \sum_r (LP_{i,r}\ \rho_{i,r}) \qquad (7)$$

Para asegurar que las soluciones son factibles, se han considerado también las siguientes restricciones:

1) Cada plan de vuelo *i* está solamente asignado a una ruta. Asi, para cada vuelo *i*, exactamente sólo un $\rho_{i,r}$ es 1:

$$\sum_r \rho_{i,r} = 1 \qquad \forall i \qquad (8)$$

2) La hora real de llegada del vuelo *i* viene determinada por su hora de salida más el tiempo de vuelo por la ruta seleccionada y el posible retraso causado por la separación mínima de seguridad:

$$t_i = d_i + \sum_r (HS_i + flight\_time_{i,r}) \times \rho_{i,r} \quad \forall i \qquad (9)$$

3) O el vuelo *i* aterriza antes que el *j,* o el vuelo *j* aterriza antes que el *i*:

$$\tau_{i,j} + \tau_{j,i} = 1 \quad \forall i,j; \; j \neq i \qquad (10)$$

4) Las restricciones de separación entre el vuelo *i* y el vuelo *j* están garantizadas por la siguiente restricción:

$$t_j \geq t_i + WTC_{i,j} - M(1 - \tau_{i,j}) \quad \forall i, \forall j \neq i \qquad (11)$$

5) La restricción por CPS se cumple ya que:

$$\sum_{j \neq i} \tau_{i,j} \geq N - (i + CPS) \quad \forall i \qquad (12)$$

$$\sum_{j \neq i} \tau_{i,j} \leq N - (i - CPS) \quad \forall i \qquad (13)$$

Como se ha mencionado anteriormente, un escenario real de llegadas al aeropuerto Adolfo Suárez Madrid-Barajas ha sido el utilizado para probar las bondades de este modelo. Puesto que este aeropuerto tiene muchas limitaciones operativas debidas al ruido, existen datos públicos de ruido disponibles en 27 puntos alrededor del aeropuerto. En los experimentos realizados, se han considerado las medidas de impacto acústico en las poblaciones de Torrejón de Ardoz (por ser la población colindante con más habitantes), Coslada y San Fernando de Henares (dado que presentan los peores registros de medidas de ruido). Esto permite tener una medida representativa y equilibrada del impacto del ruido global en las áreas circundantes de las dos pistas de aterrizaje del aeropuerto de Madrid.

Para seleccionar los intervalos de tiempo utilizados para analizar y comparar los resultados después de ejecutar el modelo definido, se quiso estudiar cómo la congestión puede influir en los resultados y las posibles mejoras encontradas por el modelo. La congestión está determinada por el número total de aviones de aterrizaje por período. Teniendo en cuenta que la cantidad de vuelos en cada muestra debe ser igual para fines comparativos (50 planes de vuelo en este caso), los períodos elegidos para el presente análisis son:

- Baja congestión - [00:00 – 8:00]
- Alta congestión - [12:00 – 13:30]
- Congestión intermedia - [20:10 – 22:10]

Las Figura 8, 9 y 10 muestran los resultados de los diferentes conjuntos de datos, según la hora del día considerada. Como puede verse, para los tres casos, todas las soluciones encontradas por el modelo son mejores que la operación real, dominando (es decir, mejorando el coste y el ruido de manera simultánea) las secuencias reales de ese día.

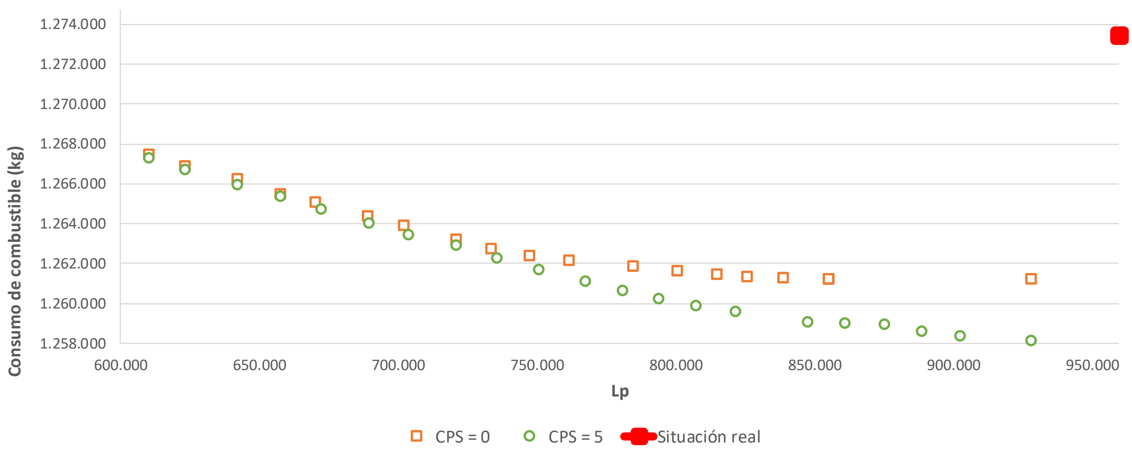

Figura 8. Soluciones encontradas para 50 vuelos que aterrizan de 00:00 a 08:00 (congestión baja). El punto cuadrado representa la secuencia real (que es peor que todas las soluciones encontradas).

Si se evalúan en estas tres figuras las oportunidades de reducción de costes al relajar la restricción de CPS (es decir, permitiendo CPS = 5 en lugar de CPS = 0) se observa en los puntos extremos de la derecha (es decir, puntos que minimizan el consumo de combustible) que en el caso de baja congestión el modelo encuentra una solución que permite ahorrar un 0,25% del combustible total, en el caso de alta congestión del 0,49%, mientras que en el caso de congestión intermedia la reducción en el consumo de combustible aumenta hasta el 1,17%.

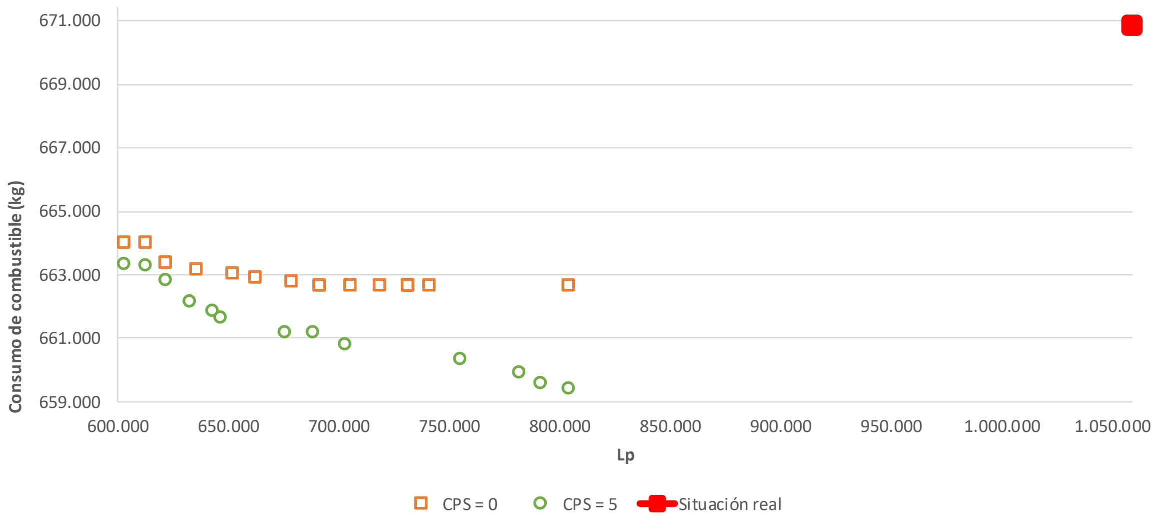

Figura 9. Soluciones encontradas para 50 vuelos que aterrizan de 12:00 a 13:30 (alta congestión). El punto cuadrado representa la secuencia real (que es peor que todas las soluciones encontradas).

Figura 10. Soluciones encontradas para 50 vuelos que aterrizan de 20:10 a 22:10 (congestión intermedia). El punto cuadrado representa la secuencia real (que es peor que todas las soluciones encontradas).

Dado que los tres puntos que representan la realidad están dominados por todos los puntos en las tres fronteras de Pareto, se pueden analizar los resultados (Tabla 2) en términos del porcentaje potencial de mejora en el consumo total de combustible y el impacto de ruido total, comparando la situación real con la mejor solución ruido (punto extremo izquierdo en la frontera) y coste (punto extremo derecho). Se puede ver que los mejores resultados, en términos de mejora del consumo total de combustible, se logran nuevamente para el escenario con congestión intermedia (para ambos CPS).

Tabla 2. Comparación del % de mejora en comparación con la solución real para los 3 escenarios (baja, intermedia y alta congestión) y dos valores diferentes de CPS

	Baja congestión		**Congestión intermedia**		**Alta congestión**	
	CPS = 0	CPS = 5	CPS = 0	CPS = 5	CPS = 0	CPS = 5
Combustible	0.95%	1.20%	3.37%	4.50%	1.22%	1.71%
Impacto de ruido	36.44%	36.44%	41.91%	41.91%	43.12%	43.12%

Estos resultados indican que cuando la congestión es muy baja o muy alta, las aeronaves llegan al aeropuerto con mayor espacio o muy cerca respectivamente, y la ganancia de aplicar el CPS es muy baja. Sin embargo, cuando las distancias son lo suficientemente grandes como para combinar diferentes aeronaves, pero no muy altas para que el orden de la aeronave no se altere sin producir grandes períodos de espera (que impacten en el consumo de combustible), la mejora lograda al aplicar el CPS es sustancial. Nótese que debe analizarse el bajo porcentaje de mejora, considerando que los procedimientos de aproximación y aterrizaje representan solo un pequeño porcentaje del tiempo total de vuelo.

Con respecto a los resultados de la mejora del ruido, se puede ver que el CPS no tiene impacto en las soluciones logradas, con mejoras con respecto al impacto del ruido real mucho más alto que en el caso del coste (más del 35% en todos los escenarios considerados). Al permitir que el modelo seleccione la pista de aterrizaje más adecuada en términos de ruido, se confirma que hay margen de mejora y puede alcanzarse reducciones importantes en términos del impacto del ruido sobre las poblaciones que rodean el aeropuerto.

Después de este análisis, se puede afirmar que la reducción del ruido y combustible se logra en el modelo como consecuencia de dos factores:

- La selección de la pista de aterrizaje más adecuada permite que el modelo logre reducciones del ruido importantes en la población que rodea el aeropuerto.
- La alteración del orden en la secuencia de aterrizaje permite que el modelo reduzca el consumo total de combustible, ya que se logran reducciones en el espacio mínimo entre aviones, reduciendo los tiempos de vuelo y alcanzando así la secuencia óptima de llegada.

Con el modelo bi-objetivo se consiguen soluciones que, al mismo tiempo, están optimizadas en ambos objetivos (minimización de combustible y ruido), encontrando soluciones que son mucho mejores que la operación real.

4. Conclusiones

Minimizar la perturbación por ruido en los aeropuertos es una tarea que requiere la implicación de varias *stakeholders*: instituciones públicas, fabricantes de aeronaves, líneas aéreas y los gestores de tráfico aéreo. Las predicciones confirman el crecimiento del transporte aéreo en el futuro, lo que aumenta el problema del ruido en los aeropuertos.

Los principales enfoques abordados en la actualidad para reducir el impacto del ruido en las comunidades cercanas a los aeropuertos consideran los procedimientos operativos y las restricciones legislativas. Sin embargo, si los esfuerzos se centrasen en desarrollar herramientas de secuenciación que eviten las maniobras de espera para los aterrizajes en las etapas de aproximación del vuelo, el ruido podría reducirse significativamente.

En esta Tesis se ha presentado un análisis de la literatura existente relativa al impacto del ruido en entornos aeroportuarios y se han presentado dos algoritmos que permiten mejorar la capacidad de los aeropuertos actuales en tiempo real y considerar el impacto del ruido producido por las operaciones de aproximación y aterrizaje a un aeropuerto sin perjudicar la capacidad del mismo y sin necesidad de cambiar la regulación o los procedimientos operativos del aeropuerto.

El análisis de los resultados del algoritmo SA desarrollado después de realizar un extenso marco experimental (que involucra 2.000 instancias para validar los resultados del algoritmo) muestra mejoras del 95% en menos de un cuarto de segundo de esfuerzo computacional. Se consideraron hasta 200 aviones en las instancias generadas, sin observar reducción en el rendimiento del algoritmo. Además, la comparación con otros algoritmos previos que utilizaron una biblioteca pública de datos muestra que el algoritmo propuesto en esta investigación obtiene resultados competitivos en un tiempo significativamente menor, cumpliendo el objetivo de poder ser utilizado *online*. Además, con el empleo de datos reales del aeropuerto de Gatwick se obtiene un tercio de mejora en el retraso total de la secuencia considerada. Por lo tanto, el algoritmo diseñado se puede utilizar en entornos reales, ya que los resultados se obtienen en un reducido tiempo de procesamiento (menos de un segundo en la mayoría de los casos) y las mejoras en el coste de la secuencia (sin variar completamente la secuencia respecto a la FCFS) son también valiosas.

El modelo bi-objetivo para secuenciar aterrizajes minimizando el impacto del ruido y el consumo total de combustible aprovecha al máximo la capacidad actual de las pistas al elegir la pista de aterrizaje y el tiempo de aterrizaje más apropiados bajo restricciones de seguridad y CPS. Al analizar los planes de vuelo reales en un día específico, se encontraron mejoras de hasta el 4,5% de la reducción del consumo total de combustible, modificando solo el orden de la secuencia de aproximación de llegadas al aeropuerto, y hasta el 43% de reducción en el impacto del ruido total.

Lo anterior confirma que la secuenciación puede mejorarse fácilmente y tener un impacto positivo inmediato en la población circundante del aeropuerto sin incurrir en retrasos ni alterar los procedimientos operativos del mismo. Es importante tener en cuenta que la congestión (número total de aviones de aterrizaje por período de tiempo) tiene un efecto relevante en las posibilidades de mejora de este modelo. Por lo tanto, ser capaz de suavizar el tráfico durante las horas pico podría tener resultados gratificantes, abriendo la puerta a lograr mejoras en términos de secuenciación. Dado que el tiempo de cálculo del modelo es muy bajo, puede ejecutarse durante la fase de descenso para respaldar a los controladores de tránsito aéreo en la mejor ruta de aproximación que debe seleccionarse para equilibrar la perturbación del ruido en las poblaciones cercanas y el consumo total de combustible.

Con esta Tesis se ha demostrado que existen alternativas para mejorar el impacto del ruido producido por las operaciones de aproximación y aterrizaje a un aeropuerto sin perjudicar la capacidad del mismo y sin ser necesario cambiar la regulación o los procedimientos operativos del aeropuerto.

4.1. Líneas de investigación futuras

Para abordar el problema objeto de esta tesis (es decir, el estudio de algoritmos para la mejora en la secuenciación de aeronaves teniendo en cuenta restricciones ambientales), es necesario en primer lugar mejorar las técnicas de monitorización-modelado-simulación para que tengan en cuenta todos los factores implicados en el problema del ruido (clima, población afectada, congestión del tráfico aéreo, capacidad del aeropuerto, etc.). Es preciso, asimismo, disponer de herramientas estandarizadas, ya que los programas existentes difieren mucho en sus métodos de cálculo y en la estructura de los datos, por lo que es muy difícil comparar los resultados de una manera consistente. Estos métodos de cálculo deben considerar no solo las diferentes fuentes de ruido, sino también ser capaces de hacer coincidir las predicciones de ruido con los datos medidos. Los estándares de validación son, por tanto, otro aspecto que requiere atención en la investigación futura para desarrollar herramientas que sean realmente útiles en la reducción del ruido en los alrededores de los aeropuertos.

Como temas para dar continuidad a esta investigación, se podría tener en cuenta las franjas horarias (o *slots*) para hacer que el algoritmo de *scheduling* sea más flexible y permitir que los vuelos se adelanten a su horario programado, lo cual agregaría valor a estos resultados.

Dependiendo de la disponibilidad de información de condición atmosférica en tiempo real más precisa, se podría obtener una predicción de ruido más exacto. Esto permitiría ajustar las decisiones tomadas por el modelo bi-objetivo desarrollado con respecto a las propiedades de propagación del ruido y la influencia del impacto del ruido en las poblaciones circundantes de la solución propuesta. Además, extender el problema para considerar todas las trayectorias de vuelo permitiría tener una visión más amplia del problema.

Finalmente, sería interesante, para ambos desarrollos, explorar la posibilidad de considerar como objetivo no sólo la reducción total de retrasos o costes, sino también la prioridad de los vuelos.

Existe entonces un amplio campo de investigación en algoritmos de optimización que ayuden a los controladores a secuenciar las operaciones del aeropuerto considerando las restricciones de ruido en tiempo real. Por lo tanto, se deben desarrollar algoritmos de optimización que tengan en cuenta las restricciones de ruido que eviten secuencias ineficientes. Los controladores necesitan estas herramientas para poder mantener la seguridad y la eficiencia, pero también para abordar los problemas de ruido y ambientales.

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6. **Anexos**

Anexo I. Publicaciones presentadas

Anexo II. Informe con factor de impacto de las publicaciones presentadas

Anexo I. Publicaciones presentadas

- Rodríguez-Díaz, A., Adenso-Díaz, B., González-Torre, P.L. (2017). “Minimizing deviation from scheduled times in a single mixed-operation runway”, *Computers & Operations Research,* vol. 78., pp. 193–202.
- Rodríguez-Díaz, A., Adenso-Díaz, B., González-Torre, P.L. (2017). “A review of the impact of noise restrictions at airports”, *Transportation Research Part D,* vol. 50, pp. 144–153.
- Rodríguez-Díaz, A., Adenso-Díaz, B., González-Torre, P.L. (2019). “Improving aircraft approach operations taking into account noise and fuel consumption”, *Journal of Air Transport Management,* vol. 77, pp. 46–56.

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Minimizing deviation from scheduled times in a single mixed-operation runway

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First-come first-served
Simulated annealing

ABSTRACT

The dynamic nature of airports demands the development of scheduling algorithms that are computationally efficient and therefore amenable to replanning when new traffic events occur. The main objective of this research is to design an algorithm with very low computational times able to minimize delays in the scheduled times of arrival and departure flights in an airport with a mixed-operation runway, under wake vortex separation and Constrained Position Shifting restrictions. The simulated annealing algorithm obtains a 95% improvement on time delays in less than one second of computation for the test instances generated, which means that it can be used online for high-demand scenarios to reduce delays. It has also been tested in a public testbed as well as in a real environment, showing an improvement of 30% in the time delays of real operations at London Gatwick airport.

1. Introduction

Some 3.1 billion passengers made use of the global air transport network for their business and tourism needs in 2013. The annual passenger total was up by approximately 5% compared to 2012 and is expected to reach over 6.4 billion by 2030, based on current projections [30]. The number of aircraft departures reached 33 million globally last year, establishing a new record and surpassing the 2012 departure figure by more than one million flights. Scheduled passenger traffic grew at a rate of 5.2% (expressed in terms of revenue passenger-kilometres or RPKs) [30].

Therefore, one of the central challenges facing the aviation industry is air traffic demand growth, which results in congestion in many airports – primarily hubs [24]. The economic cost of delay is enormous and will worsen as traffic demand increases. In 2010, the annual cost of US delays was $32.9B [6].

The efficiency and effectiveness of Air Traffic Management (ATM) is enabled by air traffic flow management (ATFM). It contributes to the safety, efficiency, cost effectiveness and environmental sustainability of an ATM system. ATFM aims to enhance safety by ensuring the delivery of safe densities of traffic and by minimizing traffic surges. Its purpose is to balance traffic demand and available capacity. ATFM relies on the clear definition of capacities (i.e. number of flights that can be handled by an airport or in a route sector), as well as on the analysis of forecasted traffic flows (number of traffic flows that are expected in an airport or in an en route sector). ATFM therefore relies on the exchange of information related to flights, airspace availability and capacity. With ATFM, the various system stakeholders collaborate to reconcile system resource constraints with economic and environmental priorities [11].

The dynamic nature of the terminal area necessitates the development of scheduling algorithms that are computationally efficient and therefore amenable to replanning when new traffic events occur [35], such as when a new aircraft enters the centre boundary or when data updates are obtained [5]. The challenge lies in simultaneously achieving safety, efficiency and equity, which are often competing objectives, and doing so in a reasonable amount of time [3]. Safety is achieved by maintaining separation between aircraft and by satisfying downstream metering constraints; efficiency is equivalent to achieving high throughput and/or low average delay; and equity is modelled by limiting the deviation from a nominal order or by minimizing variance in delay.

However, few solution approaches have been able to simultaneously model all three components and optimally solve the runway scheduling problem in a computationally tractable manner. One reason for this computational hurdle is that most runway scheduling models are, from a theoretical perspective, inherently hard to solve [9].

Lieder et al. [32] mention that no efficient methods have been proposed in the literature for the arrival-landing problem (ALP)

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that are capable of solving large problem instances. The most common solution approaches are dynamic programming (DP) approaches [20]; branch-and-bound (B&B) algorithms [2]; mixed-integer programming (MIP) formulations [9], which are solved with a standard solver; and heuristic solution approaches [36]. However, these implementations resort to heuristic or approximate approaches that produce "good" solutions in short computational times (not in real time) but are not suitable for large problems and therefore, not useful to apply in real environments.

Managing take-offs and landings of any airport is a complex problem that plays an important role in airport management. Runways and air controllers are limited resources, so air traffic needs to be planned carefully in order to limit peak demand and satisfy as many airlines' requirements as possible. However, unpredictable delays make it almost impossible to schedule planes with precision and in advance [4]. Indeed, the initial schedule needs to be reorganized when planes are close enough to the airport, i.e. when they approach the TRACON (Terminal Radar Approach Control Facilities – between 5 and 50 miles from the airport), or are on the ground (delays on the ground cost half as much as they do in the air) [31].

Hence, congestion delays materialize either on the ground, where aircraft have to wait before accessing a runway, or during the flight, where they are deviated from their intended trajectory. Delays may also propagate through the whole transportation network when the schedule buffers are tight. Congestion delays can be managed at a strategic level (by runway expansion or shorter separation standards), a pre-tactical level (by splitting flows and sectors) or a tactical level (by sequencing and re-sequencing aircraft) [27].

Our work deals with the fact that aircraft scheduling needs fast algorithms that help air traffic controllers to take real time decisions. These algorithms need to be able to process large amounts of data in a very short time. In this paper, we will evaluate a simulated annealing (SA) algorithm designed to calculate the landing and/or departure times, minimizing the total delay from the estimated landing time (ELDT) or from the estimated time of departure (ETD), subject to wake vortex separation (WVS) requirements and constrained position shifting (CPS). Following the Gwiggner and Nagaoka [27] classification, this research is placed at the tactical level and focused on airports with single, mixed-operation runways that need to optimize their resources to deal with capacity problems. We have considered three factors of interest for the algorithm evaluation: number of aircraft, wake-turbulence category and number of shifts of the aircraft from their initial position in the sequence. An important condition that we propose to cover is to obtain online results as requested in real operations. To our knowledge, no previous work has addressed this scenario.

The paper is organized as follows: Section 2 describes the problem of the runway bottleneck and different approaches that have been studied in this field. In Section 3, the proposed solution is presented and the SA algorithm defined. Section 4 provides a description of the experimental tests carried out in order to analyse the behaviour of the algorithm. Section 5 presents the numerical results obtained, not only from the experimental tests but also from the results of the algorithm in the real environment of Gatwick airport. Finally, a short summary is given in Section 6, together with suggested topics for future research in this area.

2. Problem description and previous approaches

The runway system, as a resource shared by all aircraft, creates a significant flow "bottleneck" that increases delays. The flow of aircraft entering the airport radar range is not very orderly [45], but a regular, balanced supply of arrival traffic is essential for the successful planning of dense arrival flows [37]. The main objective of this research is to explore the possibility of a time-efficient metaheuristic to develop an algorithm that minimizes deviations from the scheduled times of arrival and departure of flights in an airport. A scenario with a single, mixed-operation runway will be considered, the goal being to deliver schedules within a few seconds.

Based on the level of airport and air traffic control (ATC) system impact, as a result of a constraint violation, two types of constraint can be distinguished [3]:

- **Hard constraints**. Being inviolable because they affect safety, they must be satisfied by all generated solutions. One of the most limiting factors for the take-off and landing frequency in airports is the danger of wake turbulence. Wake vortex effects are generally proportional to aircraft weight and the lighter the following aircraft, the more it suffers from wake vortex effects, therefore demanding greater separation from the leading plane [4]. The required separation times between successive aircraft (the WVS) depend on the types of the two planes involved; the order in which aircraft land/take-off plays an important role in the capacity of the runway [7].
- **Weak constraints** can be violated but the smaller the violation the better the solution quality. An example is the scheduled take-off times (or slots). A slot is the scheduled time of departure or arrival available, or allocated to, an aircraft movement on a specific date at the so-called capacity-constrained airports (also referred to as slot-controlled, slot-restricted, slot-constrained, or slot-coordinated airports). In flight scheduling, flights have an optimal schedule time to respond to time-dependent demand and the requirement of frequency plans, of available fleets and of aircraft routings, among others. However, the capacity limit of runways could mean that some flights cannot operate at their expected time. Hence, it is acceptable to modify the schedule times of some flights from their optimal times [15].

Controllers have limited flexibility in reordering aircraft, and requirements in scheduling solutions are fairness and safety. In this study, WVSs (measured in minimum time separations between flights) will be considered as hard constraints, and time of arrival/departure and sequence order as weak constraints.

To tackle the latter, CPS is taken into account. The CPS approach is based on a fundamental underlying principle that involves the specification of a parameter, which limits the maximum number of position shifts (forward or rearward) that any aircraft will receive with respect to its first-come, first-served (FCFS) position [5]. Dear [20] observed that CPS increases the runway throughput rate, treats individual aircraft equitably and fits well within the capabilities of today's computers because updating the solution avoids "global" re-sequencing, amongst other characteristics.

Psaraftis [38] was the first to develop a polynomial-time algorithm for scheduling under CPS. This algorithm relied on all aircraft of the same type being identical, which did not accommodate time-window restrictions on aircraft or precedence relationships among aircraft, thus effectively scheduling all aircraft of a certain type in FCFS order. Trivizas [47] proposed a search-based algorithm. His model also failed to account for time-window restrictions and precedence constraints. The difficulty of incorporating all operational constraints within a CPS framework even led to a conjecture by Carr [16] that, in general, runway scheduling under CPS had exponential complexity.

Bianco et al. [14] consider two parameters, namely the maximum position shifting (MPS) to prevent an aircraft from being excessively delayed, and the relative position shifting (RPS) to limit the pilots' and controllers' workloads during aircraft resequencing.

Malaek and Naderi [34] described a new procedure for the real time dynamic scheduling of arrival aircraft via computing optimal sequences, which eliminates most of the shortcomings in k-CPS (k being the maximum number of position shifts) while respecting its optimal nature to minimize the makespan and mean delay time. The new approach, referred to as dynamic position shifting (DPS), allows operational considerations to be easily implemented. However, the complexity of computations increases linearly with respect to the total number of aircraft and runways, due to the elimination of recursive computations and the maximum number of allowable position shifting being computed dynamically as a function of traffic flow. Their algorithm behaves very similarly to that of FCFS in the normal traffic while it acts similarly to that of k-CPS methods in heavy traffic. However, it is only valid for arrivals as it is dependent on the transition times in the TRACON and the times required for aircraft to travel from the meter fixes to the runway threshold.

There is an interesting stream of research on models and algorithms for the control of a terminal manoeuvring area (TMA) that is based on job shop scheduling as discussed in Bennell et al. [10]. From this point of view, the TMA can be viewed as a single-machine [13] or as a job shop scheduling problem [10]. Bianco et al. [13] show that the scheduling problem is equivalent to the Cumulative Travelling Salesman Problem with Ready Times. The problem becomes more complex if both rescheduling and rerouting are implied in balancing the runway workload and minimizing delay propagation. When taking these two problems together into consideration, job shop methodology is a useful way of modelling the problem. Therefore, heuristic algorithms are required to compute good quality solutions in a short computation time [42]. D'Ariano et al. [18] use a truncated branch and bound algorithm to compute aircraft schedules with fixed routes which is then incorporated in a tabu search (TS) scheme for aircraft rerouting. Also Samà et al. [40] develop and compare different models for simultaneous aircraft scheduling and routing, including strong traffic disturbances.

However, none of them can offer online solutions with their approaches. D'Ariano et al. [19] developed three formulations based in graphs that offer online solutions by assigning to each aircraft the start time from the fixed, and all relevant points in such a way that all aircraft conflicts are resolved. Samà et al. [43] make use of alternative graphs, which consist of dividing the problem into multiple steps, enabling the dynamic management of aircraft for large time horizons. Graphs are also used by Samà et al. [41] to examine the trade-off between some classical performance indicators (tardiness, priority, throughput, and number of deadline violations) in a very complete and interesting study.

Other methodologies are present in the literature covering this scheduling problem. For example, Tavakkoli-Moghaddam et al. [46] examined ways of landing aircraft with the least waiting time in time windows under critical conditions using a fuzzy programming approach and an estimator for the landing sequence of planes. However, the degree of satisfaction for more than 20 planes in the sequence is less than unity, which makes this approach not particularly useful in real environments.

Ernst et al. [22] presented a specialized simplex algorithm, which evaluates the landing times, and then a problem space search heuristic is used as well as a B&B method for both single- and multiple-runway problems. Their objective is the landing problem meeting the separation criteria between all pairs of planes (not just successive ones) and where each plane has an allowable time window. However, the scenarios described consider no more than 50 planes.

Metaheuristics approaches are also present in the literature, including hybrid genetic algorithms (GAs). Ghizlane et al. [26] studied the multiple runway case of the aircraft landing problem (MRALP), through four hybrid algorithms that use two computational heuristic search techniques, namely, TS and GAs, offering competitive solutions in terms of quality and robustness. However, in the best-case scenario (instances of fewer than 50 planes), results are achieved in more than 50 s. Genetic search methods were previously studied by Hansen [28], with the purpose of investigating the utility of the genetic search approach using characteristic sets of TMA problems instead of particular solutions for certain airports, and also by Hu and Di Paolo [29] who designed a GA with uniform crossover to tackle the aircraft arrival sequencing and scheduling (ASS) problem in multi-runway systems. Other than scheduling, Liu [33] developed a solution procedure based on a genetic local search (GLS) algorithm for solving the runway dependent Airport Layout Plan (ALP) for determining the runway allocation, sequence and landing time for arriving aircraft. However, these algorithms are evaluated with small sets of planes and without considering their use in real environments.

Other metaheuristics that deal with more realistic scenarios were also considered. Pinol and Beasley [36] in their study presented the scatter search and bionomic algorithm applied to landing problems involving up to 500 aircraft and five runways.

None of these authors deals with the mixed-operation runway scheduling problem in real time and with a large number of flights in the sequence. One of the main purposes of this research is to develop an algorithm that can find good results in real time, in order to be applied in real situations.

3. Proposed approach

As stated above, the scenario considered is a sequence of flights in a single mixed-operation runway subject to CPS. The scope under research here is to develop a suitable model that finds a schedule as similar as possible to the optimal one in a very short time. The optimal schedule is a sequence of flights with target times satisfying the minimum safety separations that minimize the total delay time of the sequence considered. Note that we have not considered programming aircraft before their estimated time as some other, more schedule-oriented researches consider (e.g. Pinol and Beasley [36]; Salehipour et al. [39]), since this procedure is not always possible in the TMA (as it implies manoeuvring operations, taxiing, etc.). This objective allows not only reducing delays, but also maximizing runway capacity, thus reducing congestion at airports.

According to the review of the literature, both exact and heuristic algorithms have been developed for scheduling problems. Given the complexity of the problem, exact methods do not perform as required for medium-sized instances [39]; researchers are using heuristic algorithms as solution approaches for the problem. Although these algorithms do not guarantee optimal solutions, their performance in delivering competitive schedules in short periods of time makes them very attractive. When looking for a fast, metaheuristic model, SA is on many occasions the chosen alternative, given its performance as well as its simplicity [12,39].

The objective is thus to minimize delays in scheduled times – in other words, to minimize the total cost (delay in the target times) considering the two following constraints: a safety interval between successive operations determined by the WVS and the runway capacity of the airport; and forcing each aircraft to comply with the CPS restriction, which means that there is a limit to the maximum number of position shifts (forwards or backwards) that any aircraft will receive with respect to its FCFS position.

Fig. 1 illustrates a pseudocode for the SA algorithm, where S_{act} is the actual solution and S_{cand} is the candidate solution to be compared with S_{act}. The parameters used for developing the SA algorithm are:

```
INPUT (To, α, Tf , L)
T ← To
Sact ← Generate_initial_solution
WHILE T ≥ Tf DO
          BEGIN
          FOR cont ← 1 TO L(T) DO
                    BEGIN
                    Scand ← Select_solution_N(Sact)
                    δ ← cost(Scand) – cost (Sact)
                    IF (U(0,1) < e^(-δ/T) OR (δ <0)
                    THEN Sact ← Scand
                    END
          T ← α(T)
          END
{OUTPUT: best Sact visited}
```

Fig. 1. Simulated annealing algorithm structure.

T_o initial temperature
α lowering rate of the temperature
T_f final temperature
L number of times that the algorithm tries to find new solutions before decreasing the temperature

As usual, when implementing SA metaheuristics an initial solution is defined as the actual one S_{act}, to start exploring the solution space looking for a better candidate. To allow scape from local optima, with a certain probability $U(0,1) < e^{(-\delta/T)}$, SA accepts worse solutions during the search, allowing a more extensive exploration.

The variables used in the following model are:

N total number of flights in the sequence
WTC_i wake turbulence category of flight i (which can be light, medium or heavy)
WVS_{ij} wake vortex minimum separation between flights i and j
p_i flight in position i in the sequence solution
v_i position occupied by flight i in the sequence solution
e_i estimated time of landing/arrival of flight i
t_i target time of landing/arrival of flight i, computed taking into account the refined planning times and WVS requirements
δ Difference between the cost (S_{cand}) and cost (S_{act})
c_i Cost penalty for unit of delay of flight i

Table 1 shows the values considered in this paper for the separation times between pairs of aircraft. These are average values based on real information from different airports.

Some authors (e.g. Bennell et al. [10]; Chandran and Balakrishnan [17]) assume that the separations satisfy the triangle inequality, that is:

$$WVS_{ij} \le WVS_{ik} + WVS_{kj} \text{for all aircraft types } i,\ j,\ k \quad (1)$$

However, Balakrishnan and Chandran [5] prove that the triangle inequality does not necessarily hold when both arrivals and departures are scheduled simultaneously. Since we are considering mixed-operation runway airports, it is not possible for us to assume triangle inequality and therefore the target times are calculated for each flight i as:

$$t_i = \max\left\{e_i;\ t_j + WVS_{ji}\right\} \quad \forall j = 1,\ \dots,\ i\text{–}1 \quad (2)$$

The objective function can then be defined as:

$$\min C_s = \min\left(\sum\nolimits_{i=1..N} (|t_i - e_i|{*}c_i)\right) \quad (3)$$

One of the main challenges when designing SA algorithms is how to guarantee the generation of feasible solutions. In our particular case, a solution is feasible when its flights in the sequence fulfil the CPS condition, and in addition the wake turbulence category (WTC) separations are met.

Fig. 2 shows an example of the process of generating a feasible solution regarding the CPS constraint (note that WTC is easier to guarantee by just delaying the flight times accordingly).

In order to generate feasible solutions, our procedure randomly chooses a position n and defines the set Ω_n={n-CPS, n-CPS+1, …, n-1, n+1,…, n+CPS-1, n+CPS} containing 2Δ flights *"CPS-compatible"* with flight n. Here Δ=(2 × CPS) − 1 represents the number of flights that are potentially exchangeable with flight n.

Then, it is necessary to find an element n'∈Ω_n fulfilling (4) and (5).

$$v_{n'} \in \left\{n\text{–CPS},\ \dots,\ n\text{+CPS}\right\} \quad (4)$$

$$p \in \left\{n'\text{–CPS},\ \dots,\ n'\text{+CPS}\right\} \quad (5)$$

In order to look for n', the different elements of Ω_n are randomly evaluated until an n' is found that meets both conditions. If both conditions are met, it is guaranteed that the exchange (or swap) of n and n' will lead to a new feasible solution S_{cand} which will be evaluated and compared with S_{act}. Note that it will always be possible to find a feasible solution around S_{act}, although not for any pair (n, n') will it be possible. For example, let us suppose an initial sequence {1,2,3} with CPS=1. If we obtain a random position n=2 and swap it with n'=3, the sequence then becomes {1,3,2}; if the next random position number is n=1, then we cannot find a CPS-compatible n' with which to swap flight 1. However, there will always be a feasible solution, which is returning to the initial sequence {1,2,3}.

If the cost of S_{cand} is lower than the cost of S_{act}, then the new current solution would be S_{cand}. In order to escape from a local minimum, the SA algorithm allows some worse solutions S_{cand} to become S_{act} with a probability $U(0,1) < e^{(-\delta/T)}$.

Table 1
Separations considered for each pair of aircraft WTC.

WTC leader	WTC follower	Separation (s)
H	H	1000
H	M	300
H	L	300
M	H	180
M	M	180
M	L	180
L	H	60
L	M	60
L	L	60

4. Experimental framework

Once the SA algorithm has been defined, a set of tests has to be conducted in order to validate the behaviour of the algorithm. The idea is to generate a large number of random instances for which we know the optimal result and compare them with the solutions found by the algorithm.

Three factors have been identified in the previous literature review as potentially influencing the results obtained. In order to quantify how relevant these factors are, we have introduced them in the procedure for the generation of the instances:

- **F1.** *Wake turbulence category of the flights* in the sequence. We have considered two different situations: one in which all the flights have WTC=Medium (F1.1.) and another where all flights have a random WTC (F1.2.) between the three categories considered (Heavy, Medium and Light). This allows us to analyse

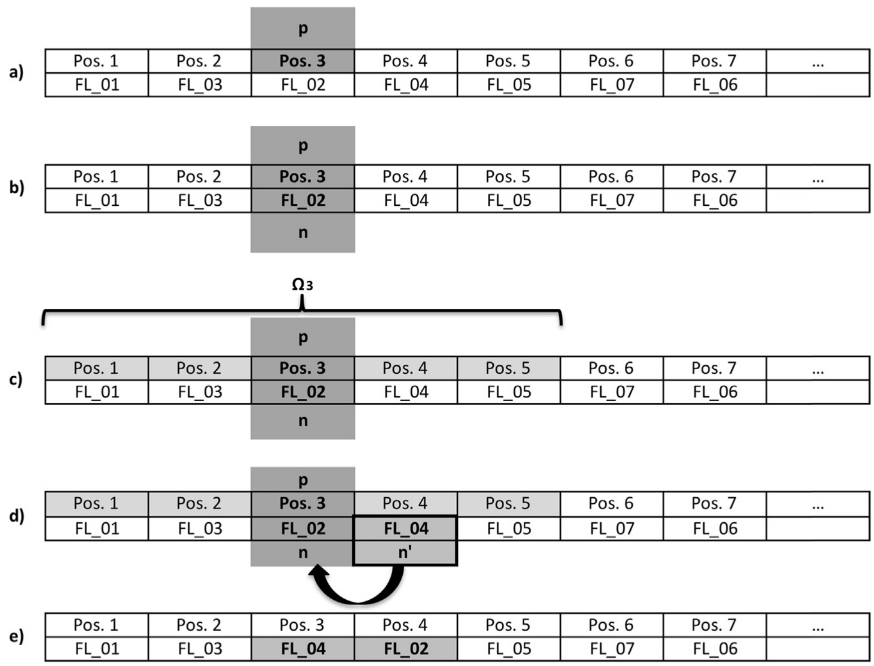

Fig. 2. Process for generating a CPS feasible solution (CPS=2): (a) Choose a random position p; (b) Find the flight occupying position p; (c) Calculate the range of positions (Ω_3) that could be exchanged with flight n; (d) Choose a random flight n' from Ω_3 fulfilling (4) and (5); (e) Exchange n and n' to obtain a valid solution.

whether having planes of the same WTC (i.e. each of them needs to satisfy the same separation between them, so the triangle inequality is satisfied) is relevant or not for the performance of the algorithm.

- **F2.** *Constrained position shifting*. Five levels have been chosen for CPS={1; 2; 3; 4; 5}, bearing in mind that controllers always wish to keep the sequence as similar as possible to the FCFS sequence received.
- **F3.** *Number of flights*. In order to have a realistically managed size sequence of planes in an airport with a single runway that can be held for a short period of time (couple of hours), we have studied sequences of 50 (F3.1), 100 (F3.2), 150 (F3.3) and 200 (F3.4) flights. Although it is not realistic for a real airport to consider so large a sequence in a mixed-operation runway (the maximum throughput capacity for a homogeneous fleet mix on a single runway is 60 flights per hour [44]), this will allow us to check the ability of the algorithm to manage extremely large instances.

4.1. Instance generation

As previously outlined, once the factors have been identified, it is necessary to generate a set of instances for which we know the optimal solution. This means generating instances of the different number of flights considered (F3) with cost 0 that fulfil the WTC considerations. These instances are then randomly shuffled in respect of the five levels of CPS considered (F2). The instances generated as a result are then considered as the input FCFS sequences for the algorithm.

Regarding the total number of instances to generate in our experiments, 50 replications were generated for each of the $2 \times 5 \times 4$ factor level combinations of the three factors considered, giving a total of $40 \times 50 = 2000$ instances. We have considered that the penalty cost for unit of delay of flight plan i is one in the generation of these instances.

The procedure followed to generate such feasible instances with cost 0 is the following:

1. Let us suppose the flight sequence $< 1, 2, 3, 4, \ldots >$ is the optimal solution

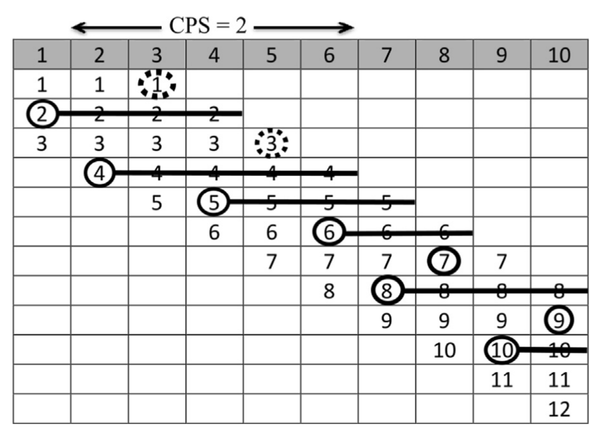

Fig. 3. Example of instance generation (CPS=2). At each iteration (column) a flight not deleted is randomly chosen, avoiding it from being selected later. When it is the last opportunity for a flight, it is forced to be chosen (case of flight 1 in column 3). Final feasible sequence: $<2; 4; 1; 5; 3; 6; 8; 7; 10; 9; \ldots>$.

2. The optimal estimated times of the flights in the sequence are calculated, taking into account their WTC separation restrictions.
3. In order to shuffle the flights according to the CPS limitation, a data structure is generated. Each column represents the position of a flight in the sequence and contains all the possible flights that can be in that position respecting the CPS limitation.

Fig. 3 shows an example of the last step for CPS=2. For example, flight 4 can be moved to positions (columns) {2, 3, 4, 5, 6} respecting the CPS=2 limitation. In order to create the random sequence that fulfils the CPS condition, we follow the next steps:

i. Starting in the first column, we randomly choose a value among those possible (for example 2 in Fig. 3).
ii. The flight selected in the previous step is deleted from all the following columns in order not to select it again (since it is not feasible to have a repeated flight in the sequence).
iii. Go to the next column. If the flight in that column is its last chance to be selected, it is automatically chosen (in Fig. 3, flight

Table 2
Descriptive results for improvement (%) regarding α and T_o parameters in the initial tuning process.

Parameters	Levels	Mean	Standard deviation	95% Confidence Interval	
				Lower bound	Upper bound
α	0.9900	91.404	0.195	91.020	91.787
	0.9990	95.360	0.195	94.977	95.744
	0.9999	96.806	0.195	96.423	97.190
T_o	200	94.073	0.195	93.690	94.457
	600	94.668	0.195	94.285	95.052
	1,000	94.829	0.195	94.445	95.212

1 of the third column). This happens when we are evaluating a column j where there is still available the flight j-CPS (it has not been deleted in previous steps). If not, repeat the previous step for the successive columns.

4.2. SA parameters tuning

The SA parameters are, as mentioned above, the initial (T_o) and final (T_f) temperatures; the cooling rate (α); and the number of iterations at a certain temperature (L), which was fixed at one.

In order to determine the optimal values for T_o, α, T_f, three levels of each parameter were considered based on previous tests and SA literature [1,21,48]: $T_o \in \{200, 600, 1000\}$; $\alpha \in \{0.99, 0.999, 0.9999\}$; $T_f \in \{0.01, 0.001, 0.0001\}$. Choosing five instances out of the 50 generated for each of the $2 \times 5 \times 4$ combinations of levels, makes a total of $(40 \times 5) \times 3^3 = 5400$ runs of the algorithm for testing the SA parameters.

Given that the data collected do not fulfil the normality assumptions (Kolmogorov-Smirnov $p = 0.000$), in order to study the influence of each of the factors in the minimization of the cost (or maximize the improvement percentage), a Kruskal-Wallis analysis seems to be the most appropriate. The results of this non-parametric analysis confirm that there are highly significant differences between the factors considered for both levels of α ($p = 0.000$) and T_o ($p = 0.043$), but not for T_f ($p = 0.567$). Level 3 of both significant factors shows the best results (Table 2). Therefore, $\alpha = 0.9999$, $T_o = 1000$ and $T_f = 0.01$ are the values chosen for the experiments to be carried out.

5. Results

In this section we present the results obtained by the algorithm proposed with the SA parameters tuned according to Section 4.2. We have used the testbed of 2000 instances generated in Section 4.1, the 12 instances publicly available from OR-Library [8] involving from 10 to 500 aircraft, and finally a real sequence of flights from Gatwick airport. The results are measured in terms of percentage of improvement,

$$\% \text{ improvement} = (C_{FCFS} - C_{solution}) / C_{FCFS} \tag{6}$$

where C_{FCFS} and $C_{solution}$ are the costs of the FCFS solution and the found solution, calculated as described in Eq. (3).

5.1. Testbed

As can be seen in Fig. 4, for 828 out of 2000 instances (41.4% of the total of instances generated), the algorithm was able to find the optimal solution (which means finding the sequence of cost 0); a 98.65% of instances achieved more than a 95% improvement in the cost of the sequence.

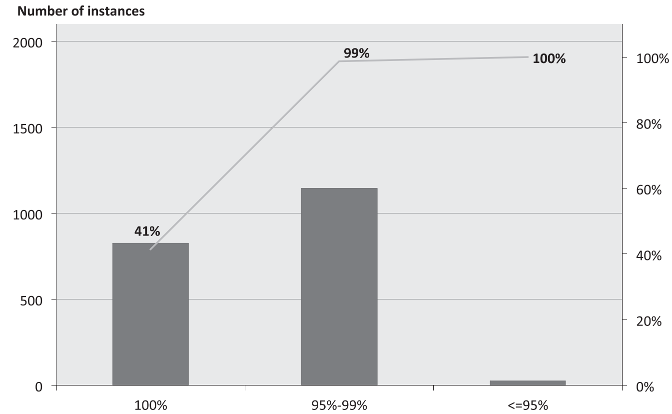

Fig. 4. Pareto chart for the improvement obtained for the 2000 instances generated. The SA algorithm finds the optimal solution for 41.5% of the instances, while only for less than 2% of the cases, the improvement found by the algorithm was smaller than 95%.

A Kruskal-Wallis test was performed in order to test the importance of the three factors considered. Results show that F3 (i.e. number of flights) is not as significant ($p = 0.214$) in the explanation of the improvement as are F1 ($p = 0.001$) and F2 ($p = 0.000$). This means that our algorithm's efficiency does not depend on the number of aircraft in the sequence considered. As shown in Table 3, factor F1.2 (different types of plane) and factor F2.1 (CPS = 1) were found to be the most difficult to manage for the SA algorithm developed. These results are reasonable as factor F1.2 implies more complexity since the triangle inequality is met and when CPS = 1 the number of possible reassignments of the aircraft in the sequence to find their best position is smaller. On the other hand, and as would be expected, the best results are achieved for high values of CPS (F2) and only one type of plane (F1.1).

Table 3 also shows the average percentage GAP as defined in Pinol and Beasley [36]. The values of the GAPS obtained show that our algorithm is able to find the optimal solution in all the cases. Lower bound values show that the worst case is a 90% improvement for some cases.

As mentioned in the objectives, computational time is very important in this study. Figs. 5 and 6 show that really good results are obtained in less than one second. As would be expected, results improve as the algorithm makes more interactions (i.e. as we allow longer computational times). As can be seen in Fig. 5, in the 15,000 iterations, the results reached average improvements of 80% in just 0.15 s while the 100% average improvement (i.e. solution sequence cost is 0) is reached in 0.25 s (in the 30,000 iteration)..

Fig. 6 shows the evolution of the improvement for the 2000 instances in different iterations. It can be seen that in the last iteration (50,000) almost all the instances have an improvement in the cost of the sequence higher than 95%.

5.2. OR-library instances

For the sake of comparison with some publicly available sets of instances, we have considered the 13 aircraft landing data files from the OR-Library [8]. In order to be able to process those 13 instances, we needed to perform some necessary adjustments, given that those instances were not designed exactly for the problem we are considering:

- We have considered that the order of the flights in the files is the FCFS sequence.
- We have considered as the estimated time of landing the target landing time.

Table 3
Descriptive results for improvement (%) regarding F1, F2 and F3. Percentage GAP means the difference in percentage between the optimal solution and the best solution. Lower bound shows the worst result obtained by the algorithm. The standard deviation shows the amount of variation of the results obtained in these trials.

Factors	Levels	Mean	Average percentage gap	Lower bound	Std. deviation	95% Confidence interval	
						Lower bound	Upper bound
F1	1	99.877	0	90.36	0.329	99.857	99.897
	2	98.789	0	92.23	1.032	98.725	98.854
F2	1	98.733	0	90.36	1.580	98.573	98.892
	2	99.373	0	90.36	0.791	99.295	99.451
	3	99.564	0	97.81	0.511	99.513	99.614
	4	99.537	0	95.51	0.520	99.486	99.588
	5	99.460	0	94.29	0.607	99.401	99.520
F3	50	99.369	0	90.77	0.952	99.284	99.453
	100	99.320	0	92.63	0.916	99.239	99.401
	150	99.363	0	92.20	0.879	99.285	99.441
	200	99.309	0	90.36	0.994	99.222	99.397

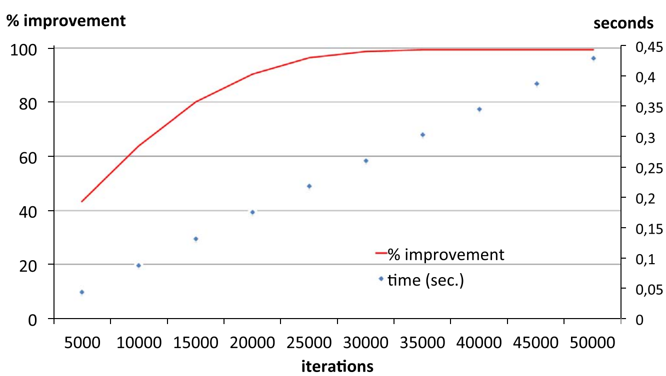

Fig. 5. Evolution of the percentage of improvement (continuous line) and computational time average (dots) in seconds for the 2000 instances generated.

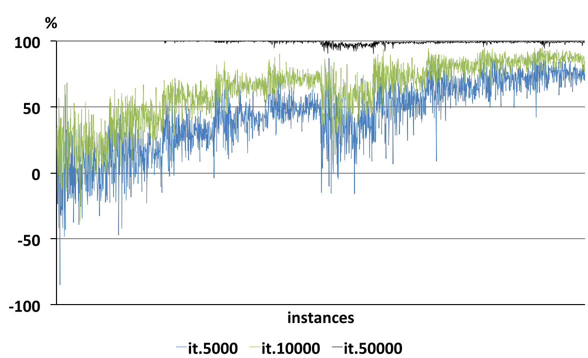

Fig. 6. Average of the percentage of improvement for the 2000 instances, depending on the number of iterations.

- Although no data about the WTC of each flight or the aircraft type is provided by the OR-library, they consider a matrix of separation time required between pairs of flights, what we can use directly.
- Since the CPS concept is not present in the OR-Library, we have computed the instances for a range of CPS values, starting at 1 and up to 49 for all the instances.

Results are compared to those obtained by Pinol and Beasley [36] and Salehipour et al. [39] in Tables 4 and 5. Table 4 shows a comparison between the percentage of improvement of the best solution found both by Pinol and Beasley [36] and Salehipour et al. [39], and our SA, calculated related to the cost of the FCFS sequence. As expected, the majority of the results obtained by these two sets of authors are slightly better than the SA approach since

Table 4
Comparative results for improvement (%) related to the FCFS sequence between the Z_{best} result of Pinol and Beasley [36] instances and the SA solution.

	$\%improvement_{best}$	$\%improvement_{SA}$
Airland1	98.26%	97.14%
Airland2	97.26%	96.81%
Airland3	98.58%	97.21%
Airland4	96.81%	94.33%
Airland5	96.44%	94.49%
Airland6	0%	58.42%
Airland7	60.99%	0%
Airland8	98.92%	98.30%
Airland9	84.77%	72.22%
Airland10	77.21%	55.37%
Airland11	81.30%	67.10%
Airland12	80.21%	65.84%
Airland13	74.91%	62.33%

their algorithms allow flights to land earlier than their estimated time, while ours does not consider this possibility based on usual airport operations. In spite of that, the percentage of improvement is not very different in most cases. The Airland 6 case deserves a special mention as our algorithm is able to improve on the results offered by the other authors. We must say that Airland 6 is the only case in which the data do not allow us to consider an earlier time of landing since the earliest landing time is equal to the ELDT. This is the situation for which the SA algorithm was designed, which makes it reasonable to claim that the percentage improvement of the rest of the cases is obtained from considering earlier times of landing.

The advantage regarding computational times of the SA algorithm as pursued (see Table 5) must be stated, given the necessity of obtaining online support. Therefore, the SA algorithm is able to obtain competitive improvements in the cost of the sequences (in most cases in less than a second), even for those instances which are not exactly aimed at the problem they tackle. Fig. 7 shows a comparison between the percentage of improvement of our algorithm and the optimal results of the instances. It also reflects the difference in processing time, denoting as the processing time of Pinol and Beasley [36] and Salehipour et al. [39], the minimum obtained by their algorithms.

5.3. Case study

Once the validity of the proposed approach has been established using the generated testbed, it is interesting to see what the algorithm behaviour is when using real data. For this purpose, Gatwick airport was chosen because it is the UK's second largest

Table 5
Comparative results of processing time (s) results for Pinol and Beasley [36] instances for the following algorithms: SA, BA (Pinol and Beasley [36]); CPLEX, SA+VND, SA+VNS, SS (Salehipour et al. [39]); SA (the proposed algorithm).

	Pinol and Beasley [36]		Salehipour et al. [39]				SA
	$time_{SS}$	$time_{BA}$	$time_{cplex}$	$time_{SA+VND}$	$time_{SA+VNS}$	$time_{SS}$	$time_{SA}$
Airland1	4	60	0.66	0	0	4	0.42
Airland2	6	90	0.49	1.59	1.38	6	0.55
Airland3	8	99	0.39	1.78	1.73	8	0.71
Airland4	8	95	5.12	1.98	2.85	8	0.73
Airland5	9	100	20.44	1.85	1.89	9	0.70
Airland6	158	274	0.1	2.12	2.14	158	0.92
Airland7	195	79	0.86	2,68	2.65	195	1.3
Airland8	42	287	0.98	7.1	7.31	42	1.46
Airland9	119	554	1000	11.59	10.12	119	2.18
Airland10	227	925	1000	20.12	20.75	227	2.54
Airland11	256	1417	1000	24.17	33.84	256	2.85
Airland12	381	2011	1000	219.03	198.85	381	3.31
Airland13	1237	5852	1000	566.82	528.84	1237	4.59

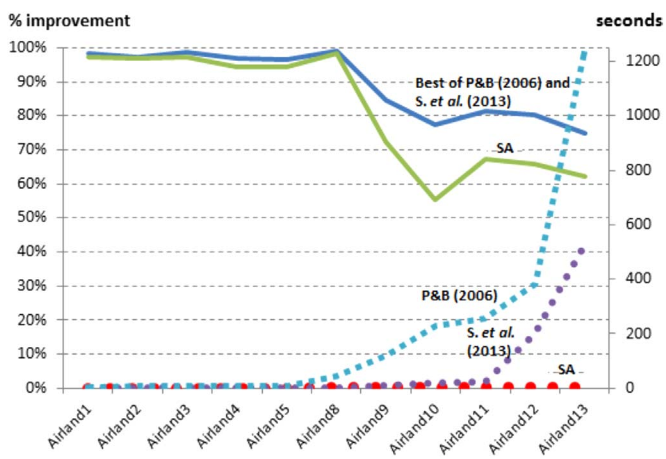

Fig. 7. Comparison of different algorithms using the OR-Library instances, regarding percentage of improvement (continuous lines) and computational time .in seconds (dotted lines).

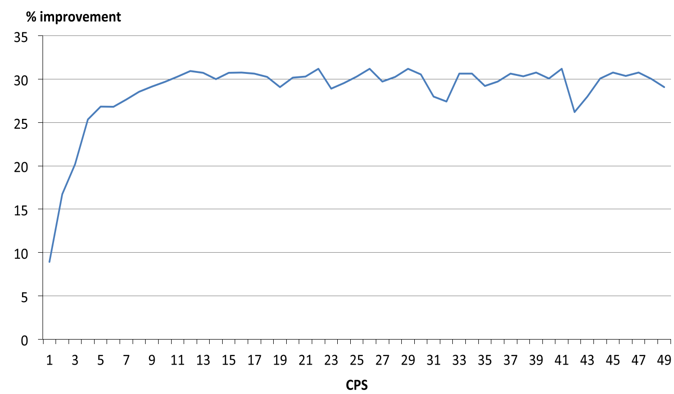

Fig. 8. Evolution of the percentage of improvement for Gatwick airport real data, for different CPS values.

airport and is the busiest single runway commercial airport in the world [25].

Flight information was collected from 7th September 2015 from 6:00 am to 9:00 am [23]. Unfortunately, FlightRadar provides only scheduled times and not real times at the runway for landing and taking-off. Therefore, in order to compute this real flight information, the following assumptions have been made:

- The FCFS sequence has been created by arranging the flights according to their "ready time" to land or take-off. Our algorithm considers the time that the plane is at the runway, i.e. "ready time" represents the time where the plane is at the runway ready to take-off or touching the runway at landing. Taking this in mind:
  - The "ready time" for a take-off has been calculated as its scheduled time plus its real taxi time from the stand to the runway.
  - The "ready time" for a landing has been calculated as its scheduled time less its real taxi time from the runway to the stand.

The minimum time separation depending on the WTC of each flight considered is based on Malaek and Naderi [34]. Since the WTC was not provided by FlightRadar24, it has been obtained by searching for the aircraft model (which is provided by FlightRadar24) in the International Civil Aviation Organization's (ICAO) database.

CPS is a theoretical parameter, so we have used 49 different values (from 1 to 49) to see how this parameter can influence the results in a real case and thus try to determine the optimal value of CPS. The SA parameter values used were the same as in our test-bed experiments, and found to work better.

The real cost of the sequence (calculated as the deviations of the actual landing/take-off times of the flights) is 1492 min. Our algorithm is able to reorganize the flights to obtain an average cost of 507 min of deviations, which means the total delay is reduced to a third of the real delay.

Fig. 8 shows the evolution of the percentage of improvement depending on the CPS after running the SA algorithm. It can be seen that the improvement rises up to 30% for CPS 10. This improvement is calculated as mentioned before, by comparing the result with the cost of the FCFS sequence. This means that allowing flights to move up to 10 positions respect their initial position in the sequence, results in a reduction of the delay of the total sequence; however, allowing flights to move more positions respect the initial FCFS does not mean that the total delay of the sequence continues improving.

Regarding its potential implementation, the algorithm is able to deliver its solutions in less than one second, which is a reasonable computational time to be used in real environments, where controllers are used to obtaining online solutions.

It is worth noting that comparing the behaviour of the algorithm using real data has certain limitations. Flightradar24 [23] only provides the scheduled times of flights, which are the ones we consider as estimated times. However, flight operations suffer from unexpected delays (related to technical problems or weather conditions for instance) that we cannot predict and take into account in the tests performed with our algorithm. However, knowing the last update of real estimated times, the algorithm is able to find better solutions by incorporating these delays in the calculation of the optimal target times for the sequences considered.

When implementing this algorithm in real environments it would be necessary to agree the value of the CPS parameter with the controllers in order to obtain the best performance of the algorithm that satisfies their requirements of minimizing the movements of flights in the initial sequence.

6. Conclusions

Airports have a serious problem of saturation. A good schedule of runways is critical, but not many optimization tools have been implemented on sites that are able to deliver quick and efficient schedules.

In this paper, an SA algorithm for a specific case (considering WVS and CPS as constraints) has been tuned and developed. The analysis of the results, after an extensive experimental framework had been carried out (involving 2000 instances for validating the algorithm results), shows that for improvements of 95% in the deviation from the target schedule, the algorithm presents good results in most cases, with just 15,000 iterations, in less than a quarter of a second. High CPS and only one type of plane make it easier to solve the problem. Up to 200 planes were considered in our data, with no reduction in efficiency.

In addition, a comparison with other algorithms that used a public library shows that our algorithm obtains competitive results in a significantly less time, fulfilling the objective of its online use. Also, real data from Gatwick airport were used to test the behaviour of the algorithm in a real situation, obtaining around a 33% improvement in the total delay of the sequence considered. Therefore, the algorithm can be used in real environments since the results are achieved in a very short time (less than one second in most cases) and the improvements in the cost of sequence (without varying the FCFS sequence completely) are valuable.

There are a number of topics for further research. In particular, taking slots (or time windows) into account to make the algorithm more flexible and allowing flights to come in ahead of their scheduled time would add value to this approach. Also, extending the problem to multiple runways would be interesting, as main and busier airports usually have a multiple-runway configuration. Finally, the possibility of considering as an objective not only the total reduction delay but also the priority of flights would be interesting.

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A review of the impact of noise restrictions at airports

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ABSTRACT

One of the biggest obstacles to the building of new airports and expanding runway capacity is environmental concerns, especially noise. In this paper, we review what has been previously studied in the literature concerning the noise reduction problem around airports from the Air Traffic Control (ATC) perspective. In order to facilitate the knowledge of the current situation, a regulation summary from the USA and EU is provided. We mainly focus our research on operational procedures, since they are one of the easiest improvements nowadays for reducing the impact of noise around airports. Moreover, the paper sums up the modelling, monitoring and simulation tools related to noise at airports proposed in the literature. Finally, special care is taken to review the optimization tools, the objective of which is to take into account the noise problem in order to help, or propose alternatives, to reduce its impact from airport operations.

1. Introduction

Airbus's Global Market Forecast 2015–2034 highlights that today, 47 aviation mega-cities are focused on over 90% of long-haul flights and nearly a million passengers a day, with 39 of the 47 experiencing various levels of congestion (Airbus, 2014). Demand is being met through more of the latest technology aircraft, and by airlines striving to increase their efficiency by filling every available seat, with average load factors now close to an impressive 80%. Air traffic demand is expected to more than double in Europe and the US, and perhaps triple in some regions, over the next 15 years (Airbus, 2014). Therefore, one of the central challenges facing the aviation industry is air traffic demand growth, which results in congestion in many airports, primarily hubs (Flores-Fillol, 2010).

Meeting this increased demand is challenging for all the industry stakeholders. Airlines around the world have responded by developing their networks and using larger aircraft. Building new airports and expanding the runway capacity of existing ones is another possible solution, but limited by environmental concerns, including noise disturbance, emissions, water pollution and habitat destruction (Laurenzo, 2006). Some impacts arise from the operation of the airport, others as a result of providing additional airport infrastructure (Upham et al., 2003). Making the most efficient use of the current infrastructure by Air Traffic Management (ATM) would be the best alternative to balance demand and runway capacity with environmental restrictions.

Aircraft noise is a particular problem during landing and take-off (Ignaccolo, 2000). Noise, described as unwanted sound (Schmidt, 2005), is known to have several adverse effects on humans, such as hearing loss, communication interference, sleep interference, higher levels of self-reported stress, anxiety, depression, psychological morbidity, annoyance,

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hypertension and coronary heart disease (Janssen et al., 2014; Salah, 2014; Ozkurt et al., 2014; Vogiatzis, 2012). Ongoing technological advances are likely to result in quieter engines, and aircraft operating from short and underutilized runways (Schneider et al., 2010). Other options that are in use today are sound insulation of buildings or land use procedures (Ganic et al., 2015). However, in order to reconcile system resource constraints with economic and environmental priorities, all the involved stakeholders (governments, aircraft manufacturers, ATC) are requested to collaborate (Bertsimas et al., 2011).

The objective of this paper is to review how airport capacity is limited by noise restrictions, with the aim of analysing the potentiality of using scheduling optimization tools in order to confront the problem. Analysing what measures are being taken today to deal with noise reduction and what can be improved from the ATC point of view, focusing on operational alternatives and models, might be interesting in order to have a starting point to understand the problem. To facilitate knowledge of the current situation about noise restrictions, a regulation summary is provided. Operational procedures are also reviewed since they are one of the easiest improvements today for reducing the impact of noise in the areas surrounding airports without impacting on airport capacity. Moreover, the paper sums up the modelling, monitoring and simulation tools related to noise in airports, that exist in the literature, since a review of this field has not been found so far and it is necessary to understand how noise impact is calculated. Finally, as already mentioned, special care is taken to review optimization tools that take into account the noise problem in order to help, or propose alternatives, to reduce it and how this impacts on airport capacity.

This paper is organized as follows. Section 2 provides a description of the methodology followed. Sections 3 and 4 describe the environmental issues concerning air traffic growth. Section 5 provides a review of the legislation, mainly from USA and Europe. Section 6 analyses another way of minimizing noise, though noise abatement operational procedures. Section 7 describes the different modelling, monitoring and simulation tools found in the literature referring to noise around airports. Section 8 deals with optimization tools and algorithms that take into account noise restrictions. Finally, a short summary is given in Section 9, together with suggested topics for future research in this area.

2. Review methodology

A literature review is useful to provide a historical perspective of the respective research area as well as a benchmark for comparing the results with other findings (Creswell, 2013). In our case we have applied a Systematic Literature Review (SLR) (Denyer and Tranfield, 2009) consisting of five steps. The first is the definition of the context, intervention, mechanisms and outcome (CIMO) of the study. In our case, this is studying how noise reduction has impacted on runway capacity from an operations point of view.

The next two steps in an SLR are the location of studies, and their selection and evaluation. Here, the literature search was carried out through the Scopus database. We considered also conference papers and documentation from international organisations (such as ICAO, SESAR, FAA) since the subject under research is of a wide scope, and official reports could add something to the study. Regarding the time horizon, we have not limited it, but all the papers found that focus on the impact of noise were from 1998 until 2016. The keywords used are: {"airport capacity" OR "scheduling" OR "procedures" OR "optimization"} AND {"noise reduction" OR "aircraft noise"}.

After a first scrutiny, some of the collected papers were discarded because they did not fit exactly the theme of the review study, leaving a total of 131 papers or official documentation. We found a large amount of papers related to noise influence on health or sound insulation that were discarded since these topics are not related to runway capacity.

The last two steps are the analysis and synthesis of the papers, and to report and use the results, which we cover in the following sections.

3. Environmental challenges in airports

The aviation industry understands that environmental responsibility is a critical component of its licence to grow. Aviation was the first sector in the world to agree to an ambitious set of global carbon dioxide (CO_2) emissions-reduction targets, which include carbon neutral growth from 2020 and a 50% reduction in net CO_2 emissions by 2050 compared to 2005 levels (ICAO, 2013). Aviation stakeholders have committed to achieve these through a four-pillar strategy including improved technology, more efficient infrastructure, and better operations.

Environmental assessment (evaluation and review, research and monitoring), environmental management (comprehensive planning that takes into account the effects of humankind's activities on the environment) and supporting measures (education, training, public information, financial assistance and organizational arrangements), are key in any approach towards successful environmental management (Abeyratne, 2002).

According to Single European Sky ATM Research (SESAR), the two main environmental issues associated with aviation are *emissions* and *noise* (SESAR, 2016). On the other hand, according to the Next Generation Air Transportation System (NextGen), the primary environmental issues that influence the capacity and flexibility of the National Airspace System (NAS) are aircraft noise, air quality, climate, energy, and water quality (Hughes et al., 2012). Both NextGen and SESAR agree therefore on two objectives: emissions and noise (Table 1).

Global emissions are related to climate change since aircraft emit gases and particles in direct proportion to the quantity of fuel burned directly into the upper troposphere and lower stratosphere; CO_2 is also emitted at airports through various

Table 1
NextGen (FAA, 2016) vs. SESAR (2016) environmental objectives.

NextGen (USA)	SESAR (EU)
Climate	Global emissions
Air quality	Local emissions
Aircraft noise	Noise
Water	
Energy	

airport operations, such as ground support vehicles and passenger surface transport vehicles. Globally, the aviation industry accounts for around 2% of all human-induced CO_2 emissions (ATAG, 2014).

Local emissions refer to aircraft operations at airports (landing and taking off, taxiing, fuel storage, engine testing and the use of auxiliary power units) that impact on local air quality through pollutants emitted during these operations. Additionally, other airport operations, such as the use of ground support equipment, airport air-conditioning, passenger cars, and many others, also affect local air quality.

Generally aircraft noise is influenced by particular factors such as the number of flights, their timing, the type of aircraft, and the flight path. Aircraft noise is a disturbance produced by any aircraft or its components, during flight, taxiing, landing and take-off. Sari et al. (2014) classify the origins of this noise into three main sources: the aerodynamic noise, the aircraft engine and other mechanical sources, while Arntzen and Simons (2014) classify aircraft noise into two categories: engine noise and airframe noise.

4. Reducing the impact of noise in airport surroundings

One of the reasons for an increase in the number of people affected by negative noise is the rise of populations in cities and their territorial expansion, since residential areas have become closer to airports (Ganic et al., 2015). Reducing the environmental impact of growing traffic demand leads to severe problems for balancing airport expansion requirements (Arntzen and Simons, 2014; Visser et al., 2008).

In 2001, the International Civil Aviation Organization (ICAO, 2001) Assembly endorsed the concept of a Balanced Approach to aircraft noise management, which was reaffirmed in 2007 (ICAO, 2007). In the Balanced Approach, the ICAO has defined four key elements that can be used to achieve an effective reduction in aircraft noise without compromising safety standards (which have to take precedence over environmental protection):

- Noise reduction at source, i.e. the aircraft. This includes the use of quieter aircraft and the implementation of noise-reducing measures on the engines, wings and landing gear of existing aircraft fleets.
- Local measures in the vicinity of the airport. These include a land-use plan tailored to noise protection zones, passive noise control and noise based take-off and landing charges.
- Noise abatement operational procedures in the air and on the ground. The range of innovative flight procedures being tested at various airports includes the continuous descent approach as well as satellite-supported approach procedures or measures that help to cut engine use on the ground. Both landing and take-off operations are critical from a noise point of view.
- Noise-based operating restrictions. These are any noise-related actions that limit or reduce an aircraft's access to an airport. They should not be used as a first resort, only after consideration of benefits gained from the other three elements, for example, noise quotas or curfews.

Following these ICAO (2007) key elements, we could classify the different noise mitigation opportunities that Capozzi et al. (2002) explore in their study, as shown in Table 2.

Various authors refer to real data from airports in their analysis. For example, Netjasov (2012) establishes a relationship between noise reduction measures used by 615 airports worldwide and the Balanced Approach categories.

Lijesen et al. (2010) constructed a bottom-up cost function, based on measures for noise reduction, such as alternative approach paths, fleet substitution and reduction of the number of flights for Amsterdam Airport. The conclusion from their analysis is that fleet substitution and alternative approach paths are viable ways to reduce noise, since reducing the number of flights can be too costly.

Another important issue is how noise is measured and in which units. A large variety of acoustic descriptors are used to describe aircraft noise (Ruijgrok, 2004). In order to select an aircraft noise descriptor, it is necessary to adjust to the issue being examined. However, the most common noise indices are expressed in terms of dB. Noise policy and legislation are most often based on average noise levels: L_{eq} (represents the time average of the total sound energy over a specified period) and its three special variants: L_{dn} (day-night average sound level), L_{den} (day-evening-night average sound level), and L_{night} (long term average sound level determined over all the night periods of a year). All of them are described in detail by Visser et al. (2008). Obviously, much information about traffic noise patterns and sound levels of individual vehicles is not taken into consideration using these average noise indices (Hume et al., 2012). In order to remediate this, regional indices

Table 2
Capozzi et al. (2002) vs. ICAO Balanced Approach (2007) noise mitigation approaches.

ICAO Balanced Approach (2007)	Capozzi et al. (2002)
1. Noise reduction at source	–
2. Local measures in the vicinity of the airport	–
3. Noise abatement operational procedures in the air and on the ground	Noise-sensitive ATM approach procedures: – Avoid dive and drive – Base leg extension into noise sensitive areas – Side-step approaches Noise-sensitive ATM departures procedures: Direct climb-to-cruise Route tracking: – Stay in precise route corridor – Follow routes over low population areas – Avoid shortcutting
4. Noise-based operating restrictions	Runway/route selection: – Fan across region – Routing older aircraft to less noise-sensitive runways – Increase the usage of noise-preferred runways Airport interactions within a Terminal Radar Approach Control (TRACON), modifying existing procedures to consider noise Night time operations: – Extend procedures to higher traffic levels – Improve efficiency so that night time operations can be initiated on time

are suitable to assess aircraft noise development around an airport: Zurich and Frankfurt airports are using the ZFI (Zurich Aircraft Noise Index) and FFI/FNI (Frankfurt Aircraft Noise Index/Frankfurt Night Index) indices respectively to measure noise impact (Schäffer et al., 2012; Schreckenberg et al., 2009). The ZFI is a noise effect index describing the integral effects of aircraft noise (annoyance and sleep disturbance) on the population in the vicinity of Zurich airport, integrating the considered noise effects to a single number valid for the whole airport (Schäffer et al., 2012). FFI describes the number of subjects highly annoyed by aircraft noise in areas within L_{dn}-contour 55 dB based on the 24 h of the day. FNI solely serves to assess nocturnal air traffic by displaying the number of awakenings additionally induced by aircraft noise emitted between 10 pm and 6am, including regions where at least 0.5 additional aircraft noise induced awakenings are expected (Schreckenberg et al., 2009).

5. Noise regulation

At a global level ICAO is responsible for developing standards for noise emissions from civil aircraft. ICAO requires Member States to adopt a balanced approach to noise management.

At the EU level there is clear guidance provided by EU Directive 2002/30 for the establishment of rules and procedures with regard to the introduction of noise-related operating restrictions at community airports. The other key piece of European legislation in this area is EU Directive 2002/493 (Environment Noise Directive). This directive required Member States to create noise maps from all transport sources in urban areas by 2007 and to adopt action plans to manage noise by 2008. The directive also aimed to harmonise methods for measuring noise across the EU. In December 2011 the European Commission launched its 'Better Airports Package' (European Commission, 2011). The package contained legislative proposals on aviation noise, among other issues. It was proposed to replace the Directive with a new EU regulation which would be directly applicable in each Member State without the need for Member States to implement the rules under local law. That was why the European Community adopted Regulation (EU) No. 598/2014 on the procedures concerning the introduction of noise-related operating restrictions. As restrictions also impact on air carriers from non-EU countries, the Regulation is compliant with international principles on noise management.

In the USA, the Federal Aviation Administration (FAA) has the authority and responsibility to control aircraft noise (FAA, 2016). Airport sponsors are primarily responsible for planning and implementing action designed to reduce the effect of noise on residents in the surrounding area. Such actions include noise abatement ground procedures and restrictions on airport use, among others. To accomplish this, airport sponsors must comply with the national programme for the review of airport noise and access restrictions under the Airport Noise and Capacity Act of 1990 (ANCA). The FAA regulation that implements ANCA is 14 Code of Federal Regulations (CFR) Part 161, Notice and Approval of Airport Noise and Access Restrictions.

Girvin (2009), in her review, compares and contrasts aviation noise policies and noise abatement measures around the world. She finds that charges applied in different countries depend on aircraft noise categories, maximum per aircraft noise threshold above which aircraft pay noise surcharges per operation, time of operation, per operation, noise-limits per aircraft, or noise quotas.

Noise charges are often used with fees, depending on the aircraft noise registration category or certification levels (Genescà et al., 2013). Generally, the noise tax increases with aircraft noise, and sometimes with aircraft weight, since heavier aircraft also tend to be noisier. The application of discounts for quieter aircraft and noise surcharges for noisier aircraft is an encouragement to airlines to use more silent aircraft (Morrell and Lu, 2000). Hsu and Lin (2005) highlight that from the airport's perspective, the busier the airport, the higher the noise fee, charged per landing, to offset the environmental damage and compensate surrounding communities for the noise impact. However, airports must deal with the trade-off between environmental improvement and revenue losses, when determining noise charge policies.

In some countries, *noise protection areas* are defined. These are urban areas that should be not flown over due to noise minimization. The distance that should be kept from these protected areas depends not only on the aircraft type but also on the weather (since the wind has an enormous influence on noise propagation) (Schilke and Feuerle, 2013.

6. Operational procedures for avoiding aircraft noise

In an ideal world, an aircraft would take off, climb to its optimal cruising altitude, and stay up there as long as possible before beginning a constant, engines-idle descent until landing. In the real world, aircraft have to coordinate with ATC, which usually interrupts climbs and descents with level-offs and turns that force them to spend more time at lower altitudes (Laurenzo, 2006). The combination of low altitude and frequent thrust transients leads to significant noise impact on the ground (Coppenbarger, 2007).

Noise abatement operational procedures in use today cover both take-off and approach phases. The term Continuous Descent Approach (CDA) has been adopted to embrace the different techniques being applied to maximize operational efficiency while still addressing local airspace requirements and constraints during the approach of the aircraft to the airport. These operations have been variously known as, Continuous Descent Arrivals (Jackson et al., 2009), Optimized Profile Descents (McConnachie et al., 2015; Hughes et al., 2012), Tailored Arrivals (Pinkerton, 2013; Elmer et al., 2008), 3D Path Arrival Management (Tong et al., 2007) and Continuous Descent Operations (Thompson et al., 2013; Robinson and Kamgarpour, 2010).

CDA (see Fig. 1) allows aircraft to approach moderately dense terminal areas, eliminating the level altitude segments and their associated thrust transients at low altitude, while flying efficient, near-idle descent trajectories that save fuel, and reduce emissions and noise (Ren et al., 2011; Weitz et al., 2005). However, these procedures are not in use everywhere because effective implementation may be difficult since aircraft require special equipment and can have a negative impact on the airspace throughput and controller workload (Jackson, 2009; Reynolds et al., 2005). ATC lacks the required ground automation to provide separation assurance services during CDA operations. Thus, CDA is currently used in low traffic scenarios only (Kuenz et al., 2007; Tong et al., 2007).

Research into terminal area operational improvements has predominantly focused on the descent phase of flight and improvements of operational performance using CDA, but few researches have considered the climb phase of flight. Noise Abatement Departure Procedures (NADPs) are the ICAO noise abatement take-off climb procedures defined in ICAO Doc 8168-OPS/611, Volume 1, Part 1, Section 7, Chapter 3 (ICAO, 2004). McConnachie et al. (2015) presented an approach for evaluating the current operational inefficiencies in the climb phase. Various references consider the Expedite Departure Path (EDP) component of the Center-TRACON Automation System (CTAS) in the USA (Capozzi et al., 2002). EDP is a decision support tool aimed at providing TRACON Traffic Management Coordinators (TMCs) with departure traffic loading and scheduling information, and radar controllers with advisories for tactical control of TRACON departure traffic. The benefits of EDP are a reduction in delay for departure operations, reduced fuel burn and reduced noise impact due to accelerated climb trajectories (Jung and Isaacson, 2002).

Boeing (2016) provides a database of real noise and emissions restrictions from 654 airports all around the word. After analysing these data, we found that 517 airports have noise abatement procedures but only 72 airports have CDA procedures implemented or are in a trial stage of development, and just five have NADP ICAO's standard as their departure procedure. The others have procedures referring to arrival and/or departure trajectories, as well as recommended flying techniques or preferred use of certain runways.

7. Monitoring, modelling & simulation for reducing noise

We have found in the literature review that there is an important relationship between monitoring, modelling and simulation tools related to deal with the noise problem around airports. Monitoring is done in a real-time environment to mea-

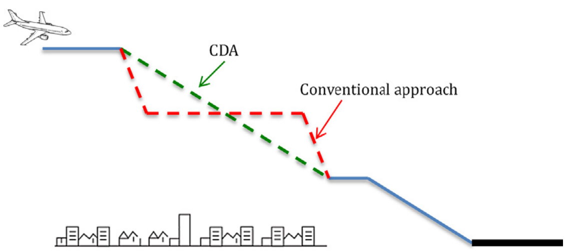

Fig. 1. CDA vs. conventional approach.

sure the impact of noise. Modelling serves planning purposes and needs, from monitoring measures to validating the models developed. *Simulation* needs both *monitoring* and *modelling* in order to assist decision making for land-use planning, design of operational procedures, and the assessment of low-noise technology and vehicle concepts (Fig. 2).

As mentioned before, the social impact of airport noise leads to the development of strict legislation globally. The legislation is based on noise monitoring, which usually combines information deriving from noise level meters and radars (Tarabini et al., 2014). This is why *noise monitoring* is considered to be the most important mechanism both for planning and noise management around airports (Asensio et al., 2010, 2011). It allows the measuring of sound level time history, identifying sound events and classifying the events produced by aircraft. Aircraft noise monitoring is carried out using a set of noise monitoring terminals (NMTs) that continuously measure the noise in the airport surroundings. Since the ultimate aim of aircraft noise monitoring is to help control the population's exposure to aircraft noise, ideally NMTs should be placed in urban areas. Urban centres, however, have high background noise levels, and the identification of aircraft specific noise is therefore a problem (Genescà et al., 2013). It is necessary then to consider the factors that can affect the uncertainty of the monitoring results. ISO 20906 deals with this by considering measuring instrumentation, residual sound, emission at the source, ground effect, etc.

Various studies in the literature deal with the monitoring problem. Asensio et al. (2009) propose a model that uses radar tracks to reduce the uncertainty to less than half of the ISO model. Asensio et al. (2010) designed a system that can detect aircraft sounds in real-time, so that its integration with a monitoring unit can improve aircraft detection rates during unattended measurements. Genescà et al. (2013) propose the use of an array of 12 microphones to measure direct aircraft noise, avoiding the effect of the ground reflections and urban background noise. In order to detect thrust reverse noise among other noise sources present in airports, Asensio et al. (2015) use a microphone array linked to a noise-monitoring unit, which enables sound pressure measurements to be transformed into sound power level estimations with good classification rates.

Since noise monitoring is essential to measure and control noise limits around airports, measures must be precise to be useful. Hence, the next step after a correct noise monitoring should be to validate the noise models developed.

Noise modelling is used to forecast current or future aircraft noise around airports (due to increases in flight volume or modification of flight paths) and to produce noise maps (Genescà, 2016; Sari et al., 2014). Different models, different implementations of the same noise calculation algorithms, different calculation methods, different data structure and different specific parameters to be adjusted by the user in order to represent the real situation, are in use worldwide. Krebs et al. (2008) present a new standardised test environment for aircraft noise calculation programmes.

The evaluation of noise in urban environments and in areas with main noise sources also represents a huge challenge, due to the high population density and the combination of different noise sources contributing to the overall acoustical environment. In particular, densely populated areas around large airports are exposed to noise from a combination of different sources. Sari et al. (2014) propose that noise generation and propagation are separately modelled according to basic physical effects.

Finally, fast but accurate *simulation* methods are required. Filippone and Bertsch (2014) classify them as best practice and scientific prediction methodologies.

Firstly, best practice tools are usually based on fully empirical models derived from ground noise measurements. The Aviation Environmental Design Tool (AEDT) is the FAA's official method to calculate noise impact (until May 2015, it was the Integrated Noise Model (INM)). The AEDT is a software system that dynamically models aircraft performance in space and time to produce fuel burn, emissions and noise. It makes full flight gate-to-gate analyses possible for study sizes ranging from a single flight at an airport to scenarios at the regional, national, and global levels (Belle et al., 2015). The European Civil Aviation Conference (ECAC) proposes a similar method (using identical equations) to INM in their Document 29 (2005). Arntzen et al. (2014) updated these methods, supplying the noise model with an augmented ray tracing solution to predict the atmospheric propagation effects, rather than just using an empirical model.

Secondly, scientific predictions methodologies of aircraft noise play a large role in the policy making process and resulting regulations. These regulations are usually based on noise contours (a line on a map that represents equal levels of noise

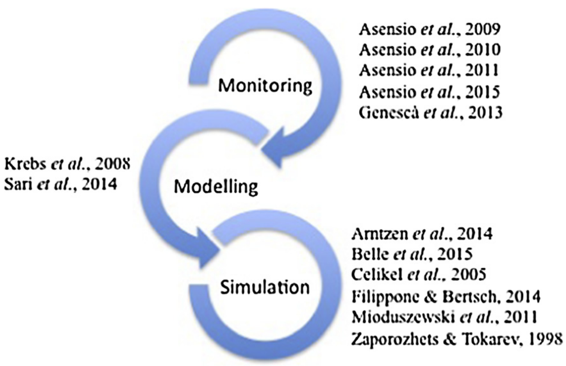

Fig. 2. Monitoring – modelling – simulation relationship.

exposure) expressed in yearly averaged metrics. Noise contours around airports are used as planning and evaluation tools, and as a component of long-range efforts by local, regional or national authorities. Aircraft noise contour assessment is a complex procedure due to the different route schemes, procedures, aircraft and types of engine in operation around an airport (Zaporozhets and Tokarev, 1998). The usage of a reliable, validated, and updated noise model is an essential step for producing accurate noise contours for the purposes of environmental noise analysis. But, noise maps are made mostly by calculations based on known and estimated parameters such as geographical data and the accurate accounting of noise source data. All these data cannot be readily available for the study areas. Therefore, assumptions and predictions are generally used to fill the gaps of model inputs (Mioduszewski et al., 2011).

However, a few approaches in the literature consider the trade-off between the different aspects needed to evaluate environmental impact, such as fuel burnt, noise exposure, and emissions produced, of future ATM concepts and procedures. Celikel et al. (2005) studied the combined use of airspace simulation, and environmental and economic tools, adding value to operational project evaluation.

8. Optimization algorithms for noise abatement

Noise abatement procedures provide an effective means of achieving further reductions in the impact of aircraft noise on communities surrounding airports. Use of noise abatement procedures, however, has been limited by guidance and navigation considerations. The primary obstacle to the implementation of these procedures remains the inability of air traffic controllers to maintain manually the precise sequencing and spacing required for maximum take-off and landing rates in heavy traffic conditions. Thus, the introduction of automation that predicts the performance and noise impact of aircraft, and uses this information to assist the controller in determining and maintaining appropriate sequencing and spacing, is critical to the successful utilization of noise abatement procedures (Clarke, 2003).

Noise-aware decision support tools are needed so that the decision process for sequencing and scheduling terminal area and en route traffic as a means of increasing overall capacity and efficiency of operation, also includes consideration of noise exposure levels, particularly for the population within the immediate vicinity of the airport (Capozzi et al., 2002).

To our surprise, there is not a large amount of literature referring to the optimization of noise-scheduling. In Fig. 3, we present the main studies found in the previous literature referring to the flight stages that can influence runway capacity.

Most research found in the literature considering optimization tools refers to flight path optimization (Visser, 2005; Salah and Abdallah, 2012; Salah, 2013). Trajectories optimization considers avoiding built-up areas, topographical details, safety requirements and ATC requirements (Filippone, 2014).

It is possible, however, to find airport noise optimization and aircraft scheduling dating back to 1984. Frair (1984) formulated an optimization mathematical model whose objective is to minimize the measure of annoyance due to arriving and departing aircraft for a given airport, obtaining a 40% reduction in noise impacts.

Temme (2007) defines an interesting method to support the air traffic controller with noise abatement routes during real-time approach planning and guiding. The sound-source aircraft, the propagation medium atmosphere including actual meteorological conditions, a three dimensional model of the earth's surface, and the population distribution around an airport, are all taken into account for the noise propagation calculation.

Hebly and Visser (2007) present a decision support system (DSS) for air traffic controllers for guiding arriving and departing traffic near airports in a safe and efficient manner, making use of the future concept of four-dimensional trajectory-based operations. While doing so, the system minimizes the negative environmental effects of the flight operations and manages their spatial allocation, both for individual movements and cumulative exposure. They formulate the problem as a Mixed Integer Linear Programming (MILP) with Constrained Position Shift (CPS) restrictions.

Prats et al. (2010) define a non-linear programing (NLP) problem for departure optimization that is solved by using a lexicographic multi-objective optimization technique. This approach allows the establishment of a hierarchical order among all different noise sensitive locations. However, the major drawback of this approach is the limitation in the number of noise sensitive locations to be considered, due to the exponential growth in computational cost.

The use of optimization tools for real-time aircraft guiding may lead to difficulties, because it requires delivering online results. Unlike Standard Instrument Departure (SID) routes, which follow fixed flight paths, arriving aircraft are guided flexibly by the aircraft controller with radar vectoring. A possible alternative is to reduce the amount of possible arrival trajectories by including the local airspace structure around the airport and taking the trajectory calculation rules of an arrival manager into account (Temme, 2007), then it is possible to reduce the number of possible flight paths significantly and to archive them together with a noise value – depending on population values – in a database. This way, the arrival manager has the possibility to take aircraft noise as well as safety, punctuality, and capacity constraints during the arrival sequencing generation into account.

An interesting and complete study has been undertaken by Zachary et al. (2010). They propose an optimization algorithm that explores the best selection of flight possibilities given to minimize noise and/or emissions by selecting available aircraft trajectories, schedules, operational procedures, e.g. time profiles of turbine power levels at take-off and climb, flap settings in take-offs and approaches, altitude variations in climb and approaches, take-off/landing runway displacements, and fleet composition, through a non-linear integer programming (NLIP) minimization problem.

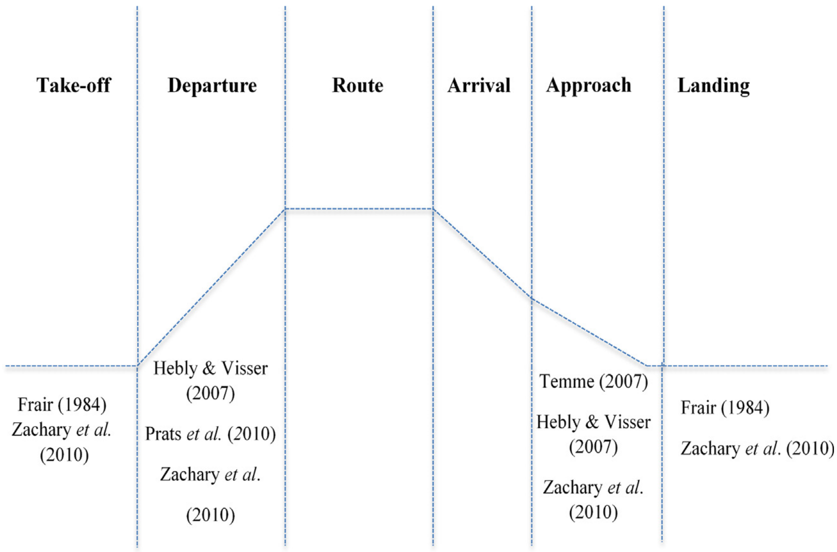

Fig. 3. Optimization algorithms depending on the flight stage.

9. Research opportunities

The main approaches addressed today to reduce the impact of noise in the surrounding communities of airports, excluding impacting on land use and/or carrying sound insulation methods, consider operational procedures and regulatory restrictions. Airports must deal with the trade-off between environmental improvement and revenue losses when determining noise charge policies, as well as with the loss of capacity when fixing regulatory restrictions. The largest airports are those that have a greater population near them and also the ones that suffer from more congestion and delays, which results in more environmental impact.

Noise can be significantly reduced if the focus is set on developing optimal scheduling tools that avoid manoeuvres in the approach stage of the flight waiting for authorization to land, and departures are able to arrive at higher altitudes as fast as possible.

Making the most efficient use of the current infrastructure is an important part of the solution. A significant amount of research has been published for optimizing the scheduling of flights in airports. In this sense, Bennell et al., 2013 review the techniques and tools of operational research and management science that are used for scheduling aircraft landings and take-offs in order to optimize airport runway scheduling. The main solution techniques include dynamic programming, branch and bound, heuristics and meta-heuristics.

Noise restrictions are almost not present when developing these algorithms. We have found just one interesting perspective to include noise in scheduling optimization. Sölveling et al. (2011) studied runway scheduling optimization based on environmental (CO_2 and noise) impacts, finding that it might produce important savings for the stakeholders implied (society, airports and airlines). There is a large field of investigation yet to be developed in terms of optimization algorithms that take into account noise as a constraint or objective of research.

Hence, optimization algorithms that take into account noise constraints avoiding inefficient schedules should be developed and tested. Controllers need these tools to be able to maintain safety and efficiency but also to address noise and environmental issues.

In order to evaluate the optimization algorithms and models developed, it is also necessary to develop standardised calculation methods that use the same data as input in order to be able to compare the results in a consistent way. These calculation methods should consider not only the different noise sources but also be able to match noise predictions with measured data. Hence, validation standards is another topic that needs future research attention in order to develop tools that are really useful in the reduction of noise in airport surroundings.

10. Conclusions

Minimizing noise disturbance around airports is a task that needs the implications for various stakeholders to be considered: institutions, aircraft manufacturers, airlines and ATC. There is a real concern by authorities that can be seen in the recent legislations and official restrictions that have been imposed.

There is also a need to improve modelling-simulation-monitoring tools that take into account all the factors implied in the noise problem (weather, population affected, air traffic congestion, airport capacity, etc.). A standardised tool would be necessary, since existing programmes differ greatly in their calculation methods and in data structure, so it is very difficult to compare the results in a consistent way.

There is a large field of research in terms of optimization tools that support air traffic controllers to help them optimize the capacity of airports without breaking the noise abatement procedures established in the vicinity of airports. Designing online scheduling tools that consider noise restrictions has not yet been studied in depth.

Predictions confirm the growth of air traffic transport in the future, thus increasing the noise problem around airports. Operational procedures need to take into account the capacity of the airport in order not to decrease the acceptance ratio of departures and arrivals. Using ICAO standard procedures worldwide for noise mitigation would be an important improvement. There is a large field of research on optimization algorithms that could help controllers schedule airport operations by considering noise restrictions.

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Improving aircraft approach operations taking into account noise and fuel consumption

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ABSTRACT

While air transport brings very significant economic and social benefits to the cities and regions served by airports, aircraft noise is the single major cause of community opposition to airport operations, becoming a critical issue that affects the sustainability of future traffic growth. However, planning operations exclusively focusing on noise impact may result in an increase of fuel consumption or delays. This paper develops a suitable bi-objective model for landing aircraft, which finds a schedule that minimises noise impact, total fuel consumption and delays, under wake vortex separation and Constrained Position Shifting restrictions. The results of this model are compared with real operations in a major European airport to assess the potential level of improvements. By comparing with real data from Madrid-Barajas airport, the research shows potential improvements of up to 4.5% reduction of total fuel consumption (without increasing noise levels) only by modifying the sequence of arrivals, and up to 43% (without extra fuel consumption) of reduction in noise impact over the populations under study.

1. Introduction

By 2040, there will be a demand of 1.5 M flights than can be accommodated, i.e. 160 million passengers unable to fly (Eurocontrol, 2018). Even with 1.5 M flights unaccommodated and therefore lost, the network remains highly congested. Therefore, one of the central challenges facing the aviation industry is air traffic demand growth, which results in congestion in many airports, primarily hubs (Flores-Fillol, 2010). Managing take-offs and landings of any airport is a complex problem that plays an important role in Air Traffic Management (ATM). Runways and air controllers are limited resources, so air traffic needs to be planned carefully to limit peak demand and satisfy as many airlines' requirements as possible (Artiouchine et al., 2008).

Building new airports and expanding the runway capacity of existing ones is one possible solution to congestion. However, this solution might result in negative environmental impacts on the quality of life of near-airport communities, such as noise disturbance, emissions, water pollution and habitat destruction (Laurenzo, 2006; Ho-Huu et al., 2017; Arntzen and Simons, 2014; Visser et al., 2008). In fact, several studies show a correlation between aircraft noise exposure and cardiovascular or psychological disease (Postorino and Mantecchini, 2016).

During recent years, the population has increased in the cities and residential areas have become closer to airports, which implies an increase in the number of people affected by undesirable noise (Ganic et al., 2015a). Aircraft noise is a major cause of community opposition to current operations and to airport capacity improvement, becoming a critical issue that affects the sustainability of future traffic growth. Noise produced by aircraft has two main sources (Prats et al., 2009): aeronautical noise, which is the consequence of the friction of the air along the aircraft, and engine noise.

During take-off, aircraft noise is mainly determined by the thrust of the engines required. Although take-off noise is significantly dominating noise issues around airports in terms of regulation and policies, due to engineer advances, higher noise reductions are expected at take-off operations, potentially increasing the importance of landing noise. Schäfer et al. (2019) found that lower fan pressure ratios and the absence of combustion noise leads to a 50% reduction in take-off noise. In contrast, during landing, the higher weight of all-electric aircraft will result in a 15% larger noise.

In an ideal world, an aircraft would take off, climb to its optimal cruising altitude, and maintain the cruising altitude if possible before beginning a constant, engines-idle descent until landing. In the real world, aircraft must coordinate with ATC which, when there are congestion delays, interrupts descents with level-offs and turns, forcing aircraft to spend more time at lower altitudes and deviate from their intended trajectory (Laurenzo, 2006). The initial schedule needs to be

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reorganised when planes are close enough to the airport, which means when they approach the TRACON – Terminal Radar Approach Control Facilities – between 5 and 50 miles from the airport (Inniss and Ball, 2004). The combination of low altitude and frequent thrust transients leads to significant aerodynamic noise impact during the arrival phase of the flight (Coppenbarger, 2007), created when the landing gear is deployed because aircraft use lower thrust.

Aircraft noise impacts on the environment significantly for several reasons (Jagniatinskisa et al., 2016): living areas are close to airport locations; operations during night time; flight noise events repeating periodically; and, compared to other transportation means, aircraft have large noise levels over the background noise. At many noise-sensitive airports, quieter aircraft are the key to minimising the impact of aircraft noise and ensuring a sustainable growth of airport capacity and air transport under increasing environmental constraints, for the benefit of the travelling individuals, airlines and their neighbouring communities (Eurocontrol, 2018).

The control of noise around airports is a complex matter because many different factors have a significant impact on the creation and propagation of noise (Ganic et al., 2015b): fleet mix (types of aircraft that are using the airport); shape and characteristics of arrival and departure procedures; airport characteristics (number of take-offs and landings, the distribution of traffic throughout the day and night, etc.); and airport location. Aircraft vary in performance regarding noise and emissions. Even two aircraft of the same type may behave differently, depending on their weight and the atmospheric conditions.

The main approaches addressed today to reduce noise impact in the surrounding communities of airports, excluding impact on land use and/or carrying noise insulation methods, consider operational procedures and regulatory restrictions (Rodríguez-Díaz et al., 2017b). Regarding airport procedures, operations are designed to serve the vast majority of aircraft under a wide range of weather and wind conditions, thus reducing the choices of aircraft with better capabilities to achieve better performance (Hebly and Visser, 2011). Regarding regulatory restrictions, the concern from authorities is expressed in terms of different legislations and official restrictions that have been imposed in many countries (Directive, 2002/30/EC, 2002). Hence, minimising noise disturbance around airports is a task that needs the contribution of various stakeholders: institutions, aircraft manufacturers, airlines and air traffic control (ATC).

However, making the most efficient use of the current infrastructure by ATM would be the best alternative to balance demand with environmental restrictions. The challenge lies in simultaneously achieving safety, efficiency and equity, which are often competing objectives (Anagnostakis et al., 2001).

There are many factors that may oppose the objective of minimising noise (Christian and Sparrow, 2013): fuel burn, time-of-flight, emissions, etc. Hence, noise should not be the only parameter considered, as there are many stakeholders with various interests involved. Exclusively focusing on noise impact may result in an increase of fuel consumption (since avoiding noise impact on population located close to the airport may imply longer routes). To balance this conflict, the scope under research is to develop a suitable model for landing aircraft that finds a schedule that minimises noise impact, total fuel consumption and delays, while making the most of the current capacity of the runways.

Moreover, in this paper we aim to prove that there is a margin for improvement in terms of noise reduction and fuel consumption, just by deciding on the most appropriate landing runway and order in the landing sequence. Here we are not considering introducing any change in the Standard Terminal Arrival Routes (STAR) of the considered airport since in the actual procedures there is still a place for considering noise impact and aiming for an efficient schedule. Our decision process starts in the approaching routes, and it is valid and applicable in general when the airport have more than one approach route, independently of the STARs involved.

The paper is organized as follows: Section 2 describes the problem of the runway bottleneck and environmental concerns, and describes different approaches that have been studied in this field. In Section 3, the proposed linear model is presented, as well as the decision variables considered used to design the model. Also, as part of the methodology, the real scenario used for testing real operations is introduced, as well as the optimisation methodology. Section 4 presents a detailed example with a limited number of flight plans to show how the model works. In Section 5 the numerical results in the real environment of the Adolfo Suárez Madrid-Barajas airport are described and analysed. Finally, a short summary is given in Section 6, together with suggested topics for future research in this area.

2. Previous approaches

Bennell et al. (2013) undertook an extensive review of optimising algorithms for scheduling flights in airports; however noise restrictions are almost not considered in the development of these algorithms. Only Hebly and Visser (2011) have studied the effects of taking into account noise measured in one point, which implies a delay driven support tool for sequencing and scheduling, under the formulation of an MILP (Mixed Integer Linear Programming) problem, where the sequencing is based on the principle of constraint position shifting (CPS). Based on the results of their model, and using the concept of fixed arrival routes, a small improvement in noise exposure in the point under study could be achieved.

As far as we know, the only optimisation algorithm for landing scheduling that considers noise impact is the one just mentioned. However, some other studies deal with the design of optimal routes that reduce the negative impact of aircraft noise on people living in the vicinity of airports. Prats et al. (2009) resolved a non-linear multi-objective optimal control problem to find the best trajectory for a given scenario, aircraft and time. Khardi (2014) presented a dynamic method to provide optimal paths that minimise aircraft impacts and fuel consumption, assessing a two-segment approach as an optimal trajectory. Ho-Huu et al. (2017) formulated a bi-objective optimisation problem by also considering noise and fuel as objectives to design optimal environmental routes. They consider the percentage of awakening to measure noise impact and present a novel application of MOEA/D (multi-objective evolutionary algorithm based on decomposition) for designing new noise abatement departure routes.

The model defined in this study calculates the most suitable landing runway and the landing times that minimise noise for the surrounding population, fuel consumption and delay. To minimise delays and fuel consumption, the CPS approach has been considered in our research. The CPS approach is based on a fundamental underlying principle that involves the specification of a parameter that limits the maximum number of position shifts (forward or rearward) that any aircraft will receive with respect to its first-come, first-served (FCFS) position (Dear, 1976; Rodríguez-Díaz et al., 2017a). Previous studies in the literature have dealt with scheduling considering noise, fuel burn, WTC or CPS as constraints, not as part of the objective function. This paper deals with all of them at the same time. Moreover, this paper develops a model that could be used in real operations and implemented in real software, given its low computational burden.

The model developed here, not only aims to optimize runway capacity as in Rodríguez-Díaz et al. (2017a) but also to optimize fuel consumption of the flights considered. One of the decisions taken consists of choosing the landing runway that minimises the noise impact of the final approach route for the surrounding population without proposing any change in the existing approach routes and operational procedures of the airport. A linear model is defined to cope with the bi-objective nature of the problem (minimise total noise impact and minimise total fuel consumption), and the ε-constraints method is used to explore the Pareto frontier. As mentioned, these optimal decisions are being tested against a real operation in a major European airport, by measuring potential improvement in cost and noise level.

3. Proposed approach and methodology

To analyse the problem and test the potential improvement in real operations, we will consider a set of instances consisting of a sequence of flights approaching an airport with various landing runways subject to CPS. As one of the aims of the sequencing is to avoid a result that produces excessive amounts of noise in the surroundings, it is necessary to select a metric to measure the impact of the noise on landing aircraft for each assessed alternative. An aggregate metric called LOUDPeople, LP (Christian and Sparrow, 2013), is considered suitable for our purpose. The result from this metric avoids that we might make the determination of assigning an unacceptably high noise level to a small population in order to reduce the impact of the noise on many citizens:

$$LP = \sum_i Population_i * 2^{\left(\frac{SEL_i - 100}{10}\right)} \quad (1)$$

$$SEL = L_{eq} + 10 * log_{10}(T) \quad (2)$$

where i represents each village in the surroundings; SEL_i is the Sound Exposure Level (in dB) normalised to 1 s at village i; T is the duration in seconds of the time period considered to measure the noise; and L_{eq} is the equivalent sound level measured at each village. Note that when T = 1 (as will happen in our study), it is $SEL = L_{eq}$.

Once we defined how to assess the noise impact, a linear model was defined to cope with the bi-objective nature of the problem (minimise total noise impact and minimise total fuel consumption). The data needed are:

N Total number of flight plans (flights) considered
R Number of approach routes in the airport under study
HS_i Scheduled take-off time of flight i from departure airport
$flight\_time_{i,r}$ Minimum flight time of flight i when using route r
K_i Consumption of fuel per second of flight i
LP_{ir} Noise impact of flight i in route r for a certain population
CPS Constrained Position Shifting. For CPS = 0, the order of flights is the initial one (1,2,…,N)
$WTC_{i,j}$ Wake Turbulence Category separation between flight plan i and j.
M A big number (classically used for modelling convenience).

The decision variables considered to define a feasible schedule are:

$$\rho_{i,r} \begin{cases} 1 & \textit{if flight plan } i \textit{ approaches using route } r \\ 0 & \textit{otherwise} \end{cases}$$

t_i Landing time of flight plan i as scheduled by the model
d_i Forced delay to flight plan i before landing, in order to assure safety separation distance between consecutive flight plans (minutes)

$$\tau_{i,j} \begin{cases} 1 & \textit{if flight plan } i \textit{ lands before } j\ (t_j > t_i) \\ 0 & \textit{otherwise} \end{cases}$$

With this notation the objective functions are:

- Minimise total fuel consumption:

$$min \sum_i (t_i - HS_i) \times K_i \quad (3)$$

- Minimise total noise impact:

$$min \sum_i \sum_r (LP_{i,r}\, \rho_{i,r}) \quad (4)$$

To ensure that the solutions obtained are feasible, the following constraints are introduced:

1) Each flight plan i is only assigned to one route. Therefore for each flight i, exactly one $\rho_{i,r}$ is 1:

$$\sum_r \rho_{i,r} = 1 \qquad \forall\, i \quad (5)$$

2) The real time of the arrival of flight plan i is determined by its departure time plus the flight time of the selected route and can have a delay so as to respect WTC separation restrictions (only the current route r must be considered in the calculation, identified because $\rho_{i,r} = 1$):

$$t_i = d_i + \sum_r (HS_i + flight\_time_{i,r}) \times \rho_{i,r} \qquad \forall\, i \quad (6)$$

3) Either flight plan i lands before j or flight plan j lands before i:

$$\tau_{i,j} + \tau_{j,i} = 1 \qquad \forall\, i,\ j;\ \ j \neq i \quad (7)$$

4) Separation constraints between flight plan i and flight plan j in the landing runway are guaranteed (in this inequation, if $\tau_{i,j} = 1$ remains $t_j \geq t_i + WTC_{i,j}$ and the separation between flight i and j is at least WTC as required; else, if $\tau_{i,j} = 0$ it remains $t_j \geq t_i + WTC_{i,j} - M$ being M a big number and therefore the constraint becomes superfluous):

$$t_j \geq t_i + WTC_{i,j} - M(1 - \tau_{i,j}) \qquad \forall\, i, \forall\, j \neq i \quad (8)$$

5) CPS constraint in landing is fulfilled (flight i must land in positions $i \pm CPS$):

$$\sum_{j \neq i} \tau_{i,j} \geq N - (i + CPS) \qquad \forall\, i \quad (9)$$

$$\sum_{j \neq i} \tau_{i,j} \leq N - (i - CPS) \qquad \forall\, i \quad (10)$$

3.1. Finding the set of Pareto efficient solutions

The design of a system with more than one objective is referred to in the literature as a Multiple Criteria Decision Making problem (Miettinen, 2008). This type of decision and planning problems involves multiple conflicting objectives that need to be considered simultaneously.

Solving a Multi-Objective Optimisation problem does not lead to a single global solution. Due to the competing nature of the objectives, it might be possible to obtain an infinite number of solutions where each unique solution assigns different priorities to the problem objectives. These solutions are known as Pareto points and constitute the so called Pareto frontier. For instance, in our case with two objectives, the set of non-dominated solutions (Pareto frontier) is defined in such a way that for each point, minimising the global fuel consumption cannot be improved without sacrificing noise impact.

The generation of the Pareto frontier can be accomplished through scalarisation or vectorisation methods (Chircop and Zammit-Mangion, 2013): scalarisation methods convert the Multi-Objective Optimisation problem into various parametric Single-Objective Optimisation problems; vectorisation methods tackle the Multi-Objective Optimisation problem directly. The first ones typically define a set of differently parameterised single-objective models and apply multiple runs of a single-objective optimiser. Laumanns et al. (2006) states that it is a difficult and sometimes impossible task to choose a sequence of parameter values, such that the whole Pareto front is discovered because the choice of the parameter values determines which specific elements of the Pareto set are found.

```
Input: Objective bounds f̲ and f̄ ∈ R, and increment δ ∈ R
P := ∅
ε := f̄
while ε ⩾ f̲ do
     x := opt(f; f'≤ε)
     if ∄x' ∈ P such that x' ≻ x then P := P ∪ {x}
     ε := ε − δ
end while
Output: Set of Pareto-optimal decision vectors P
```

Fig. 1. Bi-objective ε-constraint Method (for objectives f and f').

One of the most popular methods to generate the Pareto front is the ε-constraint method (Haimes et al., 1971). Its logic works by choosing one objective function as the only objective and the remaining objective functions as constraints; by a systematic modification of the constraint bounds, different elements of the Pareto frontier are obtained. The method relies on the availability of a procedure to solve constrained single-objective problems.

Algorithm in Fig. 1 gives an implementation of the method (Chankong and Haimes, 1983) for the case of two objectives. The idea, as stated before, is to iteratively increase the constraint bound by a predefined constant δ. The necessity to choose such a value represents also the main drawback of this approach. Since only one solution can be found in each interval, the discretisation must be sufficiently fine not to "miss" substantial Pareto-optimal solutions. In the worst case, the difference between objective vectors might be as small as the machine accuracy of the computer used to run the algorithm.

In our case, the following specific procedure was used:

- Minimise only the global consumption, which indicates the superior limit of total noise impact (point on the far right in our frontiers).
- Minimise only the total noise impact (point on the far left).
- Solve the model being the objective function the minimisation of the global fuel consumption, but adding a new constraint that limits the total noise impact according to some ε proportions ([1; 0.95; 0.90; …; 0]), in the segment of the noise range defined by steps 1 and 2.

3.2. Scenario description

To test the capabilities and efficiencies of our model and analyse the results, we will consider a real scenario with data from arrivals at Adolfo Suárez Madrid-Barajas Airport, which is the biggest airport in Spain and ranks 5th in the EU in terms of passengers (AENA, 2018). This airport operates in two different configurations that determine the direction of departures and arrivals. In the North configuration, which is the preferred one (Eurocontrol – Public Airport Corner, 2018), airplanes take off and land, heading north. In the South configuration, airplanes take off and land, heading south.

Adolfo Suárez Madrid-Barajas Airport has four runways, composed of two parallel runways on a north–south axis separated by 1.8 km, and another two parallel runways on a northwest–southeast axis separated by 2.5 km. Depending on the configuration, the runways have different denominations (Fig. 2 shows the layout of the runways and their names in both configurations). In this way, in the North configuration, aircraft take off using runways 36 L and 36 R (left and right respectively) and land using runways 32 L and 32 R.

Adolfo Suárez Madrid-Barajas Airport has various correctives to reduce noise levels in compliance with European Directive 2002/30/EC, such as the prohibition of night-time operations of aircraft with noise levels of four or higher (according to EASA scale), and operating restrictions due to noise quota from 23:00 to 07:00 local time.

To collect noise information for our experiments, the WebTrack tool of the Spanish National Airports Agency (AENA) has been used. WebTrack allows for checking noise levels caused by different aircraft by using the trajectory of the airplane in the surroundings of the airport, both for landings and arrivals (Fig. 3 shows a screenshot of this tool). This function is accomplished thanks to the data provided by the noise monitoring system SIRMA ["*Sistema Integral de Ruido de Madrid-Barajas*"] (SIRMA, 2018). This system receives information on both the noise recorded at the 27 Noise Monitoring Terminals (NMTs) installed around the airport, as well as radar and flight plan data from the SACTA system ("*Sistema Automatizado de Control de Tránsito Aéreo*"). The WebTrack tool provides information about the aircraft (flight number, approach route and altitude) and associates these data with the corresponding aircraft's noise emission level for each NMT, which is necessary for feeding our model.

Table 1 details the location of the 27 NMTs, average noise of each NMT for 2017 caused by aircraft, the population of each affected village and whether this NMT noise measure corresponds to landings or departures, taking as a reference the North configuration (the preferred one). Analysing Table 1, out of 27, only seven reflect the noise produced by arriving aircraft (which is what we are analysing). The biggest population of these seven locations is in Torrejón (NMT 20), and the locations with the worst records of noise measures are Coslada (NMT 11) and San Fernando de Henares (NMT 10). Considering the North configuration, Coslada and San Fernando de Henares are the NMTs that register the worst noise records because they are under the final approach route of aircraft landing on runway 32 L.

Also, since the objective of this study is not only to reduce the noise impact on the populations with higher noise records but also to consider the overall population impacted on, we will also take into account the NMT of Torrejón de Ardoz since this population is closer to the final approach route of aircraft landing on runway 32 R. Although the noise records are not as severe as those for Coslada and San Fernando, the population impacted on is more than double that of Coslada and San Fernando. This allows us to have a representative and balanced measure of global noise impact on the surrounding areas of both landing runways. So, for our research, these three NMTs will be considered for measuring noise impact and gathering individual noise impacts with the WebTrack tool, as the other NMTs reflect a smaller noise impact.

In our paper, noise estimation is based on single events modelled by AENA following ISO 20,906:2009, and a metric that allows us to use these real data gathered by the NMTs, thus obtaining the noise disturbance in the affected population. Another possibility would have been using noise contours maps, which are a graphical representation of the significant levels of noise in a given territory, obtained by measuring a set of representative points, over different periods. Although in different occasions they were used in the airports neighborhoods (ICAO, 2008; FAA, 2013), and are widely used for legislation purposes, noise assessment and study of noise effects in the population, however they are not so frequently employed in the literature for scheduling optimisation purposes (Tian et al., 2018; Kim et al., 2018).

Noise data was chosen for a full day that Adolfo Suárez Madrid-Barajas Airport operated using the North configuration, i.e. 20th January 2018. Timetables for each flight plan were collected using an online flight tracker (FlightRadar24, 2018).

The following assumptions were made in our experiments:

- Noise over San Fernando de Henares, Coslada and Torrejón de Ardoz was taken when all the aircraft were overflying the corresponding NMT sensors of these populations
- Average noise produced by each type of aircraft was determined for each runway to calculate the alternative noise caused by the aircraft if landing on the alternative runway (Table 2). The use of generic aircraft types has been validated by Torija and Self (2018) for computing aviation noise outputs.
- Fuel consumption data for the whole flight are average data per aircraft extracted of ICAO Carbon Emissions Calculator

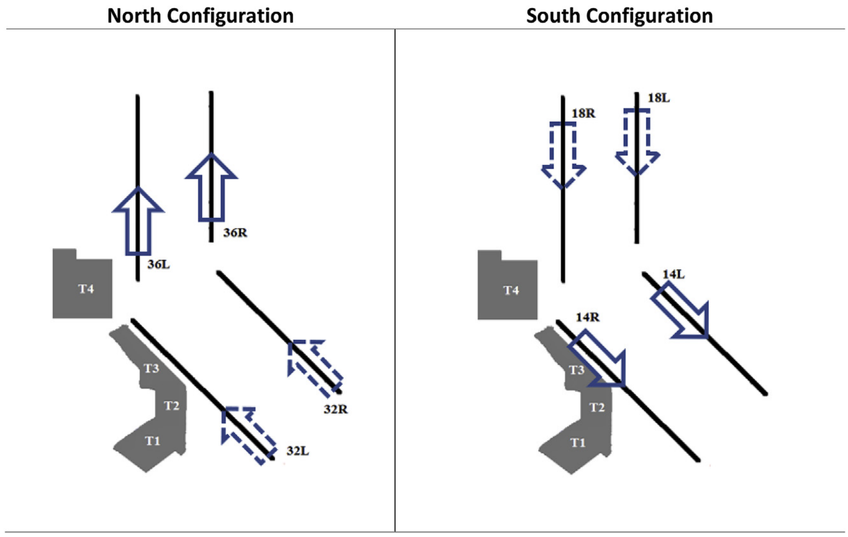

Fig. 2. Adolfo Suárez Madrid-Barajas airport - North and South configurations. Solid arrows represent the direction of departures and spotted arrows represent the direction of landings.

Fig. 3. WebTrack screenshot example (WebTrack AENA, 2018).

Methodology document (ICAO Carbon Emissions Calculator Methodology, 2016). This is a proxy of the real consumption data.

- Aircraft landing at the 32 R runway take 5 min more approach time than those landing on the 32 L runway.
- Wake vortex minimum separation considered is the one established by Document 4444 of OACI.
- Given the bi-criteria nature of the model, the ε-constraints methodology is used to find the Pareto frontier for each instance.

All the computational experiments are done considering different time slots, different CPS and the real flight time of each flight. The optimisation software used to solve the models is LINGO v17.

4. A first example of the model solution

For a better understanding of the model and the study framework, a detailed example of just five flight plans that landed in Adolfo Suárez Madrid-Barajas Airport on 20th January 2018 is first presented. Details of those flights are provided in Table 3.

Considering CPS = 2 (i.e., each flight can only shift at most two positions in relation to its original position in the sequence); we ran the model, forcing five different maximum noise levels to find five points in the Pareto frontier. Fig. 4 shows the result given by the model compared to the real solution. The diamond points represent solutions found by our model in the Pareto frontier, and for each point, the sequence and landing runway of each flight plan are specified. The square point reflects the real solution (what actually happened that day) and the sequence of landings, and the runways where the flights landed.

Table 1
Scenario description. Population taken from the Spanish National Institute of Statistics, with reference date January 2018 (INE, 2002). NMTs are grouped by Arrivals/Departures, recording the noise when Adolfo Suarez Madrid-Barajas Airport operates in the North configuration.

NMT	A/D	L_{eq} day (dB)	L_{eq} night (dB)	Location	Population (2017)
3	D	53	32	Dehesa Vieja	78,203
4	D	54	45	Fuente del Fresno	1265
24	D	50	23	Ciudalcampo	609
26	D	50	44	Club de Campo	3500
27	D	58	39	La Granjilla	500
2	D	53	31	Algete	15,476
5	D	50	44	Urbanización Santo Domingo Sur	2917
21	D	50	43	Urbanización Santo Domingo Norte	
25	D	53	53	Prado Norte	1877
1	D	39	38	La Moraleja	114,864
6	D	54	46	Fuente el Saz	6424
16	D	44	22	Tres Cantos	46,046
18	D	47	39	El Molar	8491
7	D	49	39	Paracuellos	23,905
9	D	62	53	Belvis	1611
23	**A**	**48**	**42**	**Los Berrocales**	**798**
12	**A**	**38**	**29**	**Alameda de Osuna**	**20,549**
13	**A**	**49**	**43**	**Barajas**	**46,876**
8	**A**	**59**	**48**	**Mejorada**	**22,948**
10	**A**	**63**	**52**	**San Fernando de Henares**	**39,681**
11	**A**	**66**	**55**	**Coslada**	**83,011**
20	**A**	**49**	**44**	**Torrejón**	**128,013**

Table 2
Average peak noise (dB) in the three NMTs, when landing on the two possible runways (32 R and 32 L).

Aircraft	Average Noise (dB)-NMT 10		Average Noise (dB)-NMT 11		Average Noise (dB)-NMT 20	
	32R	32L	32R	32L	32R	32L
A319	55	74	55	76	55	54
A320	57	74	57	77	56	56
A321	55	74	56	77	56	55
A332	58	74	59	77	58	55
A333	55	74	55	77	57	55
A343	55	78	55	81	59	56
A346	56	79	56	81	59	56
AT75	53	72	53	75	57	53
AT76	55	71	56	74	56	56
B738	56	75	57	77	56	55
B763	56	75	57	78	59	56
B764	56	78	57	81	59	56
B77W	56	75	57	78	59	56
B788	55	74	56	77	56	53
B789	55	75	56	77	57	52
CRJ2	53	73	54	75	54	53
CRJX	55	73	55	75	54	54
E190	58	71	58	74	56	56
E195	58	73	58	76	56	56

It can be seen that both the landing runways and the sequence of landings chosen by the model change depending on the point of the Pareto frontier. When the model calculates the best solution to minimise total fuel consumption (i.e., not limiting at all the noise level, thus finding the point in the far right in Fig. 4), it proposes that the aircraft consuming the most in the sequence, lands as early as possible considering the CPS restriction imposed. This means for flight QR149 (FP5), which in the real sequence lands in the fifth position, the model proposes it to land in the third position. However, when the model calculates the best solution to minimise total noise impact, it can be seen that it chooses the 32 L runway for all the flights in the example, as this runway and its approach route is the one that minimises the population disturbed by the noise generated by lading aircrafts. It can be seen that the CPS does not have an impact on the result when minimising the total noise impact, since the model chooses the same order as the initial sequence (when minimising noise, only the election of the most appropriate landing runway is taken into account for this objective).

Comparing the total real fuel consumption with the best solution found by the model in this small example, our model is able to reduce almost 2% of total fuel consumption (more than 1 ton of fuel of the total consumption of the flights considered in this instance), only by changing the order of the landing sequence. If the same analysis is performed in terms of total noise impact, the result is that more than a 30% total noise impact reduction is achieved.

5. Results and discussion

To evaluate the influence of the value of CPS, a first set of data has been computed, considering different values of CPS: from the lower value CPS = 0 (i.e., the sequence of landings in the same order as the real one, FIFO), to CPS = 5 (Rodríguez-Díaz et al., 2017a, noted that controllers always wish to keep the sequence as similar as possible to the FCFS sequence received, and the limit of 5 was defined in their study). As always occurs when relaxing constraints in optimisation models, results for CPS = 5 are no worse than for CPS = 0 in terms of total fuel consumption (kg), achieving a total reduction of 2000 kg for the best case of CPS = 0 vs. the best for CPS = 5 (see Fig. 5). When compared to the real sequence, the improvements are almost 20,000 kg of total fuel reduction. For the other values of CPS, the results are always between the bounds of the solution found for CPS = 0 and CPS = 5. Therefore, the next set of experiments were performed, considering only these two extreme values for CPS.

To select the time frames of data used to analyse and compare the results after running the defined model, we study how congestion can influence the results and the possible improvements found by the model. Congestion is determined by the total number of landing aircraft per period. Fig. 6 shows the number of airplanes that landed in every hour period at Adolfo Suárez Madrid-Barajas Airport the day of the data set.

As can be seen, between 8:00–9:00 and 12:00–13:00 are peak periods, while during the night, the number of landing aircraft is significantly smaller. Taking into account that the number of flights in each sample need to be equal for comparison purposes (50 flight plans in this case), the chosen periods for our analysis are:

Table 3
Flight plans data for simplified real example (STD-Scheduled Departure from origin airport; fuel data taken from ICAO, 2016).

ID	Callsign	Origin	Aircraft	STD	Tflight (min)	Runway used	WTC	Fuel (kg/s)
FP1	UX9161	Las Palmas (LPA)	B738	20-1-18 10:00	152	32 L	M	0.694
FP2	UX4042	Alicante (ALC)	AT75	20-1-18 11:30	63	32 R	M	0.172
FP3	UX9047	Tenerife (TFN)	B738	20-1-18 10:00	154	32 L	M	0.694
FP4	IB8711	Lyon (LYS)	CRJX	20-1-18 11:10	85	32 R	M	0.444
FP5	QR149	Doha (DOH)	B77W	20-1-18 05:00	457	32 R	H	2.083

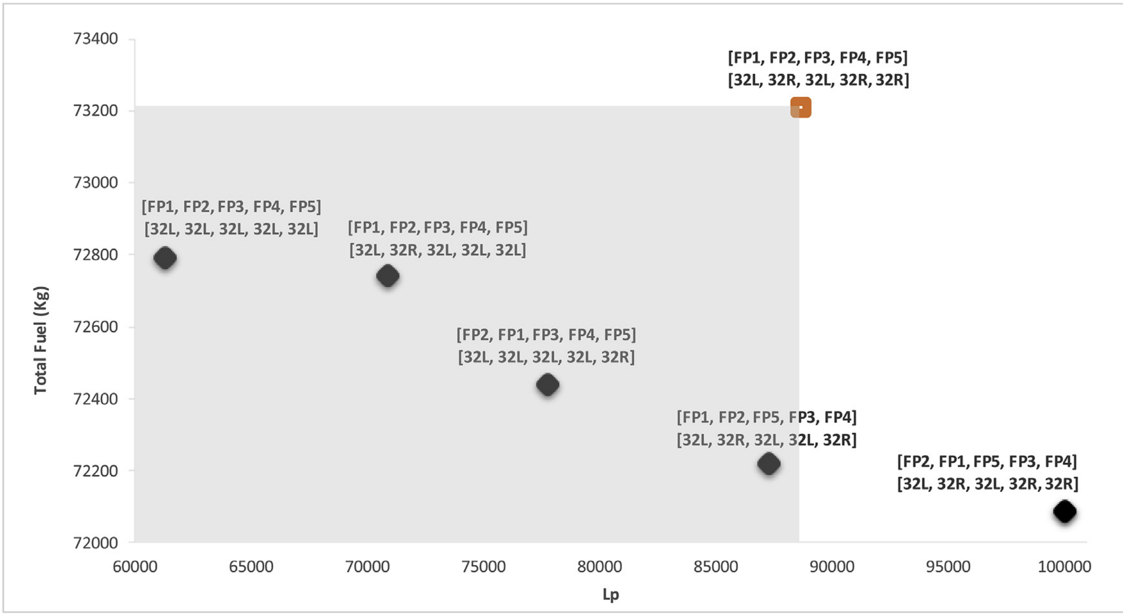

Fig. 4. Alternative sequences found by the model for 5 FPs with CPS = 2. Diamonds are solutions in the Pareto frontier, and the square point is the real schedule that day. All points in the shadowed area dominate (are better in both cost and noise) than the real schedule operated.

- Low congestion - [00:00–8:00]
- High congestion - [12:00–13:30]
- Intermediate congestion - [20:10–22:10].

Figs. 7–9 show the results of different sets of data, depending on the time of day considered. As can be seen, for all three cases, all the solutions found by the model are better than the real operation, dominating (i.e., being better in cost and noise simultaneously) the real schedules of that day. As noted before, the best solutions are obviously found for CPS = 5.

If we evaluate in these three figures the opportunities for cost reduction when relaxing the CPS constraint (i.e., allowing CPS = 5 instead of CPS = 0) we observe in the right extreme points of the figure (this means, points that minimise just fuel consumption), that in the Low congestion case we find a solution which allows to save 0.25% of total fuel, in the High congestion case 0.49%, while in the Intermediate congestion case the reduction in fuel consumption goes up to 1.17%.

Given that the three real operation points are dominated by all the points in the three Pareto frontiers, we can analyse the results in terms of the potential percentage of improvement in total fuel consumption and total noise impact, comparing the real situation with the best solution regarding noise (extreme left point in the frontier) and cost (extreme right point; see Table 4). It can be seen that the best results, in terms of total fuel consumption improvement, are again achieved for the scenario with Intermediate congestion (for both CPS).

These results indicate that when congestion is very low or very high, aircraft arrive at the airport with higher spacing or very close respectively, and the gain of applying CPS is very low. However, when the gaps between aircraft are big enough to combine different aircraft optimising the WTC but not very high so that the order of the aircraft is not altered without producing large waiting periods (impacting on fuel consumption), the improvement achieved by applying the CPS method is higher. We must point out here that the low percentage of improvement must be analysed, considering that the approach and landing procedures represent only a small percentage of the total flight time.

Regarding the results for noise improvement, it can be seen that CPS has no impact on the solutions achieved, with improvements in respect to the real noise impact much higher than in the cost case (more than 35% in all the scenarios considered). Allowing the model to select the most appropriate landing runway in terms of noise, confirms that there is place for improvement and can lead to important reductions in terms of noise impact over the populations that surround this airport.

After this analysis, we can state that noise and fuel-burnt reduction

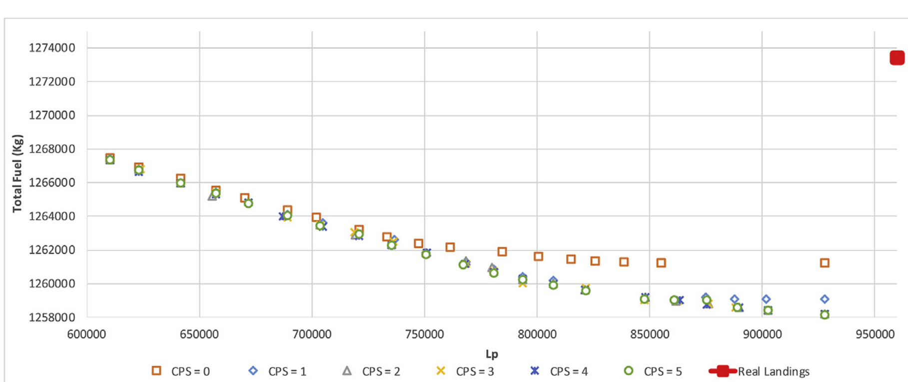

Fig. 5. Pareto frontier for 50 flights (corresponding to the Low congestion time frame) with different values of CPS. All solutions found are better than the real schedule operated.

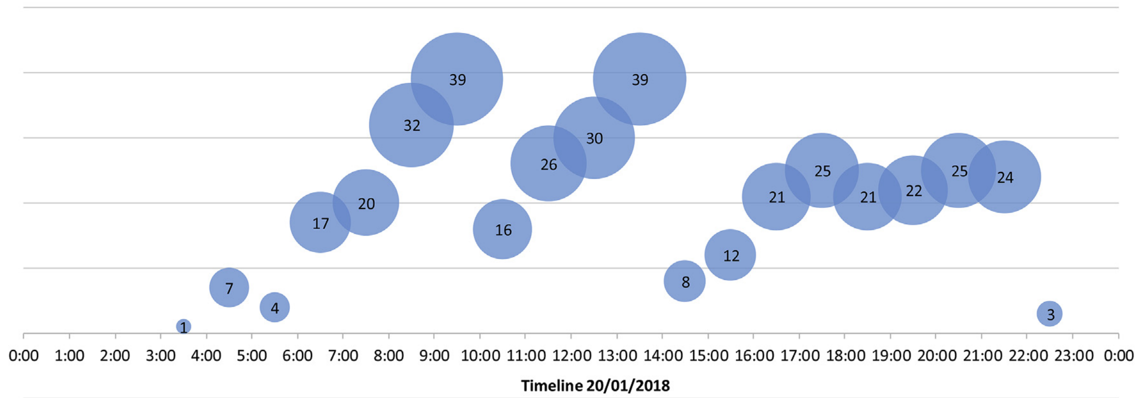

Fig. 6. Number of flights landing in every hour slot on the 20th January 2018 in Adolfo Suárez Madrid-Barajas Airport.

is achieved in our model as a consequence of 2 factors:

- Selecting the most appropriate landing runway allows the model to achieve reductions of overall noise in the population surrounding the airport.
- Changing the sequence of arrival allows the model to reduce the total fuel consumption since it leads to reductions in the spacing between aircrafts, reducing flight-times and selecting the optimal sequence of arrival.

With our bi-objective model we achieve solutions that, at the same time, are optimized in both objectives (fuel and noise), finding schedules which are much better than real operation.

Having observed the potential for improvement in both noise and fuel consumption, it could be interesting to test how the type of aircraft influences the potential improvements. Figs. 10 and 11 show the difference between the real operation and the two best alternatives for both criteria (i.e., the difference in fuel consumption and noise impact between the real data and the best solution found when minimising fuel consumption, and the best solution found by the algorithm when minimising the noise impact for the testbed of intermediate congestion).

Fig. 10 shows that when minimising fuel consumption, Airbus 332 has an average improvement of 450 kg when CPS = 5 (which is a 0.39% of its total consumption) while for CPS = 0 the fuel average saving is 150 kg (0.14% of its total consumption). It is reasonable to observe that the biggest improvements are for highest CPS due to higher improvement margins. It is also interesting to note that the largest percentages of total fuel reduction, in comparison with the total amount of fuel consumption per aircraft, are for AT75, A319 and B38M.

Fig. 11 shows that when minimising noise impact, Airbus 319 has an average improvement of LP = 14,000 for both CPS = 5 or CPS = 0, which contributes to a reduction of 18% in the noise impact of this aircraft in the surrounding populations. For Airbus 333 or Boeing 788, the model can achieve reductions of around 50% of noise impact in the populations affected by the final approach route.

6. Conclusions

In this paper a suitable bi-objective model for scheduling the landing of a sequence of aircraft by minimising noise impact and total fuel consumption (while limiting delays and maximising runway capacity) is presented. The model makes the most of the current capacity of the runways by choosing the most appropriate landing runway and landing time under wake vortex separation and CPS restrictions. It is also important to note that the proposed approach does not imply any change in the STARs or the operational procedures of the considered airport.

By using this model, we tested the potential improvements that are possible to attain when comparing current operational routines with the best alternative found by the model. The scenario considered in order to validate the proposed approach real data of landing aircraft at the Adolfo Suárez Madrid-Barajas Airport.

By analysing real flight plans on a specific day, improvements of up to 4.5% of total fuel consumption reduction were found, by modifying only the order of the approach sequence of arrivals at the airport, and up to 43% of reduction in total noise impact, which confirms that scheduling can be easily improved and have an immediate positive impact on the surrounding population of the airport without incurring delays and harming fuel consumption. Aircraft with the worst records of noise are those that have the highest possibilities of improvement, and aircraft that have lower consumption are those with lower absolute

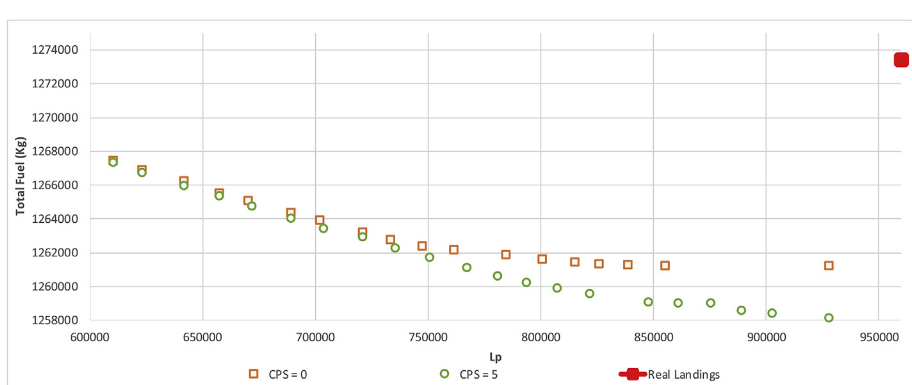

Fig. 7. Solutions found for 50 flights landing from 00:00 to 08:00 (Low congestion). The square point represents the real sequence (which is worse than all the solutions found).

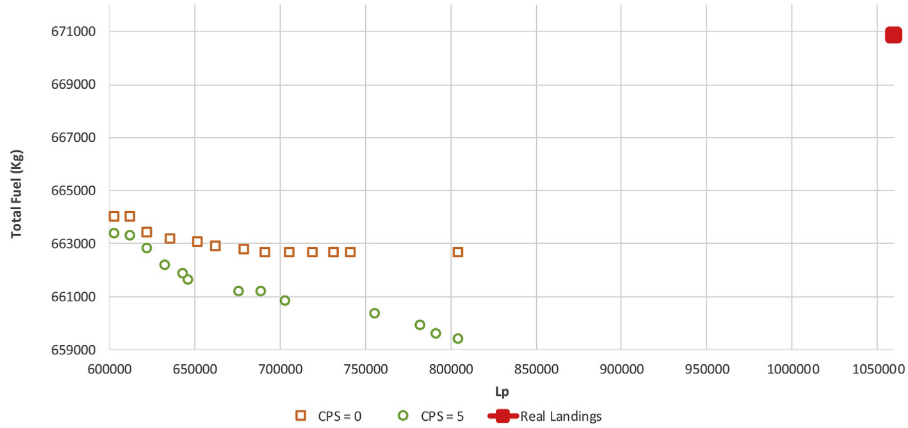

Fig. 8. Solutions found for 50 flights landing from 12:00 to 13:30 (High congestion). The square point represents the real sequence (which is worse than all the solutions found).

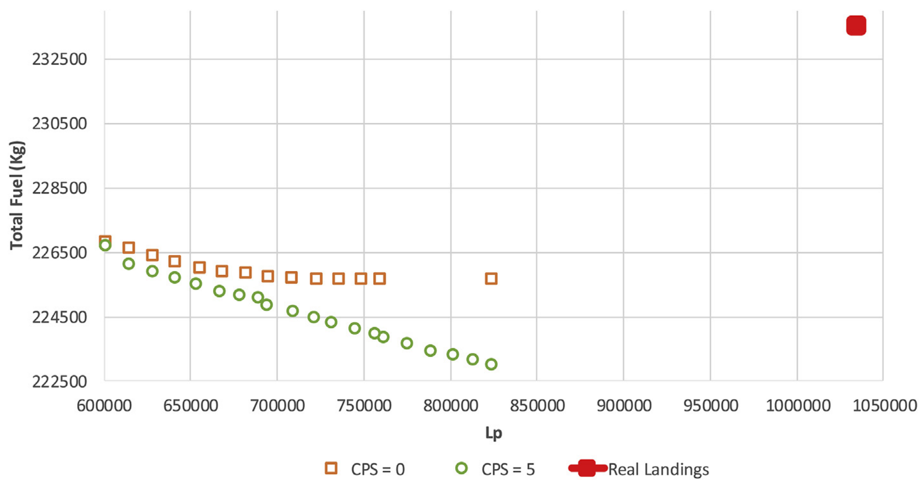

Fig. 9. Solutions found for 50 flights landing from 20:10 to 22:10 (Intermediate congestion). The square point represents the real sequence (which is worse than all the solutions found).

Table 4
Comparison of % improvement compared with real solution for the 3 scenarios (Low, Intermediate and High congestion) and two different values of CPS.

	Low congestion		Intermediate congestion		High congestion	
	CPS = 0	CPS = 5	CPS = 0	CPS = 5	CPS = 0	CPS = 5
Fuel	0.95%	1.20%	3.37%	4.50%	1.22%	1.71%
Noise impact	36.44%	36.44%	41.91%	41.91%	43.12%	43.12%

values of fuel reduction in kg but higher relative reductions in comparison to the total fuel consumed by the flight.

Lastly, it is important to note that congestion (total number of landing aircraft per time period) has an important effect on the possibilities of improvement of this model. Although for all three cases with different flight densities, all the points found by the model are better than the real operation, and dominating (i.e., being better with regard to cost and noise simultaneously) all of those in the current operation, the best results in terms of total fuel consumption improvement are achieved for the scenario with Intermediate congestion. Hence, being able to smooth the traffic over peak hours could have rewarding results; opening the door to achieving improvements in terms of having wider scheduling options that take into account noise reduction and fuel consumption as objectives.

Regarding the practical application of the model, while the route segment of the filed flight plan does not usually change during the flight itself, the STAR, the approach route and the runway might change depending on the weather conditions (such as wind), and air traffic congestion around the airport, among other factors. This is why the filled flight plan route ends not at the destination airport but at the point where a STAR begins, since the STAR, approach route and landing runway are usually assigned to the pilot during the en-route phase of the flight. Since the computational time of our model is very low, our model can be run during this phase to support the air traffic controllers on the best approach route that needs to be selected in order to balance noise disturbance in nearby populations and total fuel consumption. Note that the complete Pareto frontier would not be needed for real implementation as it was only used for our experiments, which reduces even more the computational time and would allow air traffic management systems to run periodically the model with the last updated data in order to find continuously the best solution.

There are a number of topics open for further research. Depending on the availability of more accurate real-time atmospheric condition information, a more accurate noise prediction could be obtained. This

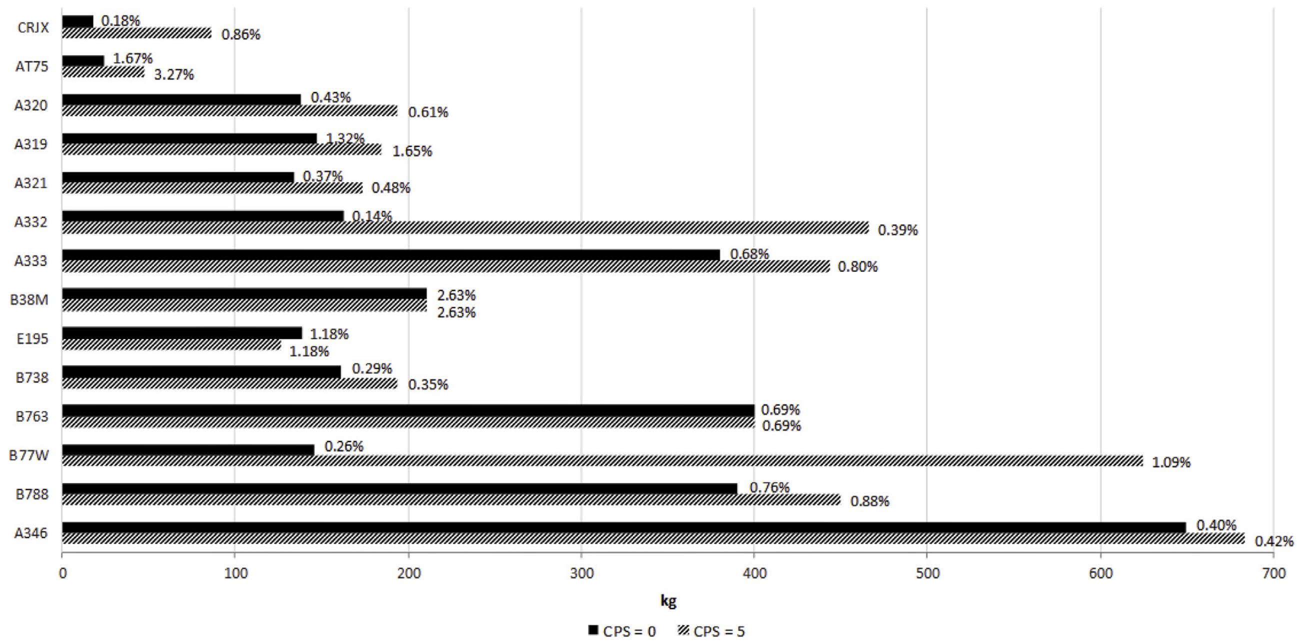

Fig. 10. Difference of fuel consumption (kg) between the real solution and the best solution found by minimising fuel consumption, for two different CPS and per type of airplane (Intermediate congestion time frame flights). For each aircraft type, the percentage of improvement in terms of fuel consumption is shown per CPS.

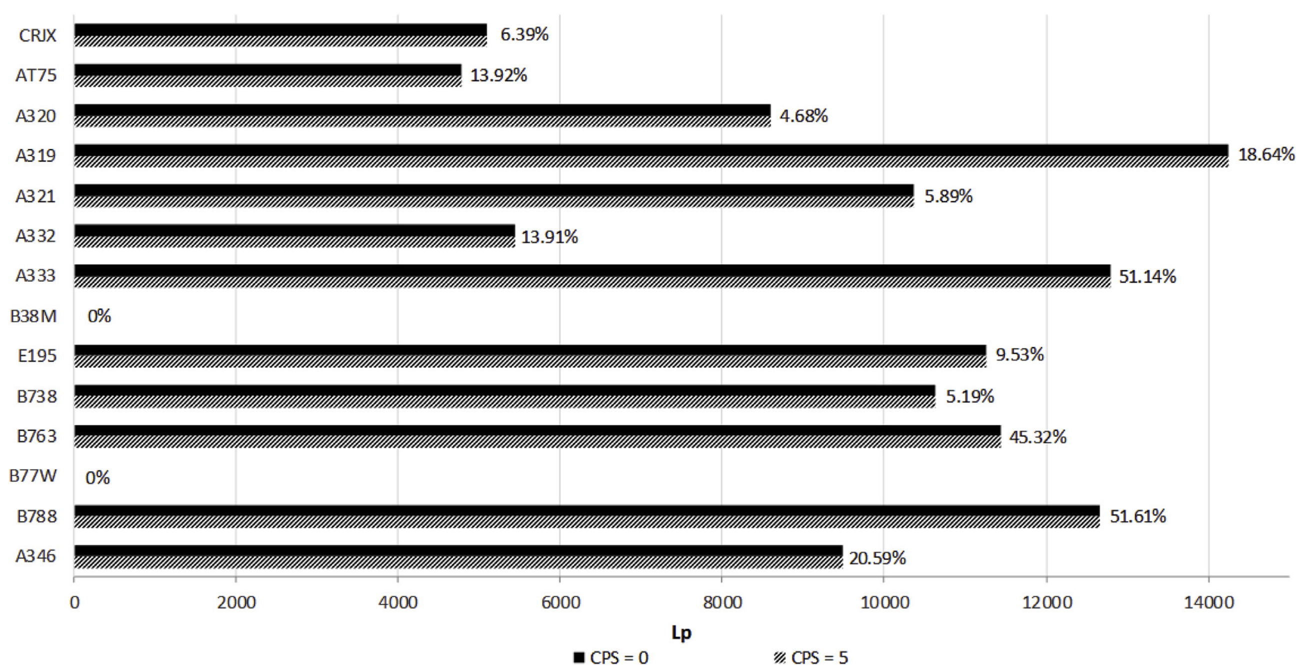

Fig. 11. Difference in noise level between the real solution and the best solution found minimising noise, for two different CPS and per type of airplane (Intermediate congestion time frame flights).

would allow for adjusting the decisions taken by the model with respect to noise propagation properties and noise impact influence on surrounding populations of the proposed solution. Also, extending the problem to consider all the flight trajectories would allow us to have a wider vision of the problem. Finally, the possibility of considering as an objective not only the total reduction but also the priority of flights would be interesting to explore.

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Anexo II. Informe con factor de impacto de las publicaciones presentadas

La siguiente lista se ha preparado con los datos de los informes de citas de revistas de Clarivate Analytics.

[A] Computers & Operations Research

ISSN: 0305-0548

Editor: PERGAMON-ELSEVIER SCIENCE LTD

Categorías: *Operations Research & Management Science*

Año	Factor de impacto	Ranking	Cuartil
2017	2,962	15/84	Q1
2016	2,600	16/83	Q1
2015	1,988	19/82	Q1

[B] Transportation Research Part D

ISSN: 1361-9209

Editor: PERGAMON-ELSEVIER SCIENCE LTD

Categorías: *Transportation Science & Technology*

Año	Factor de impacto	Ranking	Cuartil
2017	3,445	7/35	Q1
2016	2,341	15/34	Q2
2015	1,864	12/33	Q2

[C] Journal of Air Transport Management

ISSN: 0969-6997

Editor: ELSEVIER SCI LTD

Categorías: Transportation

Año	Factor de impacto	Ranking	Cuartil
2017	2,038	17/31	Q3
2016	2,357	10/33	Q2
2015	1,084	21/32	Q3