様　式　C－19、F－19－1、Z－19　(共通)

科学研究費助成事業　　研究成果報告書

令和　2 年　6 月　5 日現在

機関番号：８２６４５
研究種目：研究活動スタート支援
研究期間：2018～2019
課題番号：１８Ｈ０５９２５・１９Ｋ２１０９２

研究課題名（和文）Synergistic ground holding algorithm based on real-time air traffic pattern classification and off-line buffer optimization

研究課題名（英文）Synergistic ground holding algorithm based on real-time air traffic pattern classification and off-line buffer optimization

研究代表者

アンドレエバ森　アドリアナ（Andreeva-Mori, Adriana）

国立研究開発法人宇宙航空研究開発機構・航空技術部門・研究開発員

研究者番号：３０７４７４９９

交付決定額（研究期間全体）：（直接経費）　　2,100,000円

研究成果の概要（和文）：交通量増加のため、ハブ空港は最大容量で運用されることが多い。そのため、混雑している時間帯において、到着空港近辺では多くの便が空中待機することになってしまう。空中待機時間を削減するために、出発制御が実施されている。しかし、出発時刻や飛行時間の不確定性のため、最適な出発制御時刻のリアルタイム算出が困難である。本研究では、機械学習を用いたリアルタイムの交通流パターン予測とオフラインの出発制御パラメータ最適化に基づいたアルゴリズムを開発した。不確定性を考慮した数値シミュレーションによる出発制御の効果を定量的に評価した。交通流パターンの予測精度が十分であったことから、本アルゴリズムの妥当性を確認した。

研究成果の学術的意義や社会的意義
A concept of a traffic pattern classifier applied to optimal ground holding was proposed.The combination of static and dynamic optimization approaches allowed near-optimal solutions easily implemented in real-world. The potential of machine learning for air traffic management was also demonstrated.

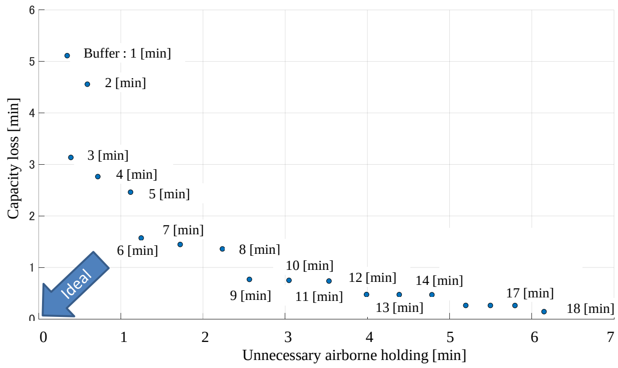
研究成果の概要（英文）：To address the issue of increased air traffic and congestions at hub airports, this research developed a novel synergistic ground holding algorithm based on real-time air traffic pattern classification and off-line buffer optimization. When the expected airborne holding time is expected to exceed a certain constant buffer value, this excess waiting is set as ground holding,i.e. aircraft are kept on the ground before departure, experiencing ground holding. In our research, we considered various real-world uncertainties to determine the optimal buffer applied by the ground holding program. We then built a simulated database and developed a machine-learning-based traffic pattern classifier which, based on traffic features, predicts the optimal ground holding control parameters and potential savings within mean absolute percentage error of 17.96% of the potential optimal ones.

研究分野：air traffic management

キーワード：ground holding　air traffic management　synergistic algorithm

1. Research background

During nominal operations, flights are scheduled so that demand does not exceed capacity at neither the departure nor the arrival airport. Weather uncertainty, however, often leads to uncoordinated demand and causes congestions in the arrival flow. In order to manage such congestions at the arrival airport, some flights can be held on the ground at the departure airport. This traffic management initiative, called ground holding (GH), is meant to reduce airborne holding, thus leading to fuel savings, lower air traffic controllers' workload and higher safety. When GH is modeled as a completely deterministic problem, the optimal time for which a flight needs to be delayed at the origin airport can be calculated accurately. In reality, however, traffic flow includes many uncertainties, such as departure delays and flight time delays, which makes the GH problem a probabilistic one. If the calculated GH is too short, the flight will still have to spend unnecessary time in the air, thus burning fuel and occupying airspace. On the other hand, if the calculated GH is too long, the flight will be able to land without any holding in the air, but landing capacity will be lost. Finding the balance between those two is the key to the GH problem. The importance of the GH problem has led to research in two major directions. Dynamic optimization of departure times can minimize airborne delays, as shown by Cox and Kochenderfer [1]. However, it allows revising the GH as new information on the arrival queue becomes available, so it includes many last-minute changes to the airline's schedules which disrupt operations. Another approach is setting a constant buffer at the arrival queue. For example, with a buffer of 10 min, if a flight is expected to wait in an arrival queue for 13 min, it will be assigned 3 min GH at the departure airport. Since air traffic control is still human-centered, such a constant buffer is easy to implement by air traffic controllers. The author conducted preliminary research using the constant buffer method and verified the tradeoff between airborne holding and capacity loss, as seen from the right figure. However, most researchers assumed optimality of the dynamic optimization and the practicality of the constant buffer method to be mutually exclusive. This research will take a synergistic approach.



2. Research goal

The goal of this research is to develop a novel synergistic ground holding algorithm based on real-time air traffic pattern classification and off-line buffer optimization. This research answers the following two questions:

1) Is there a ground holding algorithm which outperforms the constant buffer algorithm in terms of airborne delay and airspace capacity, but can still be easily implemented in real air traffic management?

2) If so, what is the relation between the optimal buffer value and traffic characteristics? Can traffic be categorized in patterns for an optimal buffer value?

3. Research method

In order to develop the synergistic ground holding algorithm, the author first builds a simulated database based on numerical simulation of ground holding program practiced in Japan, i.e. the constant buffer method. The author evaluates each GH control based on airborne delay costs, ground delay costs, and lost throughput costs. Next, a traffic pattern classifier is developed which predicts the optimal ground holding control parameters based on traffic features. This approach enables a simulation of both past and future traffic initiatives, and thus can be used in immediate as well as long-term, tactical level planning and performance analysis. The general concept of the developed algorithm is shown in Figure 1. The input of the real-time component consists of traffic features, which might include the initial estimated time of arrival (ETA) queue or the corresponding traffic density, uncertainties related to departure and flight times, as well as capacity prediction. The traffic pattern classifier feeds the traffic features into a pre-trained machine learning algorithm to determine the class to which the current traffic most likely belongs to. Each class is characterized by the potential results of the ground holding when performed for this class's traffic and the optimal ground holding decision parameters associated with it. For example, Class A might mean high effect of the ground holding program, i.e. traffic should be managed through ground holding to achieve fuel burn savings, reduction of air traffic controllers' workload and increased air traffic safety; Class B, on the other hand, might mean that the effect of ground holding cannot compensate for uncertainties in the environment and the air traffic managers are therefore not advised to enforce ground holding program. Once the traffic is classified, the optimal ground holding parameters will be extracted from a database created beforehand. This database is the output of the off-line component of the algorithm. Based on the ground holding optimal control parameters, departure times can be assigned to each flight part of the ground holding program.

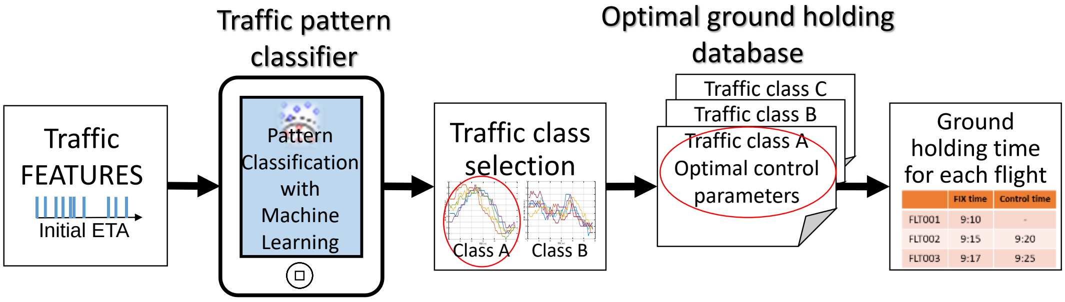


Figure 1. Operational concept of the proposed ground holding algorithm

4. Research results

(1) Optimal ground holding database generation

First, the ground holding database needs to be built. The author starts by determining the optimal buffer for each simulated traffic scenario (ETA queue) by evaluating the total savings gained by ground holding when considering airborne delay (i.e. path stretching in the vicinity of the arrival airport), ground delay and throughput loss. Each traffic scenario is described by an Estimated Time of Arrival queue (ETA queue) for 30 aircraft. Assuming required separation of 2 min on arrival, 30 aircraft account for 1 hour traffic. To account for departure time error and flight time prediction errors, Monte Carlo simulations are conducted. The results for two sample traffic scenarios (ETA queues) are shown in Figure 2. Altogether, there are 30 flights with ETAs unevenly distributed between 0 and 60. The ground holding effect for ETA1 and Buffer varying between 1 min and 15 min is shown in Figure 2(left). The horizontal axis shows the Buffer value in minutes, while the vertical axis shows the cost compared to the nominal case, and lower values mean decreased cost, i.e. negative values, of mean savings. For each value, simulation results are shown by a box plot. The median value is shown in red, and the bottom and top edges of the box indicate the 25th and 75th percentiles. The whiskers show all points but the outliers. From these results it is obvious that the total delay cost determined according to Equation (3) varies with Buffer values. The median total cost is minimum for Buffer = 6 min (median cost savings are 7800 EUR). With the increase of Buffer value, however, the effect of departure time and flight time uncertainties decreases, so from the operational perspective the optimal Buffer choice is not straightforward. Small Buffer leads to more ground holding, so the ground delay costs is maximum for Buffer=1. On the other hand, airborne delay costs increases with Buffer value.
Next, consider another sample ETA queue (Figure 2(right)). The traffic is highly concentrated at the beginning, and sparse after that. The general trend for total costs, ground delay cost, airborne cost and lost capacity cost are similar to those observed for ETA1. However, most savings are achieved for Buffer=11 min (median savings 2794 EUR), which is considerably less than the savings for ETA1. For Buffer values less than 7, ground holding control will likely induce extra costs, not savings (the median exceeds zero).

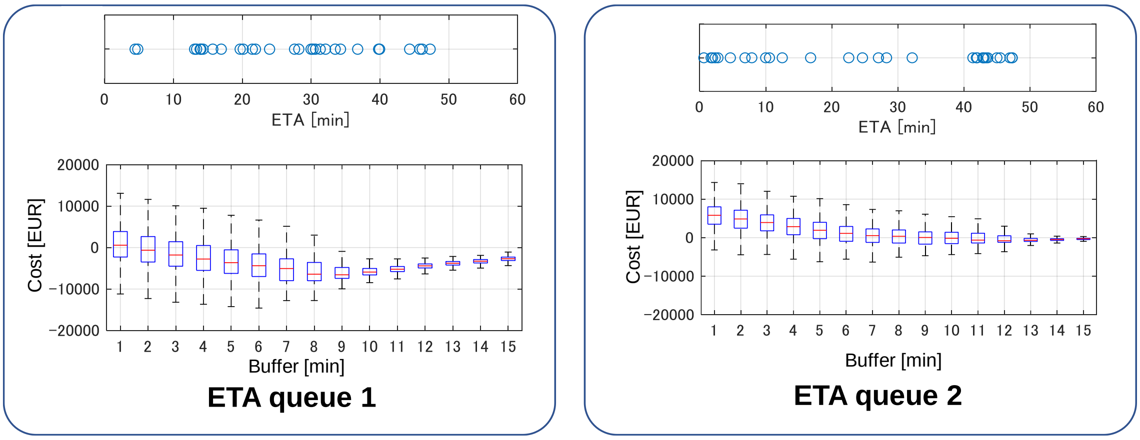


Figure 2. Sample traffic scenarios results

These two sample ETA queues illustrate two important control results:
1) Savings due to ground holding are dependent on the ETA queue. Choosing the optimum Buffer

value might not be sufficient to produce sufficient savings, i.e. the ground holding effect for some ETA queues is limited.
2) The optimum Buffer value which minimizes the cost function depends greatly on the individual ETA queue.

Therefore, if the air traffic manager can correctly classify the ETA queue pattern, i.e. the traffic pattern, they will be able to set the optimum ground holding program parameters (here, choose the Buffer value) and decide whether to actively pursue the ground holding program application to this particular traffic in view of the potential savings.

Following the methodology described above, a database for 1000 different ETA queues is generated. To account for departure time and flight time uncertainties in each ETA queue, 1000 run Monte Carlo simulations are done. As a results, the generated database has the following information for each ground holding control: ETA queue (ETA for all 30 flights in the queue), median value of the cost function for each Buffer between 1 and 15 min, the optimum Buffer which minimizes the median value of the cost function, traffic parameters such as separation required at the control fix, uncertainties distribution parameters of the departure and flight times.

(2) Traffic pattern classification

A traffic pattern classifier which applies machine learning techniques to aid traffic controllers in their decision on ground holding program parameter settings is developed. As with any machine learning problem, choosing appropriate features which describe the characteristics of the input and the phenomena involved is the key to correct classification. Each traffic scenario is described by relative traffic density, i.e. the number of scheduled arrivals in respect to available capacity.

The problem is formulated as a regression problem. We use support vector machine with a quadratic kernel. The classifier is developed in MATLAB® 2018b and uses Statistics and Machine Learning Toolbox.

① Potential cost savings prediction for each traffic scenario (ETA queue)
The optimal predicted savings versus the true savings (based on the numerical simulations developed earlier) are shown in Figure 3. Round mean square error (RMSE) is 451.5 EUR. The high accuracy of the prediction shows that a decision on whether ground delay should be introduced for a certain ETA queue can be made based on the cost savings predicted by the traffic pattern classifier. The buffer selected to achieve those savings corresponds with high accuracy to the optimal one (RMSE is 1.28 min).

② Robustness investigation (i.e., if Buffer is selected with a certain error, how much will the achieved savings differ from the potential optimal ones)
Choosing a Buffer according to the prediction results is sub-optimal control (unrealised savings) when the predicted and true Buffer values are different. Such unrealised savings due to erroneous Buffer selection are shown in the histogram in Figure 4 (average value is 297.5 EUR). In the original data, however, the optimal cost sensitivity to Buffer value is not particularly strong around the optimal Buffer, which explains the relative good performance and high accuracy with mean absolute percentage error of 17.96% and RMSE of 472.4 EUR.

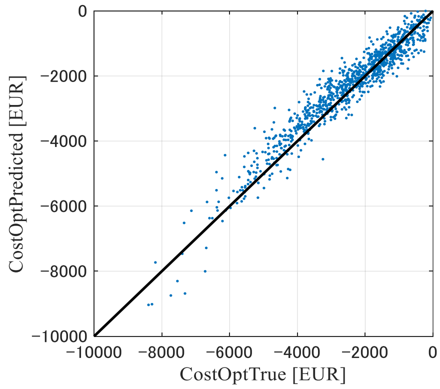


Figure 3. Optimal savings prediction

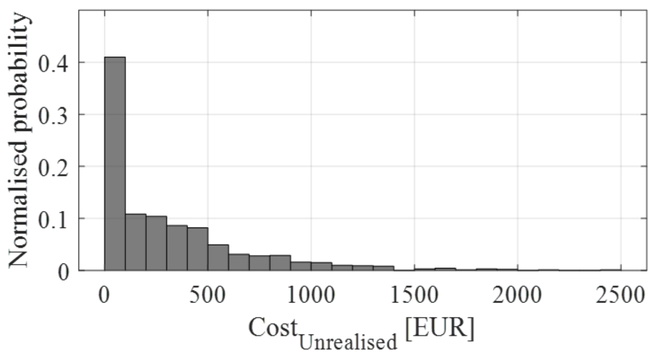


Figure 4. Unrealised savings

The presented results demonstrate the feasibility of the traffic pattern classifier concept and its application to traffic management initiatives, in particular ground holding. Discussions with air traffic management personell have identified the need for a more transparent machine learning technique, which could make the "black box" governing the classifier into a grey one, i.e. visualize some of the decision steps in the classification process and provide this information to controllers. Such a "grey box" approach will be essential if the traffic pattern classifier is to be used in practice.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　0件）

１．著者名 アンドレエバ森 アドリアナ，松野 賀宣，又吉 直樹	４．巻 68
２．論文標題 空中待機と地上待機のコストを考慮した出発制御時刻	５．発行年 2020年
３．雑誌名 日本航空宇宙学会論文集	６．最初と最後の頁 31-37
掲載論文のDOI（デジタルオブジェクト識別子） 10.2322/jjsass.68.31	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Adriana Andreeva-Mori, Naoki Matayoshi
２．発表標題 Operational Concept of Traffic Pattern Classifier for Optimal Ground Holding
３．学会等名 Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019)（国際学会）
４．発表年 2019年

１．発表者名 アンドレエバ森 アドリアナ、松野　賀宣、又吉　直樹
２．発表標題 効果的な出発時刻制御のための航空交通流パターン認識
３．学会等名 日本航空宇宙学会年会講演会
４．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考