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A method for emission allowances allocation in air transportation systems from a system-of-systems perspective

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A B S T R A C T

Market-based mechanisms, especially emission trading schemes, are proposed as a means to control system-wide aviation emissions. Although auctioning has gained some recent popularity, free allocation of emission allowances is still favored by many to incentivize airlines' participation in the outset of an emission trading program. However, current methods for free allocation – grandfathering method and benchmarking method – have their limitations, such as placing heavy workload on regulators and a lack of transparency and flexibility. To overcome some of the limitations, this paper proposes a multi-stakeholder dynamic optimization method from a system-of-systems perspective. The method delegates part of the regulators' responsibility to airlines, and grants airlines flexibility to plan, negotiate, and request for emission allowances. The inclusion of the regulators' allowance allocation decision-making and airlines' fleet allocation decision-making ensures a holistic understanding of the problem. Specifically, the method combines transfer contract coordination mechanism and approximate dynamic programming to coordinate the allowance consumption between the participants. We apply the method to a ten-route air transportation network where two representative airlines compete for the allowances. The results demonstrate that the total network-wise profit from each airline's independent decisions can approach the globally efficient solution in an ideal centralized case without violating the emission constraint.

1. Introduction

According to the International Civil Aviation Organization (ICAO), the aviation carbon dioxide (CO_2) emissions account for over 2 percent of the total CO_2 emissions, and are expected to experience a growth of 300–700 percent by 2050 compared to the level in 2005 (European Commission, 2018). Market-based mechanisms have been proposed and adopted by many countries to control the system-wide aviation carbon emissions. The European Union (EU) Emissions Trading System (ETS) (i.e., cap-and-trade scheme) (European Commisions, 2018) is generally accepted as one of the most effective market-based mechanisms for emissions control. The main idea is placing a cap on the total amount of greenhouse gases – primarily CO_2 – that can be emitted each year and allow the participants to trade in the emission allowances (i.e., permits or credits). A central question of designing an emissions trading system is how the emission allowances are initially distributed among the participants. Although auctioning has gained some recent popularity, free allocation of emission allowances is still favored by many to incentivize participation in the outset of an emission trading program (Burtraw and McCormack, 2017). However, current methods for free allocation – grandfathering method and benchmarking method – have their limitations. For example, the regulators in both methods suffer from the heavy workload of determining the allowances distribution for each participant. The opacity of the allocation process is also a serious concern of the society, not to mention the chances of windfall profit for the participants that are over-subsidized for their emissions (Carbon Market Watch, 2016a). Therefore, devising a market-based mechanism that make transparent the give-take of relevant stakeholders is of utmost importance. Our solution is to delegate part of the regulators' responsibility to the participants. Specifically, there is a need to design a mechanism for emissions trading that can maintain optimized profit without overrunning cost while 1) alleviating the burden of the regulators on collecting and processing information and 2) increasing the transparency of

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Nomenclature

$pax^k_{l,i,t}$	number of passengers on aircraft i on route l for airline k during year t
$Price^k_{l,i,t}$	ticket price for each passenger on aircraft i on route l for airline k during year t
$Cost^k_{l,i,t}$	operating cost per trip of aircraft i on route l for airline k during year t
$x^k_{l,i,t}$	number of trips that aircraft i flies on route l for airline k during year t
$emission^k_{l,i,t}$	marginal emissions produced by aircraft i on route l for airline k during year t
$permit_t$	total emission allowances during year t
$demand^k_{l,t}$	market demand on route l for airline k during year t
$BH^k_{l,i}$	block hours for aircraft i on route l for airline k
$EMH^k_{l,i}$	equivalent maintenance hours of aircraft i on route l for airline k
TH^k_i	turnaround time of aircraft i for airline k
$fleet^k_{i,t}$	fleet size of aircraft i for airline k during year t
$capacity^k_i$	seat capability of aircraft i for airline k
$M^{k,j}_{l,i,t}$	value of a transfer contract that airline k needs to compensate to j for emissions generated from flights of aircraft $i \in \mathscr{I}^k$ on route l during year t
$est\_x^j_{l,i,t}$	airline k's estimation of the number of trips allocated on aircraft $i \in \mathscr{I}^j$ on route l by airline j
$\overline{V}^k_{t+1}$	airline k's value function approximation from $t+1$ to the end
θ^k_{t+1}	coefficient of basis functions of airline k's value function approximation
γ	discount factor
k, j	index of airline
$\mathscr{K}$	set of all airlines
i	index of aircraft
$\mathscr{I}$	set of all aircraft
l	index of route
$\mathscr{L}$	set of all routes

the allocation process. This need motivates our search for a new approach to the problem.

Multiple stakeholders, primarily airlines and regulators, are involved in an aviation emission trading system and collaborate as a system-of-systems (SoS). The regulators and each individual airline operate independently and pursue distinct objectives regarding profit and emitted pollution. The regulators aim to optimize emission allowances allocation decisions that can lower the global carbon intensity while each airline strives to maximize individual economic profit by optimizing its fleet assignment. Both the emission allowances allocation problem and airline fleet allocation problem have a long-term modeling horizon, which reflects the evolutionary development feature of an SoS problem. Therefore, this paper addresses the design of an emissions trading system as an SoS problem that accounts for the independence of airlines, the interactions among airlines and between regulators and airlines, and the evolutionary nature of the decision-making process. The SoS approach provides a structural framework to include all the relevant entities and places an emphasis on the decentralized and evolutionary features. Specifically, this paper employs a Multi-Stakeholder Dynamic Optimization (MUSTDO) method (Fang et al., 2018) that integrates approximate dynamic programming (ADP) and transfer contract coordination mechanism (TCCM). ADP (Powell, 2010) is a well-recognized method for addressing multi-stage decision-making problems under uncertainty. An airline's fleet assignment problem can be very complicated due to the size of an air transportation network and the variety of uncertainties. As a flexible modeling and algorithmic framework, ADP has the potential to convert complex and intractable problems to manageable forms using various approximation strategies. TCCM (Hirshleifer, 1956) was a tool for revenue management in multi-divisional corporations, in which each division has an independent profit goal. The mechanism deals with the problem of assigning a proper value to the products and services that are exchanged between the divisions. The key idea of TCCM is to align the objectives of the individual participants to that of the SoS manager. It is a simple and straightforward method with the potential to lead local decisions to approach the SoS-level optimality. The combination of ADP and TCCM allows for exploration of the intertwined effect of the stakeholder interaction and intertemporal interaction. This paper modifies the original MUSTDO method for this emission allowances allocation problem and provides a more decentralized perspective on the initial allowances allocation, compared to the existing methods.

We summarize the contributions of the proposed method as follows. First, the method relieves the regulators from collecting full information and directly calculating the emission allowances for each airline. The regulators only provide the mechanism and the limit of aggregated emissions instead of determining the specific number of allowances for each airline. The airlines communicate and trade (transfer contract) with each other by following the given mechanism. This process also improves the transparency and robustness of the allocation due to the reduction of government power. Second, each participating airline obtains more flexibility to plan out the portion of present and future emission generation. An application to a ten-route air transportation network in the United States demonstrates the effectiveness of the method. Overall, viewing an aviation emissions trading system as an SoS helps the decision makers to build a holistic picture that includes the interactions of various stakeholders and their evolution over time.

This paper consists of six sections in total. Section 2 introduces the background of aviation carbon emission reduction and related work on emission allowances allocation methods. Section 3 provides the formulation of an individual airline's fleet allocation problem that aims to maximize profit with operational and emission constraints, as well as a benchmark problem where the regulators are assumed to possess centralized authority. In Section 4, we describe a solution approach – the modified MUSTDO method that integrates approximate dynamic programming and transfer contract coordination mechanism. Section 5 demonstrates the effectiveness of the proposed method by conducting a series of experiments and studies in a ten-route U.S. air transportation network. Section 6 concludes the paper and provides the future research directions.

2. Background and related work

2.1. Aviation emission policies and market-based mechanisms

In response to the goal of emissions reduction, stakeholders are pursuing primary strategies including aircraft technology advancement, operational improvement, use of alternate fuels, and market-based measures (MBMs, e.g., carbon tax, emissions trading scheme, offsetting) (Grote et al., 2014). For example, the National

Aeronautics and Space Administration (NASA) has developed environmentally sustainable aviation technologies, primarily through its Environmentally Responsible Aviation (ERA) project (Collier, 2010) and Advanced Air Transport Technology (AATT) project (Heidmann et al., 2017). The Federal Aviation Administration (FAA) pursues improved operational strategies, e.g., more precise routes, via the Next Generation Air Transportation System (NextGen) program. However, studies have shown that advanced aircraft technology alone only minimally reduces the growth of carbon emissions and even the combined use of cutting-edge aircraft technology and low-carbon fuels may not be able to reduce the growth of aviation emissions to the significant degree desired (Moolchandani et al., 2017), (FAA Office of Environment and Energy, 2015). Thus, flexible market-based mechanisms are critical as a complementary strategy in quickly integrating advantageous technology and operational innovations into current systems and in turn controlling the system-wide emissions.

The EU ETS, initiated in 2005, was the first and largest international trading system for controlling the carbon emissions and started to include all departing and arriving flights since 2012 (European Commisions, 2018). Many countries and regions including Norway, Switzerland, New Zealand, Alberta, New South Wales, United States Regional Greenhouse Gas Initiative (RGGI), and Tokyo among others, are all proponents of the ETS (International Energy Agency, 2010). The primary methods of distributing initial emission allowances include grandfathering method, benchmarking method, and auctioning method. The former two methods are for the free emission allowances while the latter charges for the emission allowances. Many papers have discussed the advantages of auctioning, including efficiency, fairness, and transparency (Zetterberg et al., 2012), (Cramton and Kerr, 2002), (Lopomo et al., 2011), (Hepburn et al., 2006). The EU ETS has also gradually replaced free allocation with auctioning (European Commisions, 2018). Although auctioning has become the dominant approach in many existing programs, free allocation continues to be a prevalent method as a starting point (Burtraw and McCormack, 2017). For example, free allocation is a feature of the expected cap-and-trade program in China, which will be the largest in the world when it takes effect in the next couple of years (Burtraw and McCormack, 2017). Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), agreed by 191 member states of ICAO in 2016, is the first international agreement on controlling emissions from international flights. The goal is to limit the net CO_2 emissions of flights between participating countries to 2020 levels, primarily through purchasing carbon offsets from emission reduction projects in other sectors. As the EU ETS is a cap-and-trade system that pre-defines an emission cap, CORSIA on the contrast is an offset scheme that has no cap. CORSIA has received many praises and criticisms since it was proposed. One of the criticisms is that CORSIA is a zero-sum game that merely compensates for aviation emissions growth somewhere else (Carbon Market Watch, 2016b). Some analysis (Scheelhasse et al., 2018) suggests a combined use of CORSIA and EU ETS to cover the international and domestic flights in terms of effective CO_2 emission reduction. While many countries are still in the process of exploring effective market-based mechanisms for domestic aviation emission reduction, this paper builds on the EU ETS style for its potential in mitigating domestic aviation emissions.

The incumbent EU ETS style solutions for free emission allowances allocation, grandfathering and benchmarking methods, are imperfect. The grandfathering approach, because it distributes the initial allowances based on the historical emissions (Zetterberg et al., 2012), attracts emitters and repels new entrants or those who already operate in an energy-efficient manner (Cramton and Kerr, 2002), (Chin and Zhang, 2013). On the other hand, the benchmarking approach allocates initial emission allowances according to the production level and a reference emission level per product (Groenenberg and Blok, 2002). The European Commission considers benchmarking as a way to "reward operators that have taken early action to reduce greenhouse gases and give stronger incentives to reduce emissions" (European Commission, 2008). However, the benchmarking method requires the regulators to collect detailed information on the production levels, energy requirements, and greenhouse gas emissions that come with the production (Groenenberg and Blok, 2002). In summary, both methods place heavy workload on the regulators and grant inadequate transparency and flexibility to the airlines, which calls for a new perspective to design a mechanism for aviation emission trading system.

2.2. Aviation emissions trading system as a system-of-systems

Current emissions trading systems depend heavily on the government agencies for a centralized allocation of the emission allowances, which conflicts with the decentralized nature of the problem. In an air transportation system, airports, airlines, aircraft manufacturers, regulators, and other entities interact with each other to achieve good quality air services. The aggregation of the interacted heterogeneous entities that possess managerial and operational independence demonstrates the key features of an SoS (Maier, 1998), (DeLaurentis et al., 2011). Five distinguishing traits, including managerial independence, operational independence, geographical distribution, evolutionary development, and emergent behavior, often characterize an SoS problem (Maier, 1998). In an aviation emissions trading system, the main stakeholders involved are the regulators and airlines. A regulator serves the role of an SoS manager with partial control authority over the participating airlines; an airline serves the role of an SoS participant with selfish objectives that may conflict with the other participating airlines and with the regulator. Such a structure composes a typical *acknowledged* SoS (Maier, 1998), (Dahmann and Baldwin, 2008). Specifically, the regulators aim at reducing global carbon intensity (i.e., ratio of carbon emissions to gross domestic product (GDP)) by designing emission allowances allocation mechanism and the airlines pursue business profit by optimizing flight allocation decision within emission limit.

In most prior work, the regulators' task of emission allowances allocation and the airlines' task of fleet allocation were often treated as separate problems. On one hand, papers like (Grote et al., 2014), (Zetterberg et al., 2012), and (Wittneben, 2009) discussed the pros and cons of various emission policies at the macro level based on the past and current practices, without accounting for the details of firm-level operations. On the other hand, the simulation models for airline operations, such as Aviation Emissions and Evaluation of Reduction Options (AERO) (Vlek and Vogels, 2000), Global Aviation Industry Dynamics (GAID) (Sgouridis et al., 2011), and Fleet-Level Environmental Evaluation Tool (FLEET) (Moolchandani et al., 2017), or optimization models (Aliabadi et al., 2018), often considered the allocated emission allowances as a unilaterally given constraint without touching upon the emission allowances allocation process. Recently, some researchers modeled the interactive relationship between the regulators (or governments) and the airlines (or firms) as a Stackelberg game (i.e., leader-follower game) (Krass et al., 2013), (Xu et al., 2016a). References (Hong et al., 2017), (Xu et al., 2016b), and (Qiu et al., 2017) combine the Stackelberg game and the Cournot game to study the behaviors of the firms and the regulators under different emission policies. In those games, the airline operational networks were kept small due to the computational complexity of game theory and the regulators still played a central role in distributing the emission allowances.

The objectives of emission allowances allocation problem and fleet allocation problem are both long-term oriented, thus long-term planning could be more beneficial than annual decision-making. Allowing long-term evolutionary decision-making can create another dimension of flexibility – the participants can trade allowances not only through the player interaction but also through time. Theoretical studies agree on the fact that the banking (i.e., saving unused allowances for future use) and borrowing (i.e., borrowing allowances from future allocation for current use) mechanism, when effective, allows for inter-temporal flexibility and in turn help reduce overall compliance costs (Rubin, 1996), (Chevallier, 2012). From an airline's perspective, banking and borrowing would allow for more flexible fleet allocation decisions to face the future uncertainties. However, less attention has been given to this inter-temporal flexibility for the major concern that unlimited borrowing may cause the participants to delay costly investments in clean technologies by borrowing allowances from future periods (Chevallier, 2012). Nonetheless, as Chevallier emphasized, simply banning the inter-temporal banking and borrowing mechanism is not the best way to grapple with the implementation difficulty; instead, the policy makers and researchers should be open to the possibility and actively search for potential solutions.

The proposed MUSTDO method provides a novel SoS perspective that accounts for both the decentralized nature and evolutionary nature of the problem, and in turn can alleviate the burden of the regulators, increase allocation transparency and improve airlines' planning flexibility. Table 1 summarizes the capability need of the method and the treatments that the MUSTDO method offers.

3. Problem formulation

Emission allowances allocation is a centralized decision-making problem if the regulators take full responsibility for the task. The regulators specify the emission limit, and also aim to maximize the global profit from the entire air transportation network because of the vital role of aviation in a nation's economy (e.g., aviation accounted for 5.4% of U.S. GDP in 2012 (Federal Aviation Administration, 2015)). This is consistent with the goal of lowering the carbon intensity – the ratio of carbon emissions to gross domestic product. In an ideal scenario where the regulators have ultimate authority, the problem is that of global optimization with an objective of optimizing economic profit under operational and environmental constraints. In reality, however, emission allowances allocation is a partially decentralized decision-making problem due to the independence of airlines. Hence each airline needs to carefully make fleet allocation decisions that not only balance profit and emissions but also balance the short-term and long-term needs. This paper pushes the problem towards the decentralized polar where the regulators only provide the emission limit and an influencing mechanism instead of distributing specific allowances to each airline. This section describes the mathematical formulation for the airlines' fleet allocation decisions in the decentralized case that can also generate emission allowances distribution, and a global fleet allocation problem in an ideal centralized benchmark case.

3.1. Airlines in the decentralized case

We use the Fleet-Level Environmental Evaluation Tool (FLEET), described in Refs. (Moolchandani et al., 2017), (Hsun et al., 2016), for modeling the fleet allocation problem. The problem formulation for each airline aims for profit maximization while not violating various environmental and operational constraints. FLEET is a computational simulation tool developed to understand how variation in external factors such as market conditions, policy implementation, and technology availability will affect aviation environmental impacts into the future (Moolchandani et al., 2017). The engine behind FLEET is a resource allocation problem set up as a mixed integer programming problem. The objective function of an airline builds upon the FLEET aircraft allocation model and pursues the long-term profit through multi-stage decisions that balance the current and future allowances consumption. Equation (1) gives the objective of airline $k \in \mathscr{K}$.

$$\max_{\left\{x^k_{l,i,t}\right\}} E\left[\sum_{t=1}^{T}\sum_{l\in\mathscr{L}}\left(\sum_{i\in\mathscr{I}^k}\left(pax^k_{l,i,t}\cdot Price^k_{l,i,t} - Cost^k_{l,i,t}\cdot x^k_{l,i,t}\right)\right)\right] \tag{1}$$

The function describes the maximization of expected profit over T years where the annual profit is defined as the difference between revenue and cost. E denotes the expectation for capturing the impact of stochastic parameters. $x^k_{l,i,t}$ is an integer decision variable describing the number of trips that aircraft i flies on route l during year t. $x^k_{l,i,t}$ is assumed to be the product of the average number of trips per day on aircraft i on route l multiplying by 365 days. $pax^k_{l,i,t}$ is a positive decision variable describing the number of passengers on aircraft i on route l during year t. $pax^k_{l,i,t}$ is treated as a continuous variable for the ease of computation. Revenue is a function of ticket price $Price^k_{l,i,t}$ and the number of passengers on each aircraft $pax^k_{l,i,t}$. Ticket price is calculated using $Price^k_{l,i,t} = PaxCost^k_{l,i,t} + Yield^k_{l,i,t}\cdot Range_l$, where $PaxCost^k_{l,i,t}$ is the cost per passenger for aircraft i on route l, $Yield^k_{l,i,t}$ is the profit margin per passenger nautical mile for aircraft i on route l, and $Range_l$ is the distance between the origin and destination in nautical miles for route l. $PaxCost^k_{l,i,t}$ is quotient from the division between the total operating cost $Cost^k_{l,i,t}$ and the average seat capacity $capacity^k_i$. The profit margin is calculated using $Yield^k_{l,i,t} = \alpha_i\cdot(Range_l)^{\beta_i}$, where the parameters α_i and β_i for each type of aircraft were obtained by the regression of historical data from the Bureau of Transportation Statistics (BTS) of the years from 2005 to 2010 (Moolchandani et al., 2013). A result of this yield model is that smaller sized aircraft have higher yield on shorter routes while larger aircraft have higher yield on longer routes. Total operating cost of each airline is a function of the operating cost, $Cost^k_{l,i,t}$, of each aircraft operated on each route and the number of trips, $x^k_{l,i,t}$.

Each airline $k \in \mathscr{K}$ is subject to a set of emission and operational constraints.

Table 1
Research gap.

Methodological Gap/Need	Treatment by the SoS-inspired Approach & MUSTDO
Alleviating the burden of the regulators	1) Airlines interact with regulators and other airlines to achieve a balanced emission allowances distribution; 2) Optimized network-wise profit is approximately achieved without full control authority of regulators
Increasing transparency and robustness of the allocation process	Regulators only provide the mechanism and total allowance limit instead of determining specific allowance distribution
Increasing airlines' planning flexibility	Airlines are flexible to decide the emission allowances consumption over time based on their own need

$$\sum_{k\in\mathscr{K}}\sum_{l\in\mathscr{L}}\sum_{i\in\mathscr{I}^k}\left(emission_{l,i,t}^{k}\cdot x_{l,i,t}^{k}\right)\leq permit_{t} \tag{2}$$

$$\sum_{i\in\mathscr{I}^k} pax_{l,i,t}^{k}\leq demand_{l,t}^{k},\ \forall t\in\mathscr{T},\forall l\in\mathscr{L} \tag{3}$$

$$\sum_{i\in\mathscr{I}^k} pax_{l,i,t}^{k}\geq MinDemRatio\cdot demand_{l,t}^{k},\ \forall t\in\mathscr{T},\forall l\in\mathscr{L} \tag{4}$$

$$\sum_{l\in\mathscr{L}} 2\cdot x_{l,i,t}^{k}\cdot\left(BH_{l,i}^{k}+EMH_{l,i}^{k}+TH_{i}^{k}\right)\leq 24\cdot fleet_{i,t}^{k},\ \forall i\in\mathscr{I}^k,\ \forall t\in\mathscr{T} \tag{5}$$

$$pax_{l,i,t}^{k}-x_{l,i,t}^{k}\cdot capacity_{i}^{k}\leq 0,\ \forall i\in\mathscr{I}^k,\ \forall t\in\mathscr{T},\forall l\in\mathscr{L} \tag{6}$$

Equation (2) constrains the total emission allowances for the entire transport network including all the airlines. $permit_t$ is the allowance limit, assigned by the regulators at the beginning, that will be depleted gradually due to the airlines' operational decisions. The carbon emissions produced by aircraft i on route l during year t is calculated using $emission_{l,i,t}^{k}=FuelBurn_{l,i,t}^{k}\cdot Fuel2CO2$ (Moolchandani et al., 2017). $FuelBurn_{l,i,t}^{k}$ is the amount of fuel consumption in pound (lbs) by airline k's aircraft i on route l at time t. $Fuel2CO2$ indicates the ratio of life-cycle CO_2 per unit of fuel (3.67 for conventional petroleum-based aircraft based on paper (Moolchandani et al., 2017)). Due to the constraint in Equation (2), an airline cannot obtain a feasible decision space directly without a coordination mechanism from the regulators.

The constraint in Equation (3) ensures that the airline does not transport more passengers than the market demand of airline k on each route (i.e., $demand_{l,t}^{k}$). The division of passenger demand among airlines can be estimated based on historical data. For the ease of comparison, we assume that the market share ratio between the involved airlines does not change over time in this paper. Reference (Hsun et al., 2016) has discussed the impact of competitive relationship between airlines on the market demand change of each airline; the model can be combined with the method in this paper for future work. Equation (4) ensures that the airline satisfies at least $MinDemRatio$ of the demand on each route to keep the airline from cutting the unprofitable routes. The total passenger demand on each route is allocated to each airline based on historical data. The constraint in Equation (5) ensures that the total number of hours for block time, turnaround time, and maintenance time for each aircraft type does not exceed 24 h times the number of aircraft of that type owned by the airline (i.e., $fleet_{i,t}^{k}$). The problem assumes that passenger demand is symmetric, and the aircraft can fly round-trips; therefore, the number of available hours is limited to 12 h. This example also assumes that an average day of an aircraft consists of block hours, equivalent maintenance hours, and turnaround time (Moolchandani et al., 2017). Block hours $BH_{l,i}^{k}$ represents the door-to-door time of aircraft type i on route l. The turnaround time TH_{i}^{k} accounts for the time needed to unload, service, and then load the aircraft between flights. Equivalent maintenance hours $EMH_{l,i}^{k}$ accounts for the unavailability of some aircraft due to maintenance, which can be calculated using the ratio $\left(\frac{EMH}{BH}\right)_i$ that describes the number of "equivalent maintenance hours per block hour of flight" for aircraft i. Equation (6) ensures that an airline flies a sufficient number of trips to meet passenger demand while considering the seat capacity of each aircraft type $capacity_{i}^{k}$.

3.2. Regulators in the ideal centralized case

In an ideal centralized case where the regulators own the full authority, the most cost-efficient solution is to maximize the global profit over the entire air transportation network without violating the emission and operational constraints. In this case, the regulators can formulate the objective function as in Equation (7). It is similar to a single airline's objective function except that it aggregates fleet from all the airlines. The constraints remain the same as those for single airlines. The solution in this case serves as a benchmark that the regulators in the decentralized case still wish to achieve.

$$\max_{\left\{x_{l,i,t}^{k}\right\}} E\left[\sum_{t=1}^{T}\sum_{k\in\mathscr{K}}\sum_{l\in\mathscr{L}}\left(\sum_{i\in\mathscr{I}^k}\left(pax_{l,i,t}^{k}\cdot Price_{l,i,t}^{k}-Cost_{l,i,t}^{k}\cdot x_{l,i,t}^{k}\right)\right)\right] \tag{7}$$

4. Proposed solution approach: the MUSTDO method

4.1. Overview of MUSTDO method

The MUSTDO method (Fang et al., 2018) was proposed to address an *acknowledged* SoS architecture selection problem in a dynamic environment. As in Fig. 1, an *acknowledged* SoS has the SoS participants pursuing individual objectives that often conflict with each other on the limited resources and compete with the objective of the SoS. Meanwhile, for an individual SoS participant, the resource conflict might occur over different stages in a period of time, that is, current decisions affect future decisions and outcomes (e.g., large consumption of emission allowances now could reduce the future use). The MUSTDO method supports the coordination of the two types of conflict through an integration of the transfer contract coordination mechanism and approximate dynamic programming.

Fig. 2 illustrates the fundamental concept of the transfer contract coordination mechanism in this paper. A transfer contract is defined as the compensation that each participant (e.g., airline 1) needs to pay to other participants with whom it shares resources (e.g., airline 2) for consuming those shared resources (e.g., emission allowances) provided by the SoS-level manager (e.g., the

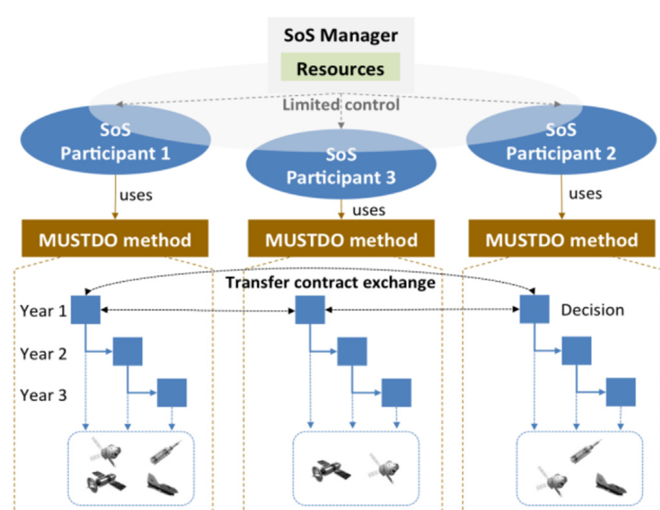

Fig. 1. Overview of the MUSTDO method.

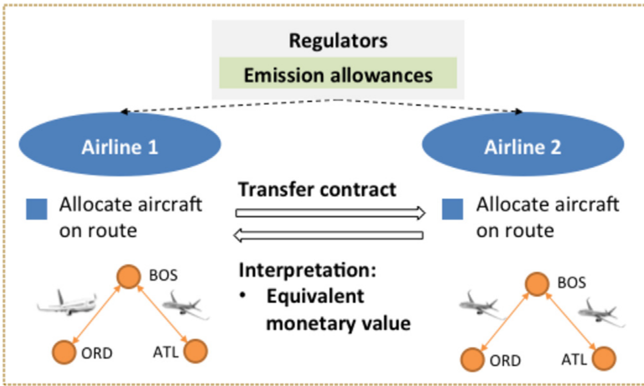

Fig. 2. Concept of transfer contract coordination mechanism.

environmental regulators). For example, if airline 1 allocates an airplane on the route from Boston to Chicago, the carbon emissions generated by this airplane consumes the shared allowances. As a result, airline 1 pays to airline 2 in the form of transfer contract for using the emission allowances because its decision causes the loss of airline 2. If the value of a transfer contract exceeds the profit to be gained from the flight, airline 1 will not allocate an airplane on the route from Boston to Chicago. This explains how the transfer contract affects the participants' decisions. The method to calculate the values of transfer contract is given in Section 3.2.

Approximate dynamic programming (Powell, 2010), (Bertsekas and Tsitsikilis, 1996) is a method in operations research for making decisions over time under uncertainty by properly leveraging approximate value functions. Similar to classical dynamic programming, ADP breaks down a complex problem into a sequence of decisions over time by defining a sequence of value functions. The value at a specific decision step can be calculated by backward induction using the Bellman equation if the problem is not complex; otherwise, statistical approximation is necessary to replace the true value function. Appropriate use of ADP can provide airlines with sequential flight allocation decisions that approach the most profitable solution over time. The diverse techniques for approximating value functions allow for appropriate surrogate modeling with sufficient fidelity in the early phases of strategic planning. Moreover, approximate dynamic programming is easy to integrate with transfer contract coordination mechanism – by connecting the transfer contract with value function approximation – to solve the dynamic allocation problem under multi-stakeholder conflict.

4.2. Formulation of the MUSTDO method

In the proposed aviation emission allowances allocation problem, the real decision makers are the airlines that follow the mechanism provided by the regulators. The objective function of each airline in Equation (1) is constrained by the total emission allowances, as given in Equation (2). The participating airlines are in a competitive relationship for the emission allowances. Unlike the formulation in the original paper (Fang et al., 2018), two types of decision variables – number of passengers $pax^k_{l,i,t}$ and number of trips $x^k_{l,i,t}$ – occur in this problem. The emission allowances, however, are only associated with the number of trips $x^k_{l,i,t}$. In other words, an airline pays the value of a transfer contract to another airline only when the former airline generates emissions from an allocated flight. Then, the objective function in Equation (1) can be written in the format of Equation (8) with the transfer contract incorporated.

$$\max_{\left\{x^k_{l,i,t}\right\}} E\left[\sum_{t=1}^{T}\sum_{l\in\mathscr{L}}\left(\sum_{i\in\mathscr{I}^k}\left(pax^k_{l,i,t}\cdot Price^k_{l,i,t} - Cost^k_{l,i,t}\cdot x^k_{l,i,t}\right.\right.\right.$$
$$\left.\left.\left. -\sum_{j\neq k} M^{k,j}_{l,i,t}\cdot x^k_{l,i,t}\right) + \sum_{j\neq k}\sum_{i\in\mathscr{I}^j} M^{j,k}_{l,i,t}\cdot est\_x^j_{l,i,t}\right)\right] \tag{8}$$

$M^{k,j}_{l,i,t}$ indicates the value of a transfer contract (i.e., monetary value) that airline k needs to compensate to airline j for the emissions generated from the flights of aircraft $i\in\mathscr{I}^k$ on route l during year t. $est\_x^j_{l,i,t}$ is airline k's estimation of the number of trips allocated on aircraft $i\in\mathscr{I}^j$ on route l by airline j. As a multi-stage decision-making problem with underlying uncertainties in the parameters (e.g., $Price^k_{l,i,t}$, $Cost^k_{l,i,t}$), ADP demonstrates great potential in managing the complexity. The core step is to break down Equation (8) into multiple single-period decisions using the Bellman equation, as shown in Equation (9).

$$V^k_t(permit_t; M) = \max_{\left\{x^k_{l,i,t}\right\}}\left[\sum_{l\in\mathscr{L}}\sum_{i\in\mathscr{I}^k}\left(pax^k_{l,i,t}\cdot Price^k_{l,i,t} - Cost^k_{l,i,t}\cdot x^k_{l,i,t}\right.\right.$$
$$\left. -\sum_{j\neq k} M^{k,j}_{l,i,t}\cdot x^k_{l,i,t}\right) + \sum_{j\neq k}\sum_{l\in\mathscr{L}}\sum_{i\in\mathscr{I}^j} M^{j,k}_{l,i,t}\cdot est\_x^j_{l,i,t}$$
$$\left. + \gamma\overline{V}^k_{t+1}(permit_{t+1})\right] \tag{9}$$

$$\overline{V}^k_{t+1}(permit_{t+1}) = \theta^k_{t+1}\cdot permit_{t+1} \tag{10}$$

The approximation of value function, $\overline{V}^k_{t+1}(permit_{t+1})$, is one of the critical and challenging tasks in ADP. Linear function is the simplest structure for an approximation with least computational complexity, hence we adopt it as the first option, as given in Equation (10). We choose available emission allowances as basis function to construct a linear value function. Because the emission allowance limit is a very critical constraint in this problem. θ^k_{t+1} represents the coefficient of the basis function $permit_{t+1}$. While an approximation inevitably brings errors, a discount factor γ, with value between 0 and 1, helps to reduce the emphasis of the value of a future state. As time goes on, the transition function captures the depletion of allowances caused by airlines' scheduled trips, as in Equation (11).

$$permit_{t+1} = permit_t - \sum_{l\in\mathscr{L}}\sum_{i\in\mathscr{I}^k}\left(emission^k_{l,i,t}\cdot x^k_{l,i,t}\right)$$
$$-\sum_{l\in\mathscr{L}}\sum_{j\neq k}\sum_{i\in\mathscr{I}^j}\left(emission^j_{l,i,t}\cdot est\_x^j_{l,i,t}\right) \tag{11}$$

$emission^k_{l,i,t}$ indicates the marginal emissions produced by aircraft i on route l for airline k during year t. What remains unknown in Equation (8) is the value of a transfer contract and the estimated decisions. Multiple methods are available for calculating the value of a transfer contract and we adopt the one proposed in reference (Fang et al., 2018).

$$M^{j,k}_{l,i,t} = \gamma\cdot\theta^k_{t+1}\cdot emission^j_{l,i,t} \tag{12}$$

In Equation (12), the transfer contract from airline j to k for allocating aircraft i on route l in year t is equal to the future value of airline k without losing the emission allowances used by airline j on that route. This method can achieve two goals. First, the network-wise profit gained by each airline's independent flight assignment decisions can approach the total profit desired by the regulators in the ideal centralized case. Plugging Equations (10) and (11) into Equation (9) and rephrasing the equation, we obtain:

$$V_t^k(permit_t; M) = \max_{\left\{x_{l,i,t}^k\right\}} \left[\sum_{l \in \mathscr{L}} \sum_{i \in \mathscr{I}^k} \left(pax_{l,i,t}^k \cdot Price_{l,i,t}^k - \left(Cost_{l,i,t}^k + \sum_{j \neq k} M_{l,i,t}^{k,j} + \gamma \cdot \theta_{t+1}^k \cdot emission_{l,i,t}^k \right) \cdot x_{l,i,t}^k \right) + \sum_{j \neq k} \sum_{l \in \mathscr{L}} \sum_{i \in \mathscr{I}^j} \left(M_{l,i,t}^{j,k} - \gamma \cdot \theta_{t+1}^k \cdot emission_{l,i,t}^j \right) \cdot est\_x_{l,i,t}^j + \gamma \cdot \theta_{t+1}^k \cdot permit_t \right] \tag{13}$$

Then, we plug the transfer contract in Equation (12) into Equation (13) and obtain:

$$V_t^k(permit_t; M) = \max_{\left\{x_{l,i,t}^k\right\}} \left[\sum_{l \in \mathscr{L}} \sum_{i \in \mathscr{I}^k} \left(pax_{l,i,t}^k \cdot Price_{l,i,t}^k - \left(Cost_{l,i,t}^k + \gamma \cdot \sum_{m \in \mathscr{K}} \left(\theta_{t+1}^m \cdot emission_{l,i,t}^k \right) \right) \cdot x_{l,i,t}^k \right) + \gamma \cdot \theta_{t+1}^k \cdot permit_t \right] \tag{14}$$

Adding together the value function $V_t^k(permit_t; M)$ of all the airlines $k \in \mathscr{K}$, we receive the Bellman equation for the objective function of the regulators in the ideal centralized case in Equation (7). This means the mechanism achieves the goal of approaching the SoS-level optimality. According to Equations (13) and (14), the method accomplishes the other goal — cancelling out the effect of incorrect estimation of others' decisions, $est\_x_{l,i,t}^j$. We can use Fig. 2 to explain the rationale. If airline 1 presumes that airline 2 allocates a trip to route from Boston to Chicago, the estimation affects two parts in airline 1's value function calculation: the received transfer contract as an increase, and the future value as a decrease because airline 1 presumes that airline 2 takes the allowances. Once the increased value is equal to the decreased value, the incorrect estimation of others' decisions has no impact on an airline's decision-making.

4.3. Workflow of implementing the MUSTDO method

Fig. 3, adjusted based on our previous work (Fang et al., 2018), describes the procedures for individual airlines to carry out the MUSTDO method. The vertical line indicates the time progression. The circles represent the airline state of fleet, passenger demand, route, and total available emission allowances, while the diamonds represent the decision points for airlines making flight allocation. The decision points are set at the beginning of each year; the annual trip allocation decision is assumed to be an average number of trips per day multiplying by 365 days. The regulators initiate the process through informing the airlines of the mechanism and network-wise emission allowances for a given period. During each decision point, every single airline runs the MUSTDO method following the steps in the red callout. An airline k first prepares the input data, including aircraft types, routes, passenger demand, ticket price, operating cost, marginal emissions, structure of value function, etc., for its fleet allocation decision-making. Airline k can reveal partial information (e.g., marginal emissions) to other airlines and the regulators. Then, each airline initiates the coefficients of the basis functions and exchanges the initial values of transfer contracts. Afterwards, airline k performs a mixed integer linear programming of Equation (13) and updates the value function and values of transfer contracts using methods like recursive least squares. Airlines communicate with each other on the updated values of transfer contracts. The process continues until the approximate future value converges. The final result provides the airlines a sequence of decisions on the number of trips and number of passengers allocated on each type of aircraft on each route, the values of transfer contracts to be exchanged, and a sequence of value functions. Once each airline completes performing the MUSTDO method, it makes the suggested decisions at that decision point only. As time moves on to next decision point, the airlines will conduct another run of the algorithm described in the red callout. Throughout the entire process, the limited involvement of the regulators decreases the workload of the regulators and increases the transparency of the process.

5. Demonstration study

5.1. Parameters setup

This paper applies the MUSTDO method to a selected air transportation network from the same origin airport, BOS in Boston, to ten other airports (i.e., ATL, DEN, JAX, JFK, LAS, MCO, OAK, ORD, SEA, SJC) that locate in ten big cities in the United States. Two representative airlines, a low-cost airline and a legacy airline, compete for emission allowances from the regulators to satisfy the passenger demand on the ten routes. We refer to paper (Moolchandani et al., 2012) to obtain the input data of a duopoly model where the total demand is segregated into two datasets, one for each airline type. Table 2 lists the fleet composition for the low-cost airline and legacy airline respectively according to paper (Moolchandani et al., 2017). Both fleets are divided into six aircraft classes based on aircraft seating capacity and they remain constant throughout the simulation. We assume a turnaround time of 0.5 h for the low-cost airline and 1 h for the legacy airline. The passenger demand on each route grows by 2.8% each year (Moolchandani et al., 2017). The discount factors of both airlines are set as 0.9. Assume that the regulator has 12 billion pounds (5.44 million metric tons) emission allowances in total for ten years to distribute to the two airlines. This value of total emission allowances is estimated based on the total emissions produced in the first year without any emissions constraint (about 0.6 million metric tons). We set the target of the total emissions over ten years as 90% of the sum of current emissions even with increasing demand. This limit can be altered according to the regulators' actual goals.

We employ the General Algebraic Modeling System (GAMS) (GAMS Development Corporation, 2017) software package to solve the mixed integer linear programming (MILP) problem. The GAMS package provides an algebraically based high-level language for the compact representation of large and complex optimization models and uses the CPLEX solver (IBM, 2018) to solve the MILP problems.

5.2. Results and discussion

5.2.1. Convergence check

Convergence is the underlying requirement of a functioning MUSTDO method. We examine the convergence status in both

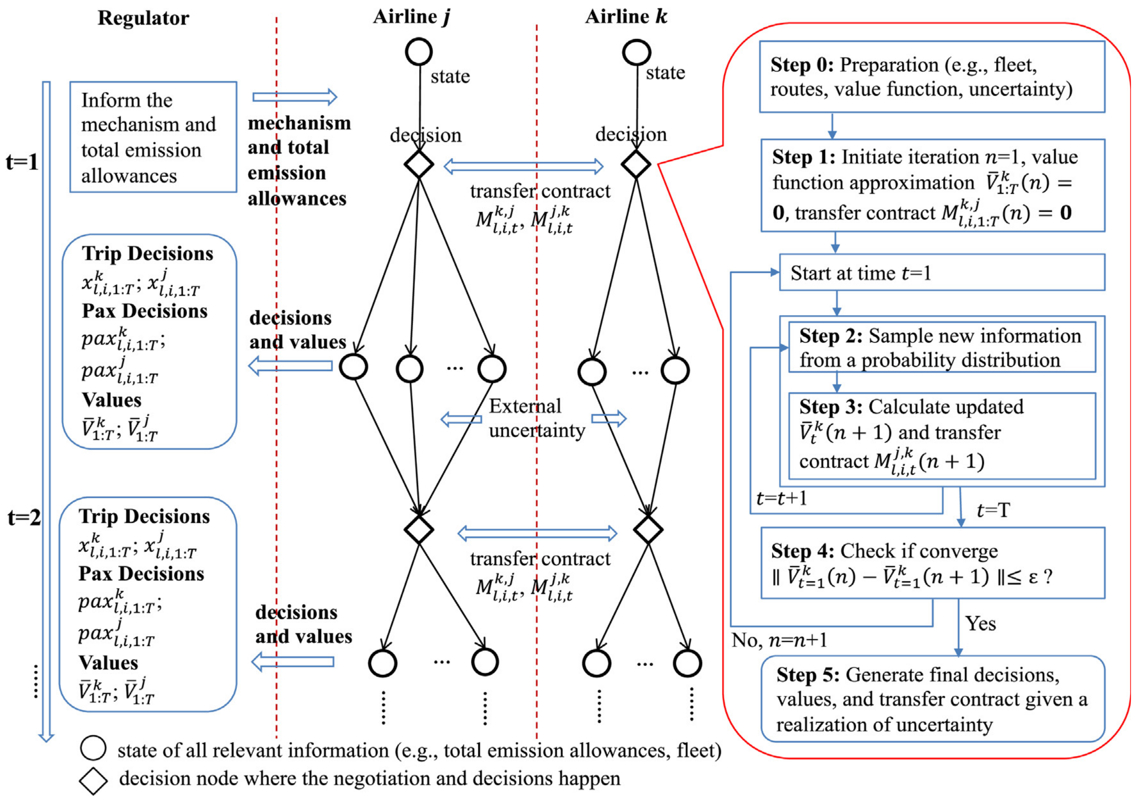

Fig. 3. Workflow of MUSTDO method.

Table 2
Aircraft types used in the study (Moolchandani et al., 2017).

Class	Seats	Aircraft Types for Low-Cost Airline	Aircraft Types for Legacy Airline
Class 1	20–50	Canadair RJ200/RJ400	Embraer ERJ145
Class 2	51–99	Canadair RJ700	Embraer 170
Class 3	100–149	Boeing 737-300	Boeing 737-700
Class 4	150–199	Boeing 757-200	Boeing 737-800
Class 5	200–299	Boeing 767-300	Airbus A330-200
Class 6	300+	Boeing 747-400	Boeing 777-200 ER

deterministic and stochastic experiments. Since the deterministic experiment is a special case of the stochastic experiment, we only demonstrate the convergence check plots in the stochastic experiment. Fig. 4 and Fig. 5 depict the value differences in the first year between successive iterations based on the formula $V^{n+1}_{t=1} - V^n_{t=1}/V^n_{t=1}$ in a stochastic experiment. As a simple illustration of how the method responding to the external uncertainties, the uncertainty in this experiment only occurs to the passenger demand $demand^k_{l,t}$ in the form of normal distribution. The given demand data serve as mean values while the standard deviations are assumed to be 10% of the mean values. 10% is a synthetic number only for the purpose of demonstration. The normalized value differences fluctuate but remain within the magnitude of 10^{-2} for both the low-cost airline and the legacy airline after 200 iterations.

5.2.2. Solution comparison

The deterministic experiments without stochastic parameters are a good starting point for the ease of comparison. To examine whether the MUSTDO method provides decision support as promised, the simplest evaluation is comparing the total profit yielded by the airlines using the MUSTDO method to the total profit produced by the hypothetical regulators in the ideal centralized case. We also include a few other methods to compare to the proposed method, as described in Table 3. The comparison revolves around the cumulative profit and emissions over time as well as annual demand satisfaction.

The profit and emissions in Case 5 serve as benchmark values to normalize the numbers from other cases. Fig. 6 compares the network-wise cumulative profit that adds together all the profit gained by both airlines during and before the present year. When the time reaches the tenth year, the cumulative profit represents the total ten-year profit. By observing Fig. 6, we can draw a few conclusions from the comparisons. First, the total network-wise profit in Case 2 is ~95% of that in Case 5; the proximity demonstrates that ADP is effective in obtaining a near-optimal solution when future parameters are not known in advance and revealed over time. Second, the 0.7% difference between the total network-wise profits in Case 1 and Case 2 proves that the transfer contract coordination mechanism in the MUSTDO method can push the independent and decentralized decisions towards the global optimality. Altogether, the comparison between Case 1, Case 2, and Case 5 shows that the MUSTDO method can provide airlines the fleet allocation decisions that approach the globally efficient

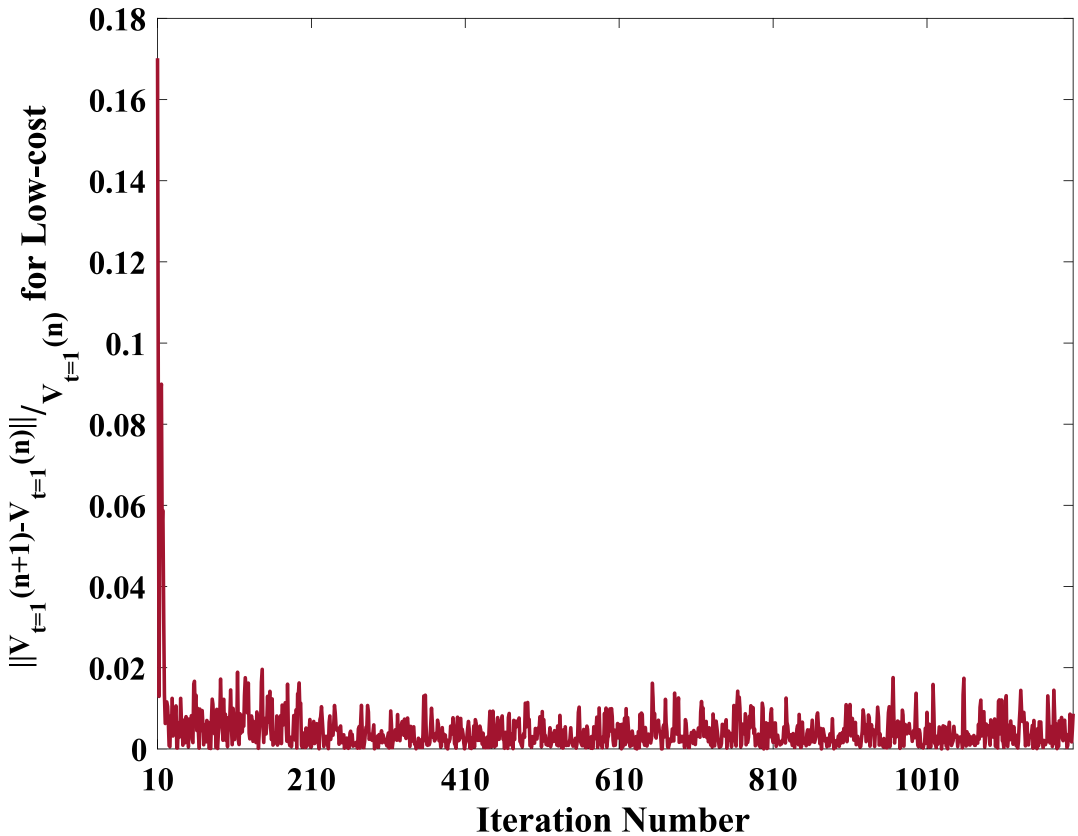

Fig. 4. Normalized value differences between iterations of low-cost airline in stochastic experiment.

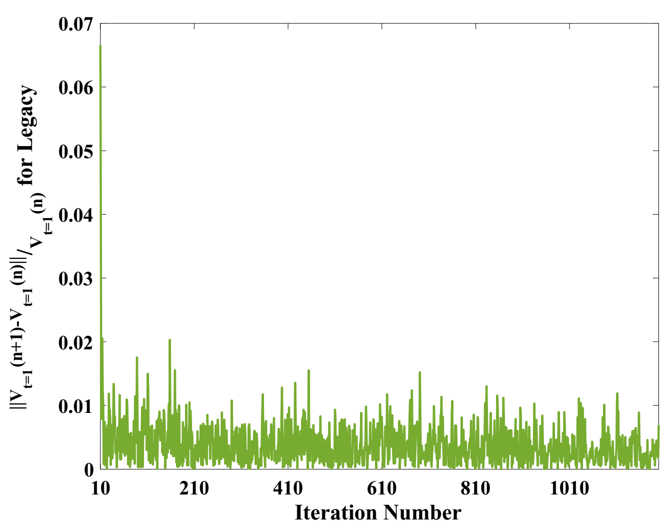

Fig. 5. Normalized value differences between iterations of legacy airline in stochastic experiment.

solution. Further, we compare Case 1 to Case 3 and Case 4 in which the regulators determine the emission allowances allocation using a pseudo-grandfathering approach. The total network-wise profit in Case 3 is 0.9% higher than that in Case 1; however, the total profit in Case 4, the one with synthetic fault during allocation, is 14.8% lower than the total profit in Case 1. In this sense, the MUSTDO method provides more robustness for the airlines than the pseudo-grandfathering approach.

Fig. 7 and Fig. 8 delineate the cumulative profit comparison for the low-cost airline and legacy airline respectively. According to the two figures, the low-cost airline seems better off using the pseudo-grandfathering approach, especially using the pseudo-grandfathering approach with fault. However, incorrect allocation will not always favor the low-cost airline; in another type of incorrect allocation, the low-cost airline is worse off. Such an instability problem that highly relies on the regulators does not exist in the MUSTDO method.

Fig. 9 displays the cumulative carbon emissions produced by both airlines over time. The trend is consistent with the cumulative profit in Fig. 6. Basing on the figure, both the MUSTDO method and the pseudo-grandfathering approach leave some emission allowances unused, but the owners of the unused emission allowances are quite different. The individual airlines own the unused emission allowances in the pseudo-grandfathering approach while the regulators own the unused emission allowances in the MUSTDO method. This special feature of the MUSTDO method can help reduce the windfall profit that might be obtained by the individual airlines.

Fig. 10 plots the trend of demand satisfaction of Case 1 (i.e., MUSTDO) and benchmark Case 5 (i.e., Centralized-Exact). The MUSTDO method generates the blue dash line that demonstrates a clear upward trend with small fluctuations in the middle, i.e., more passengers are served by the airlines as time passes. As a contrast, the green solid line does not demonstrate a clear trend. The difference attributes to the current selection of value function approximation in the MUSTDO method — a linear value function approximation with emission allowances as basis function. Emission allowances and future value are positively correlated, i.e., more emission allowances are equivalent to larger future values. At the beginning, the sufficient amount of allowances indicates large future values, which reduces the use of allowances at the current

Table 3
Description of the experiments.

Case Index	Short Name	Experiment Content
Case1	MUSTDO	Decentralized Case: Using the MUSTDO method
Case2	Centralized - Approximate	Ideal Centralized Case: Using ADP if the future information is unknown
Case3	Pseudo-Grandfathering	Partial Decentralized Case: Using an alternate method that assigns fixed emission quotas according to historical data
Case4	Pseudo-Grandfathering with Fault	Partial Decentralized Case: Using alternate method that assigns fixed emission quotas unfairly due to inaccurate information
Case5	Centralized Exact	Ideal Centralized Case: Formulating problem as a large mixed integer linear programming (MILP) if the future information is known in advance

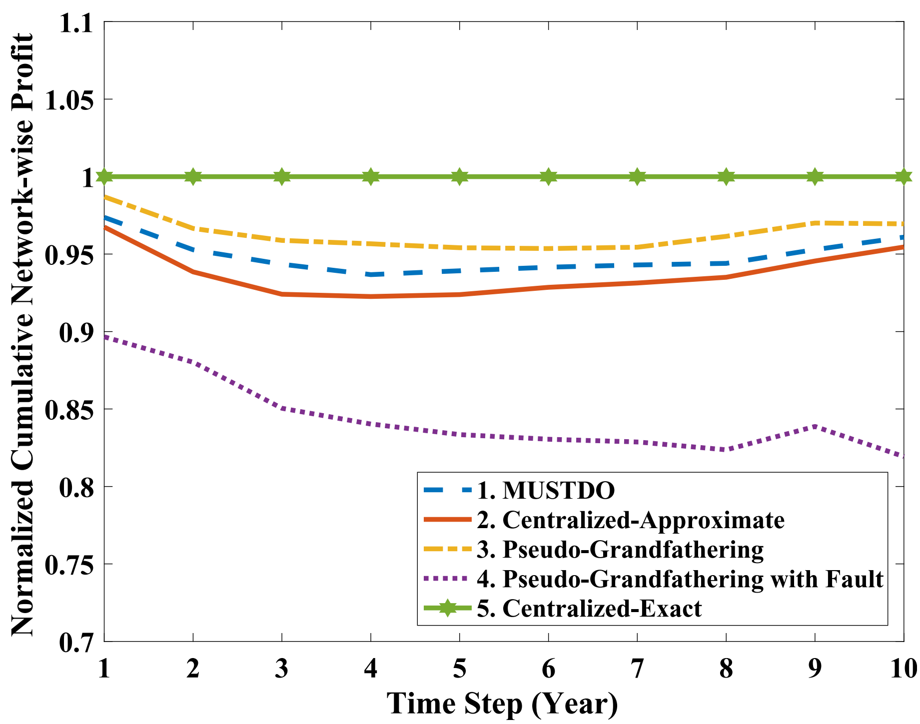

Fig. 6. Normalized network-wise cumulative profit comparison under different experiments.

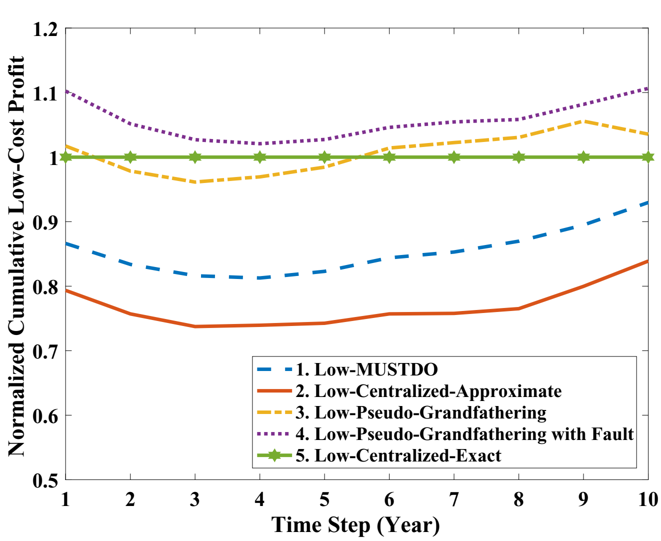

Fig. 7. Normalized cumulative profit comparison of low-cost airline under different experiments.

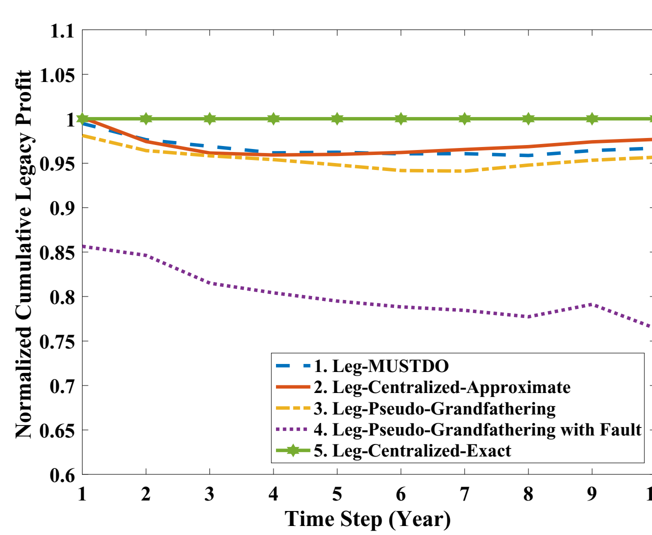

Fig. 8. Normalized cumulative profit comparison of legacy airline under different experiments.

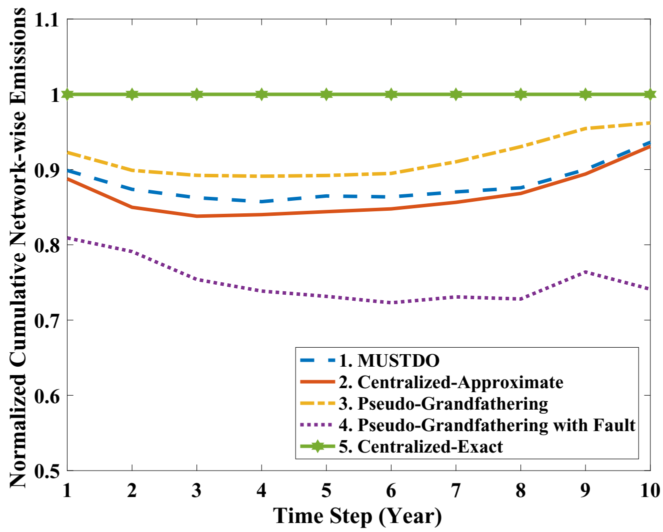

Fig. 9. Normalized network-wise cumulative emissions under different experiments.

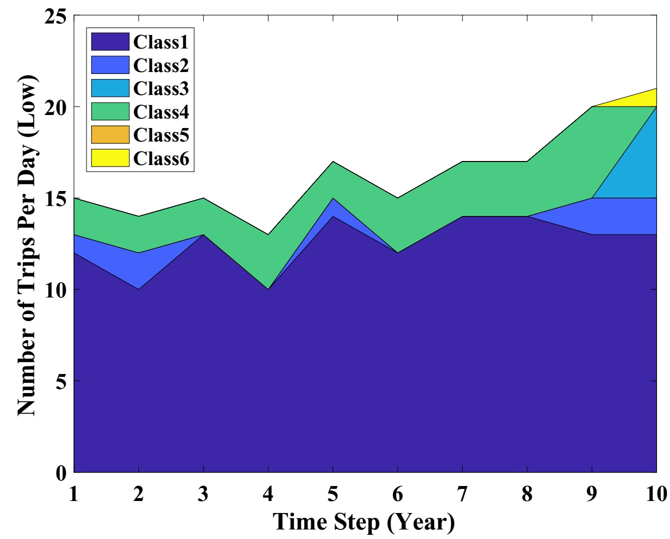

Fig. 11. Average number of trips allocated over time on classes of aircraft of low-cost airline.

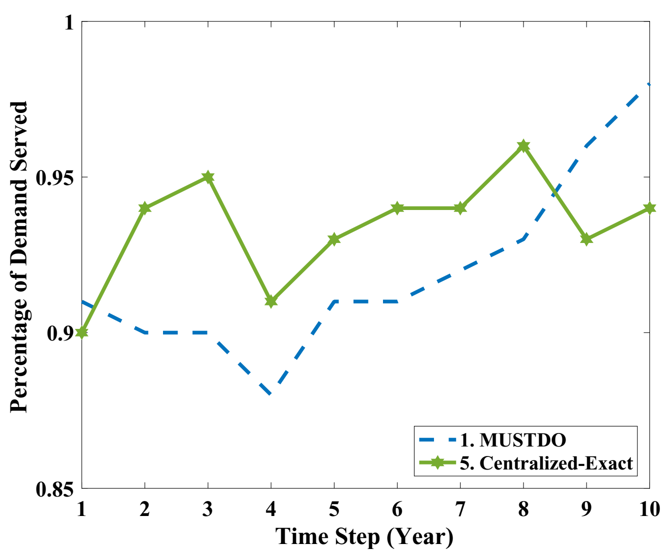

Fig. 10. Percentage of demand satisfied each year.

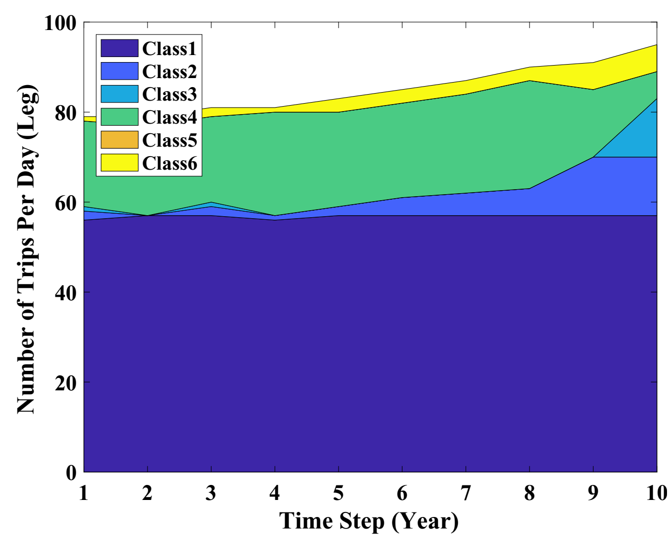

Fig. 12. Average number of trips allocated over time on classes of aircraft of legacy airline.

stage. However, as time reaches the end, the future values of the remaining emission allowances at that time decrease so that the allowance consumption increases largely. Although the trends are slightly different, the two airlines still satisfy around 90% of the passenger demand using the MUSTDO method, with the benefit of increased flexibility for the airlines and decreased workload for the regulators.

5.2.3. *Decision support for the airlines*

The MUSTDO method provides airlines decision support for determining aircraft allocation on each route that can satisfy the passenger demand. We will not list all the decisions produced by the method, but only summarize the average number of trips allocated per day on different classes of aircraft for the low-cost airline and the legacy airline, as shown in Fig. 11 and Fig. 12. According to the plots, both airlines use aircraft of class 1 most frequently. Part of the reasons lie in the high passenger demand on the short/middle-haul routes – Boston to Atlanta for the low-cost airline and Boston to Chicago for the legacy airline – where small aircraft are qualified to provide services. Very few aircraft of class 5 and class 6 are used by the low-cost airline because they are not cost-effective concerning the profit and emissions. Even the legacy airline only takes a couple of aircraft of class 6 to cover the demand on the long-haul routes from Boston to Denver, Las Vegas, and Seattle. The suggested decisions reflect some of the real situations even though the transport network selected in this case is small (and can be expanded).

Fig. 13 shows the aggregate values of transfer contract from the low-cost airline to the legacy airline each year. The negative sign represents reverse flow. The airlines are in charge of interpreting the values of transfer contract and they all have to agree on the common unit. The simplest way is to use monetary value since the objective function aims at optimizing profit. Take the first year as an example, the legacy airline needs to pay approximately 0.8 million dollars in total to the low-cost airline for the carbon emissions caused by the allocated trips. The value of transfer contract equals zero in the tenth year because the future value of the tenth year

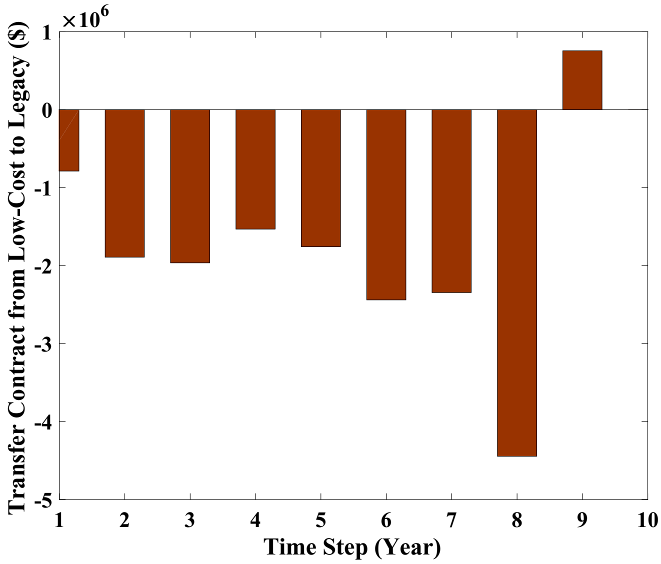

Fig. 13. Values of transfer contract from low-cost airline to legacy airline.

equals zero. The sequence of trip allocation decisions and the values of transfer contract constitute the output of the MUSTDO method.

5.2.4. Sensitivity studies

Among the several influential parameters in the MUSTDO method, two representative ones are the total emission allowances and the discount factor. Assigning proper quantity of total emission allowances is one of the key challenges that many governments are struggling for. In this sensitivity analysis, we vary the total emission allowances from 8 billion pounds to 16 billion pounds. The number of 16 billion pounds reaches the maximum volume of the emissions to be generated under the given market demand. The number of 8 billion pounds is the appropriate amount of allowances for the method to produce feasible solutions considering other constraints. Fig. 14 shows that the percentage difference between the total profit (combining both airlines) from the MUSTDO method in the decentralized case (i.e., Case 1) and that from the benchmark Case 5 remains moderate.

The discount factor plays an important role in planning out long-term decisions where the future profit should be discounted with respect to the base year. We used the discount factor of 0.9 in the main study and now we expand the range to 0.8, 0.85, 0.95, and 1.0. Each airline selects its own discount factor but needs to communicate with other airlines for a mutual agreement. We assume that both airlines use the same discount factor in this study for simplicity. Fig. 15 shows the gaps (in percentage) between total ten-year profit of both airlines gained from the MUSTDO method (i.e., Case 1) and that obtained from in Case 5. Based on the plot, the gap becomes smaller as the discount factor decreases. This is relevant to the linear value function approximation in the MUSTDO method. The discount factor reduces the error of the future value prediction and helps to balance the allowance consumption on the current and future decisions. We also note that the difference becomes negative when the discount factor is 0.8. This happens because the heavily discounted future value leads to substantial allowance consumption at the beginning. As a result, the rest insufficient emission allowances for the last few stages cause small violation of the operational constraints. Overall, even with different values of discount factor, the decisions from the MUSTDO method yields total profit that are close to the globally optimized profit obtained using a large MILP in the ideal centralized case (within 8%).

6. Contributions and future work

To control the impact of aviation emissions on the environment, market-based mechanisms, especially emission trading system, play an important role in the current emission policies. This paper proposed a novel emission allowances allocation method – MUSTDO – from an SoS perspective that reflects the decentralized nature of the problem. The MUSTDO method that combines approximate dynamic programming and transfer contract coordination mechanism was applied to a ten-route U.S. air transportation network where two representative airlines (i.e., low-cost airline and legacy airline) compete for the emission allowances from the regulators. According to the results, the airlines can use the MUSTDO method to provide fleet allocation decisions (along with values of transfer contract) that produce total network profit close to the profit that a hypothetical regulator with full authority aims to achieve in an ideal centralized case. This feature provides the regulators an incentive to delegate the allowance allocation tasks to the airlines and in turn reduces the workload of the regulators and increases the airlines' flexibility to make fleet allocation

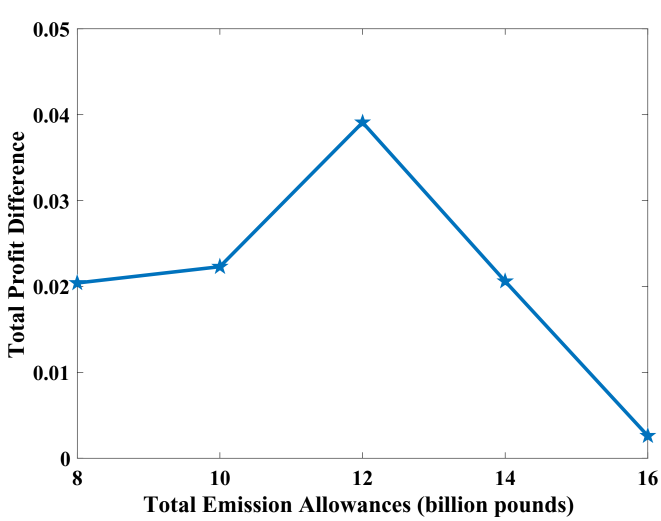

Fig. 14. Differences between total profit from MUSTDO method (case 1) and MILP (case 5) with different total emission allowances (discount factor = 0.9).

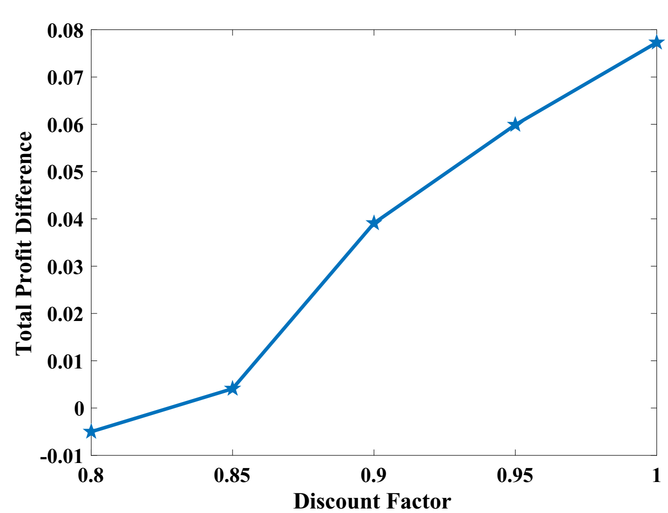

Fig. 15. Differences between Total Profit from MUSTDO Method (Case 1) and MILP (Case 5) with Different Values of Discount Factor (Total Emission Allowances = 12 billion pounds).

decisions. Moreover, the MUSTDO method generates total profit close to that from a pseudo-grandfathering approach with accurate allocation, but the former is more robust than the latter to the failures of inaccurate or unfair allocation. The additional sensitivity studies further demonstrate that the MUSTDO method remains useful under different values of total emission allowance and discount factor.

The proposed method provides a different perspective to treat the emission allowances allocation problem. However, future work remains for enhancing practical implementation. To start, the method assumes a closed trading system where the airlines do not trade emission allowances with the companies outside the structure. When switching from the closed trading system to an open trading system, the impact of the carbon price in the market on the values of transfer contract should be taken into account. Second, the fleet allocation model of the airlines is more complex than the one used in this paper. Other factors such as the market share change, fuel price fluctuation, and aircraft types change should also be incorporated in the model. Third, the linear value function approximation in the MUSTDO method may be insufficient to capture the airlines' future values, hence we need to seek more sophisticated approximations (like piece-wise linear value function approximation). Our future work will focus on these perspectives to increase the practicability of the proposed method.

Acknowledgements

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