Business and Economic Concepts for a Privacy-Preserving Marketplace for ATFM Slots

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Abstract—In case of a congestion in the European air traffic network, the Network Manager issues a regulation which causes flights to be allocated a new slot. The current operating procedure is to use a first-planned first-served (FPFS) policy to allocate new slots to the flights. Since different flights have different cost structures, the FPFS policy may not be optimal in terms of overall economic utility for the airspace users. In the SlotMachine project we aim to build a privacy-preserving online marketplace where airspace users can participate in optimization sessions regarding the allocation of ATFM slots to flights. In this paper, we present different options regarding the deployment of the SlotMachine system, and we discuss the question of the market mechanism that the SlotMachine project must tackle.

Keywords—flight prioritization, market mechanism, heuristic optimization, air traffic flow management

I. INTRODUCTION

The management of the European air traffic network reacts on foreseen congestion at airports or in the airspace by issuing a regulation, which limits the number of flights that can be processed in a given time span. A regulation may affect flights by significantly delaying the flight with respect to the originally scheduled time, and flight delay often has a major impact in terms of costs on the airspace users [1]. The comparatively low profitability in the air transport industry of around 1 to 5% of the income [2] means that effective optimization mechanisms for air traffic flow management (ATFM) slot allocation are of paramount importance in order to mitigate the impact of a regulation on the overall costs of airspace users.

In the SlotMachine project [3], [4] we aim to build a privacy-preserving online marketplace where airspace users can participate in optimization sessions regarding the allocation of ATFM slots to flights. The core components of the SlotMachine system are the Heuristic Optimizer and the Privacy Engine. The Heuristic Optimizer employs an evolutionary optimization algorithm, e.g., a genetic algorithm, to find optimal flight lists in an iterative manner. The Privacy Engine employs secure multiparty computation [5] to evaluate the candidate solutions found by the Heuristic Optimizer. The advantage of the SlotMachine system is as follows: No single party, not even the SlotMachine system, knows the secret preferences of all the participating airspace users regarding the flight list.

In this paper, we present different options regarding the deployment of the SlotMachine system, and we discuss the question of the market mechanism that the SlotMachine project must tackle. While the choice of deployment architecture of the SlotMachine system influences the role of the Network Manager, the choice of a market mechanism has implications on the equity and fairness of the system as well as the acceptance of the system by airspace users. In this paper we present the intuition of two market mechanisms, which the SlotMachine project will further investigate.

The remainder of this paper is organized as follows. In Section II, we present the state of the art. In Section III, we discuss the economic and deployment use cases of the SlotMachine system. In Section IV, we discuss potential market mechanisms for the SlotMachine system. We conclude the paper with a summary and an outlook on future work.

II. STATE OF THE ART

In the European air traffic network, if the Network Manager (NM) detects an upcoming capacity reduction (congestion), the NM activates a regulation and allocates new slots to flights affected by the regulation. The current operating procedure is to use a first-planned first-served (FPFS) policy to allocate new slots to the flights, which largely preserves the original sequence of flights. The FPFS policy is well accepted by stakeholders due to the fact that FPFS preserves equity and minimizes the total delay in a regulation [6], [7].

Since different flights have different cost structures, the FPFS policy may not be optimal in terms of overall economic utility for the airspace users. The User-Driven Prioritization Process (UDPP) [8] gives airspace users the possibility to resolve capacity constraints in a way that allows the airspace users to maximize utility, following the assumption that airspace users themselves best know the optimal sequence of their flights. The current procedure allows the order of two flights to be swapped, but only if the flights have the same “most-penalizing” regulation and if the flights are operated by the same airline or group of airlines associated through an agreement [9].

Equity and fairness are important aspects of an ATFM slot swapping system. In the context of ATFM slot allocation, one
definition of the term “fairness” is that it is the quality of distributing the costs caused by a regulation among airspace users such that each participant in the market bears a share of the costs that fulfils the airspace user’s individual threshold for satisfaction [10]. The challenge is to find a measure that quantifies individual satisfaction thresholds. Equity, on the other hand, measures how uniformly the costs of a regulation are distributed among participants, regardless of the individual satisfaction thresholds [10].

From the fundamental theorems of welfare economics [11] follows that the airspace users themselves are the ones that best know their own preferences regarding slot allocation, providing an argument in favor of a decentralized slot allocation mechanism. Under ideal conditions, a slot allocation negotiated under a market mechanism in which airspace users can trade their slots will be Pareto optimal, i.e., the social welfare will be maximized, and no other slot allocation can be negotiated without deteriorating the welfare of at least one participant. In particular, the Coase Theorem [12] states non-existent or negligible transaction costs in a market mechanism will lead to optimal resource allocation reached through the market mechanism. In reality, however, there are limiting factors causing a negotiated slot allocation to deviate from the optimum.

- **Externalities** [13]. The allocation of a particular slot to a specific airspace user affects the possibilities of other airspace users.
- **Asymmetric information.** Not all participants may have access to the same information, which may create trust issues of the participants in the market.
- **Bounded rationality** [14]. The rationality of participants is limited by the available information, cognitive abilities, and the finite time available for making a decision.
- **Market incompleteness.** Market incompleteness would occur if there are not enough slots for all participants.

A number of market mechanisms have been proposed related to slot swapping, where airspace users can participate with the goal to allocate the resources in the most efficient manner, i.e., those participants that value a resource most should be allocated the resource. Rassenti et. al. [15] propose a combinatorial auction mechanism based on sealed bids to allocate airport time slots among competing airlines, allowing airspace users to submit a number of bids for combinations of airport landing or take-off slots. Ball et. al. [16] demonstrate how market mechanisms may be the answer to many of the current system’s disadvantages of slot allocation. Ranieri et. al. [17] describe an auction mechanism for distributing delay among different flights, using a centralized decision-making process to minimize the total delay as a first step and then as a second step introduces a decentralized decision-making process that maximizes each individual’s welfare. None of these mechanisms, however, satisfies all the requirements for a market mechanism for slot allocation. Specifically, Myerson and Satterthwaite’s impossibility theorem [18] states that for any bilateral trade where there is asymmetric information, e.g., due to the difficulty to know the real valuations of market participants regarding different slots, no market mechanism can satisfy at the same time the requirements of individual rationality, budget balance, allocative efficiency, and incentive compatibility. We also refer to Castelli et al. [7] for a discussion of the theorem in the context of ATFM slot allocation.

### III. Business and Deployment Use Cases

The SlotMachine system provides a means for airspace users to optimize the steering of their flights, and thus optimize their operations by reducing the delay of critical flights during a regulation. Based on internal key performance indicators, closely linked to the airspace users’ business priorities, the airspace users may participate in a marketplace for the exchange of ATFM slots. In particular, we consider the following use cases regarding the market mechanism.

- **Delay optimization.** How much reduction of delay on important flights can be achieved through switching flights?
- **Cost/utility optimization.** Using weights, airspace users can define in a more fine-grained way the preferred take-off times and allow for a detailed analysis of the benefits achieved for each airline
- **Credit handling.** The use of credits finally allows prioritization across multiple flights and gives airspace users the greatest flexibility in planning over a longer time period; credits also allow to investigate market mechanisms in terms of restricting the durability of credits or allowing credits to be exchanged between locations (in the hybrid or decentralized deployment scenarios).
- **Bundling flights.** For smaller airlines it could be interesting to not only exchange single flights but create bundles across multiple (smaller) airlines to achieve a levelling field with large alliances.

The different components of the SlotMachine prototype can be deployed in the following ways. For a description of the components please have a look at [4].

- **Centralized.** All components of SlotMachine except the multiparty computation nodes are hosted by a single stakeholder, most probably by the organization also providing the Network Management Function (NMF).
- **Hybrid.** The SlotMachine components (Controller, Heuristic Optimizer, and Privacy Engine) are hosted in multiple instances and report possible flight lists to the Network Management Function; those instances operate independently from each other and require a trusted stakeholder as operator.
- **Decentralized.** In this scenario all SlotMachine components are hosted in a decentralized way by the airlines and do not require any trusted party.

#### A. Business Use Cases

Within an airspace user’s operations, the dynamics of the European and local environment are taken into account through several parameters, known only by the operations
center of the airspace user. By defining business priorities dynamically and computing departure and arrival times thanks to operators’ and data scientists’ knowledge, airlines are expected to be able to deliver the following three times, which should be the reference for the SlotMachine optimization.

- **Time not before.** This is the time which the flight should not depart before. It can either be the Scheduled Time of Departure published to all passengers, or it could be a later time, e.g., if any connecting passengers are arriving late to this flight or if a crew rotation with aircraft change was delayed.

- **Time not after.** This is the last time (or maximum delay) that the airline could accept before having to deal with considerable consequences and costs. For example, for the connecting passengers in the considered flight, the time not after would be the maximum delay that allows to still catch the connection at the arrival airport, or the time of a maintenance event which cannot be postponed. The time not after could also be linked to an arrival or departure curfew.

- **Time wished.** This would be the wished time at which the airline would like to depart, to smoothly operate the flight. This would correspond normally to the less operational and delay costs for the airline. This time should be the reference for the SlotMachine allocation and equity calculations.

The more time an airline allows between the time not before and the time not after, the more margin for improvement is given to the SlotMachine system for optimization. Therefore, the flexibility that each airline is giving to the system thanks to the margins time not before and time not after should be taken into consideration in the credits allocation and the equity measurements. For very important flights, a priority could be indicated by the airline, to ask for more probability that this flight will get a slot near the time wished. The priority could be also managed by allowing the airspace user to specify a number of credits that the airspace user is willing to pay to get the wished time slot. It is worth noting that the time wished does not always have to be in the middle between the time not before and the time not after. The time wished could be placed anywhere between the time not before and the time not after, and could even be at the margins of the acceptable time window, i.e., time wished equals time not before or time not after. Evolutionary algorithms are employed to solve the market mechanism problems.

**B. Deployment Use Cases**

In a centralized environment (Fig. 1), the Network Management Function, which in Europe is assumed by the Network Manager, is at the center of slot swapping. Each airspace user provides its priorities and margins to the SlotMachine system. The SlotMachine system, searches for the best new slot sequence to match the preferences of all participating airspace users and proposes new flight lists to the participating airspace users. The airspace users evaluate internally if the offer can be accepted, or if they are willing to spend more credits to ensure a better slot to a very important flight. Once all airspace users have answered to the SlotMachine system regarding the acceptability of the proposed flight lists, and at least one proposed flight list is acceptable for all airspace users, the NMF receives all accepted offers, checks the solutions for feasibility, and chooses the best feasible flight list. Finally, the NMF releases the new flight list, which makes it official. The centralized approach allows an overview of the situation, as all requests and offers are collected by the same stakeholder. Therefore, the predictability, for example, for the airports, would be greater if a constant communication is established with the NMF. Since the airlines must coordinate with only a single user, i.e., the NMF, the workload will not be too high, which is an important point for airspace users, especially for small airlines not having the possibility to develop semi-automatic or fully automatic tools to support decision-making for the participation in the SlotMachine optimization process.

However, the evaluation of the offers proposed by the NMF could still be time-consuming for airlines, as the mechanism to decide if additional credits should be spent on a particular flight for a given slot could be tricky to automatize. If a semi-automatic tool is implemented by the airspace users, making a decision regarding the spending of credits could still be manageable.

In a hybrid environment (Fig. 2), the slot swapping is conducted among the airspace users themselves, which returns the airspace users the best achievable positions (slots) in the flight list, and then enables those airspace users to trade. The airspace users send the preferences to the SlotMachine, which then enables the airspace users to trade and exchange slots in order to either improve the position of a flight, e.g., by spending credits, or to accept to free one of their slots for another airlines, i.e., earning credits. Once an agreement is reached, the requests are sent to the NMF, which assesses the proposition from a network perspective, and implements the new slot sequence accordingly. This is a very flexible system, enabling to trade directly between the two affected stakeholders. Moreover, no real prioritization needs to be communicated, as the airlines are choosing themselves if they agree to trade a slot or not. However, this would lead to a very high workload for the airlines, which is not really sustainable during normal operations, except if a dedicated position is created for that (which would be a change of mentality within airlines, as well as additional costs). Moreover, if the trading time is lasting too long, no airline would be able to deal with the process, as operations are a very dynamical environment, which requires flexibility and quick decision and implementation. Last but not least, the data security could be a problem, as airlines would be able after a certain time to identify which slot and flights other airlines are prioritizing regularly. Finally, this system would be advantaging local situations, but not automatically improving the European network situation, as very specific trading would occur, and only on the basis of pairwise coordination.

The decentralized environment (Fig. 3) puts the focus on the airport or area of congestion. It could be either an
The NM, based on the prioritisations given by the Airspace Users, tries to find offers consisting of inter airlines flight list to further reduce the impact on the airlines involved.

The Airspace Users evaluate the received offers and actively decide whether to accept or refuse each offer + credits.

The NM matches the accepted offers to produce the Flight Prioritization Solution.

The airline evaluates its flights and decides on asking for an exchange between airlines and decides on the possibility of absorbing some delay to earn credits or to use some credits (if available) to prioritise one or more flights.

The NM analyses the airports request to accept or reject them according to schedule restrictions. Then, it matches the accepted offers to produce the Flight Prioritization Solution.

The airport evaluates the Flight List and decides on asking for an exchange between airlines and decides on the possibility of absorbing some delay to earn credits or to use some credits (if available) to prioritise one or more flights.

Timeline   Network Management   Airspace User

Fig. 1. UDPP Flight Margins + Centralized Flight List trading + Credits (based on Mechanism B from BEACON) [19], [20]

Timeline   Network Management   Airspace User

Fig. 2. UDPP Flight Margins + Hybrid Flight List trading + Credits (based on Mechanism C from BEACON) [19], [20]

Timeline   Network Management   Airports   Airspace User

Fig. 3. UDPP Flight Margins + Centralized Flight List trading + Credits (based on Mechanism B from BEACON) [19], [20]
airport (departure or arrival regulation) or an airspace (En-route regulation). The prioritization from all affected and participating airspace users would be communicated to the SlotMachine, owned by those “responsible” for the congestion. The NMF would communicate the actual flight list, on which the congestion owner, e.g., an airport, for easier and clearer explanations, would base a proposition of slot exchanges, based on the prioritization and margins of all participating airspace users. This proposition is sent to all airspace users, which accept or reject to spend/win credits depending on the changes proposed by the airport. Once the trading results are gathered and consolidated by the airport, the new flight list is sent to the NMF, which analyzes the network impact and implements accordingly the new flight list.

IV. MARKET MECHANISM

A slot swapping system must overcome two main challenges. First, the system must ensure that its participants cannot “game” the system to obtain an improper advantage over their competitors. In other words, airspace users must be given an incentive to report honest preferences and reporting dishonest preferences must not pay off. Second, the system should promote equity and fairness over time. The system should not work to the advantage of only a single or a few participants but ideally benefit all the participants.

In the following, we briefly discuss requirements for a market mechanism for the SlotMachine system. We then briefly sketch two options regarding the design of a market mechanism that could be used in conjunction with the SlotMachine system.

A. Requirements

In the following, we briefly describe desirable properties identified in literature on market mechanisms in general [21] and the allocation of resources in Air Traffic Management (ATM) in particular [7]; we refer to literature for a more detailed, formal definition.

- Individual rationality. A mechanism that a rational airspace user will participate in without a regulator enforcing participation must always give each participant a non-negative payoff; the problem of individual rationality is also referred to as “participation constraint”.
- Budget balance. The mechanism shall require no outside subsidization for the mechanism to work. The mechanism shall generate no profit that needs to be allocated among actors other than the participating airspace users. Otherwise put, a governing authority’s sole interest should be the proper operation of the market which should not require external financing and not turn a profit for the authority.
- Allocative efficiency. The slot allocation produced by the market mechanism, among all feasible slot allocations, maximizes the global welfare (or utility) of airspace users.
- Incentive compatibility. An airspace user shall not be able to increase the payoff by misrepresenting the preferences regarding the slot allocation, under the condition that all other participants are honest.

Other important requirements for the market mechanism are the following.

- Decisions of airspace users participating in the market should not negatively impact non-participating airspace users.
- Airspace users have a right of non-participation, without penalty.
- The transactions must be transparent for the participants.
- Financial competition must be avoided but perhaps it is possible to collaboratively establish a win-win financial compensation scheme.
- Equity and fairness should be guaranteed.

B. Utility-Based Optimization

An important concept in economics, utility represents the satisfaction that the consumer of a good experiences [17]. In the context of slot allocation, utility serves as a representation of the preferences of airspace users regarding slots. More specifically, in this paper, similar to Ruiz et al. [22], we understand the term “utility” as the perceived value for an airspace user in case a certain slot is allocated to a flight operated by the airspace user. For simplicity, in this paper, also similar to Ruiz et al. [22], without loss of generality, we assume that utility has a direct relationship to the economic profits generated by the airspace users through the operation of flights, even though the concept of utility may also factor in any indirect profits and costs as well as any type of non-economic preferences.

We consider airspace users as utility-maximizing agents. Therefore, an airspace user has a time-variant utility function for each operated flight. Each airspace user’s objective is to maximize the utility of the slot allocations to their flights. Since the exact utility function for a flight is difficult to discern, in the SlotMachine project, we consider utility functions derived from margins. Figure 4 shows a utility function based on such margins. The utility is highest for the time wished slot and decreases for slots later than the time not after and earlier than the time not before.

The goal of the SlotMachine system is to optimize social welfare by enabling a more efficient allocation of ATFM slots that is closer to the optimal preferences of the airspace users than the baseline allocation, e.g., the first-planned first-served sequence. Optimizing the social utility requires at some stage that the airspace users reveal their utility functions or their real slot valuations for each of their flights. These values are sensitive business information and airspace users will not disclose such information. In addition, due to the asymmetry of the information with regards to the real slot valuations, the airspace users could generate strategies consisting of giving wrong valuations, e.g., by overvaluing or undervaluing the slots, with the purpose of taking advantage of other market participants. This problem is typically solved with the design of strategy-proof market mechanisms, often based on advanced auctioning mechanisms.
In the SlotMachine system, privacy-preserving multiparty computation will allow to exploit the private utility functions of airspace users for optimization of slot allocation. Zero-knowledge proofs will allow to enforce certain rules on the inputs submitted by the airspace users. The SlotMachine system will employ a heuristic optimizer to find optimal flight lists over multiple iterations. In each iteration step, the found flight lists are evaluated in a privacy-preserving way by the Privacy Engine. Due to the fact that a heuristic optimization algorithm is employed, the found solution may or may not be optimal, but we assume that the heuristic optimizer will generally find a solution close to the optimum. The following observations hold under that assumption.

A key aspect of equity and fairness in UDPP is that the resource allocation should avoid financial competition and should ensure equal access for all airspace users irrespective of financial resources and the number of operated flights. From an economic point of view, a market mechanism based on utility maximization works best with monetary exchange, albeit in a cooperative setting rather than a setting of financial competition. If monetary exchange is undesirable in the short and medium term, real currency could be replaced by “credits”, even though such a system would not be ideal from an economic point of view. In particular, a potential market mechanism for the SlotMachine system could be derived from a mechanism proposed by Redondo Rodriguez [23], based on utility maximization, consisting of the following steps.

1) Obtain valuation for each slot per flight. Each airspace user will employ a secret fitness function to obtain a weight table defining the utility of each slot for a flight. Figure 5 illustrates how utility functions can be represented in vector form to obtain a weight map with valuations specified in some monetary unit, ideally a real currency, e.g., euros, or otherwise credits.

2) Calculate the social value of the baseline flight list. Taking into account both the initial slot allocated to each flight, e.g., using first-planned first-served policy, and the valuation of the allocated slot by the airspace user for that flight, the total social utility can be obtained by simple aggregation.

3) Finding a sequence that maximizes the social welfare. The collected weight maps from the airspace users become the input for a heuristic optimizer (Fig. 5) that works together with the Privacy Engine employing multiparty computation to provide the private inputs. Note that due to the fact that a heuristic optimization algorithm is used, there may be a better solution. Still, the found solution will be better than the baseline. Using a heuristic optimizer also has the advantage that the private inputs can remain private because the Privacy Engine can be used for evaluation of the solutions.

4) Redistribution of welfare in an equitable manner among all the participants. The optimal allocation of a certain slot by an airspace user during congested periods at an airport generally causes negative externalities to other airspace users wishing to be allocated the same slot. The same slot can only be allocated once and, therefore, a flight may be allocated a suboptimal slot. Thus, reaching an equitable situation requires the distribution of the individual costs caused by the externalities in an equitable manner among the participants that have to bear the costs. For that purpose, the SlotMachine system may charge a congestion fee to those flights having a direct benefit from the optimal allocation of the slots to compensate the other airspace users for the externalities generated by such allocation of slots, distributing the total social welfare gains in an equitable way (Fig. 6), i.e., each flight will have the same share of the total welfare gain [23]. Since the allocation of slots will be (close to) the optimum and the welfare will be redistributed in a proportional manner with regards to the baseline utility of each flight, the final outcome of the market mechanism will be fair.

The utility-based market mechanism meets the four wished market mechanism requirements if real money is used.

1) The market mechanism satisfies the individual rationality constraint because it is guaranteed that all the participants will be better off after the market transactions.

2) The market mechanism is budget-balanced because network management does not need to pay to reach the equilibrium due to congestion fees, which are redistributed to market participants via compensation refunds.

3) The market mechanism reaches allocative efficiency because the outcome after optimization will be close to Pareto optimal. Note that the solution found by a
heuristic algorithm may not necessarily be the optimum. 4) The market mechanism is strategy-proof because the airspace users’ inputs are monitored and recorded using privacy-preserving technologies. Furthermore, the individual interests are aligned with the social interests since everyone is better off in case the adopted flight list is the social optimum or at least close to the social optimum.

Let us now assume that exchange of real money, even in the form of congestion and compensation fees, is not desired by airspace users. A system of credits — “a virtual currency with no monetary value” [8]— can be put in place to allow airspace users to indicate values of each slot for each flight and to enable redistribution of social utility, which is a common way to align the individual incentives with the system goals and to achieve fairness [24]. In this case, the SlotMachine system could periodically allocate credits for airspace users to place valuations on slots for flights. Airspace users would accumulate credits in form of compensation fees and have to spend credits for congestion fees. In order to participate in an optimization, airspace users would have to possess a sufficient number of credits. From an economic point of view, the utility-based market mechanism would not be ideal when credits are used but would still be technologically feasible.

C. Auction-Based Market Mechanism

In the SlotMachine project, we also consider an alternative mechanism based on combinatorial auctions. The proposed mechanism is inspired by VGC auctions [21].

Game theory allows for the analysis of the interdependent decision-making processes in general and air traffic flow management in particular (see [25] and [26] for additional information). Accordingly, three fundamental forces will keep an airline from abandoning cooperative behavior (see [27]). First, “goodwill” is a “powerful force” to support cooperation [27, p. 27]. Second, Contestability Theory [28] suggests that an airline may adhere to cooperative behavior due to “peer pressure”, aiming to avoid the provocation of countermeasures by competitors [27, p. 27]. Third, the system may perform (limited) supervision and enforcement [27, p. 27]. Fairness should be addressed as well.

Money transfers are now not allowed but rather a system of credits is employed. Credits, like any currency, can be linked to “assets” that give them an intrinsic value. In SlotMachine, credits facilitate the exchange of slots so that airspace users have flexibility to manage the delay allocated to their flights and in turn the cost of such delay. Airspace users could accept more delay in some flights when the delay is relatively cheap and spend credits in exchange of better slots (less delay) when the cost of delay is relatively high.

Airspace users will have an initial credit endowment, e.g., 100 credits. This endowment is not proportional to the number of flights operated by the airspace user since airspace users with more flights may require more credits to protect their important flights, but they also have more flights to generate those credits.

For each of the flights participating in the market, the respective airspace user will provide as input one of the following options.

1) **Offering** a slot in exchange of a new slot (that can be later or earlier to the current slot) plus a number of credits that is directly proportional to the delay variation accepted if the exchange is produced. If the exchange is produced the airspace user will receive one credit per minute of delay variation accepted.

2) **Bidding** for a new (better) slot and offering credits to one or more flights that would accept changing their positions to enable the flight asking to get the best position possible.

3) **Asking and offering.** It may also happen that the airspace user would like a flight to be moved to another slot in order to improve utility. If the requested exchange is not feasible the airspace user could still be willing to accept credits in exchange for a slot outside the margins.

V. Summary and Future Work

The SlotMachine project develops a privacy-preserving marketplace for ATFM slots. In case of regulations, airspace users may submit preferences regarding departure/landing slots to the SlotMachine system, which conducts an optimization of the flight list at an airport to maximize overall utility of airspace users. In this paper, we discussed different deployment use cases and market mechanisms for the SlotMachine system. Future work will further investigate the stakeholder acceptance and technological feasibility of the proposed deployment use cases and market mechanisms.

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