A Privacy-Preserving Marketplace for Air Traffic Flow Management Slot Configuration

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***Abstract*—In case of reduced capacity and congestion at an airport, flights are delayed, which means additional costs for the airlines. The amount of costs incurred by an airline differ between flights and depend on various factors, e.g., passenger compensation and costs for crew replacements. Some flights can wait longer than others before the delay causes significant additional costs. From a global perspective, it would be beneficial to prioritize the flights based on the incurred costs. Airlines, however, will be reluctant to share those costs. Therefore, we propose the SlotMachine system for flight prioritization that keeps confidential inputs from airlines private in an encrypted form that not even the system can read the costs. Using multi-party computation in combination with a heuristic optimization algorithm, the SlotMachine system finds an optimal flight list. A flexible credit system may ensure fairness and equity over time: Airlines may earn credits by accepting additional delay, which can be spent for prioritizing flights in the future.**

***Index Terms*—flight prioritization, multi-party computation, evolutionary algorithm, heuristic optimization**

I. Introduction

Passenger numbers are expected to rise again, and the aviation industry will once more be confronted with increasing flight volume in the face of limited resources at airports and in the air. At the same time, airlines are struggling with increased cost pressure from a growing number of market participants while the highest safety standards demand compliance with complex processes. The ongoing *SlotMachine* project, funded by EU Horizon 2020, investigates a more efficient allocation of slots in Air Traffic Flow Management (ATFM) in cases of congestion at airports, allowing automated prioritization of flights from different airlines. To this end, SlotMachine employs heuristic optimization algorithms in conjunction with secure multi-party computation and blockchain technology in order to protect confidentiality of sensitive inputs; not even the SlotMachine system will be able to read airlines' sensitive inputs.

The SlotMachine project is a joint research effort between Frequentis, EUROCONTROL, AIT Austrian Institute of Technology, Johannes Kepler University Linz, Austria, and Swiss International Airlines, aimed at envisioning a new kind of marketplace for flight prioritization in air traffic management. The platform shall enable more flexible, faster, scalable and (semi-)automated processing of flight prioritization transactions in a fair and trustworthy way. Built with a privacy-first approach, SlotMachine protects sensitive airline data from competitors and airport operators and therefore fully unleashes the potential of flight prioritization exchange.

The EUROCONTROL Network Manager restricts ATFM slots in situations of increased flight volume and safety-critical overloads. An ATFM slot is an allocated time of departure that regulates time over congested areas along the flight route, including time of landing. Until now, these slots have only been possible for simple exchanges between two flights from the same airline company and are seen as helpful means for airlines to prioritise expensive flights in order minimise delays and keep costs down. Reasons for different costs of individual flights are, for example, the provisioning of connecting flights for passengers or work-time restrictions for crew members. Airlines want to keep the cost structure of their flights confidential, as they fear a competitive disadvantage when disclosed. SlotMachine uses blockchain technology and secure multi-party computation to extend the existing User-Driven Prioritisation Process (UDPP) solution, which is currently in development in the EUROCONTROL NET Unit within SESAR 2020, with the possibility to keep private the participating airlines' confidential information such as the cost structure of flights.

The principal components of the SlotMachine system are the Heuristic Optimizer and the Privacy Engine. The Heuristic Optimizer employs an evolutionary optimization algorithm (see [7], e.g., a genetic algorithm, or another heuristic optimization algorithm to find incrementally improved flight lists. After each optimization step, the Heuristic Optimizer sends candidate flight lists to the Privacy Engine, which returns a fitness value computed over the encrypted preferences for the slots submitted by the airlines for each flight.

SlotMachine allows secure, auditable transactions without the need for a central broker, whereby stakeholders are able to enter flight prioritization transactions without disclosing information to other participants. By demonstrating the feasibility of a privacy-preserving platform for exchanging ATFM slots, the foundation can be laid for the development of a product that will be an essential element in the aviation industry in the future. It contributes to a better use of existing resources at airports, higher efficiency of airlines, lower emissions, and shorter delays for passengers.

The remainder of this paper is organized as follows. In Section II we provide background information. In Section III we discuss the design of the SlotMachine system. In Section IV we describe the main components. In Section V we discuss market mechanisms. In Section VI we review related work. We conclude the paper with a summary and an outlook on future work.

II. Background

In this section we first describe the flight prioritization problem that SlotMachine aims to solve. We then introduce the user-driven prioritization process for inter-airline slot swapping developed by EUROCONTROL.

A. Flight Prioritization

For an airline, delay of a flight means additional costs. The incurred costs depend on the flight and may be due to, e.g., passenger compensations or required crew replacements. The costs of a delay are typically not proportional to the extent of the delay. Rather, a non-linear step function often describes the incurred costs of a flight depending on the extent of the delay (Fig. 1). Hence, each flight has one or more delay targets. If a flight overshoots the delay target, i.e., departs after the delay target, the costs of the delay bounce up.

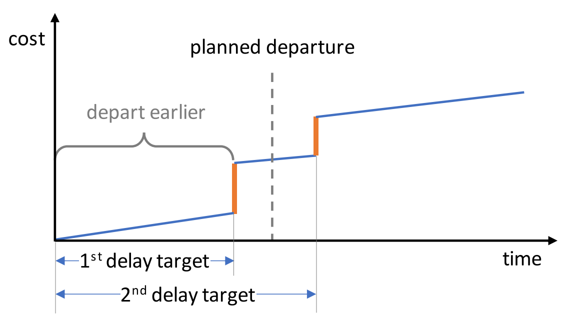

Fig. 1. Non-linear cost function for flight delay

The flight prioritization problem boils down to queue reordering based on the flight delay targets (or margins). Consider, for example, the three flights (A, B, C) and their cost functions shown in Fig. 2. Reduced capacity causes the flights to depart later than scheduled. Network management may decide on the following order, based on the original schedule: First departs Flight A, then Flight C and Flight B. Flight C, however, has a very wide margin whereas Flight B has only a narrow margin, hitting the first delay target comparatively early. From a global perspective, it would therefore be beneficial for Flight B to depart first, then Flight A and then Flight C.

B. User-Driven Prioritization Process

The objective of User-Driven Prioritization Process (UDPP) [14] is to transfer the resolution of a congested situation from the owner of the resource (for example, the Flow Management Position (FMP) dealing with arrival flights) to the user of the resource (i.e., the airlines), best placed to decrease the impact of the problem on their operations. The SlotMachine will bring an additional final step, allowing further optimising the AU solution with inter-airline and across congested situations exchanges.

UDPP brings the performance improvement of the ATM system three areas. (1) Flexibility for the Airspace Users (AUs), the possibility to react to imposed Air Traffic Flow Management (ATFM) delays by re-positioning their flights according to their business needs. (2) Equity for AUs, allowing flexibility to all AUs is considered acceptable only if this has no negative impact on other AUs' flights. Equity means that for each individual flight not participating in UDPP, there is no increase of delay. And (3) AU Cost Efficiency (AUC), which is the driver for prioritisation decisions by AUs, aiming to reduce the impact of the additional delay caused by a regulation.

The UDPP concept enables each AU in a capacity constraint to exchange its flight positions and redistribute its total delay among several of its own flights, reducing the cost/impact of delay. The UDPP concept final structure includes several innovative features, which each AU can use uniquely or combined as appropriate:

1) Fleet Delay Reordering (FDR) is similar to slot swapping involving more than two flights. The AU can reorder its flights within the constraint using only its own slots by assigning a priority value on each flight. The automation uses the priority to put flights in the best position, but not before the original schedule.
2) Selective Flight Protection (SFP) allows to protect the schedule of a specific flight (Pflight) even when there is no direct slot allocated to the AU at this schedule time. To do so, the AU must have a minimum of one slot before the original schedule of the protected flight. This earlier flight is moved to a later slot and the protected flight is moved forward to its schedule. Flights of the other AUs in between the protected schedule and the earlier flight moved backwards are improved
3) Margins - requested by AUs to automatically find the best position of each flight based on "time windows" (Time not before; Time not after). Many AUs' constraints on flights are linked to external constraints expressed in absolute time. When numerous flights are involved, flights prioritisation becomes a very complex task for the AU and automation is needed. The Margins feature allows assigning "time windows" - Time not before and Time not after- to each flight in combination

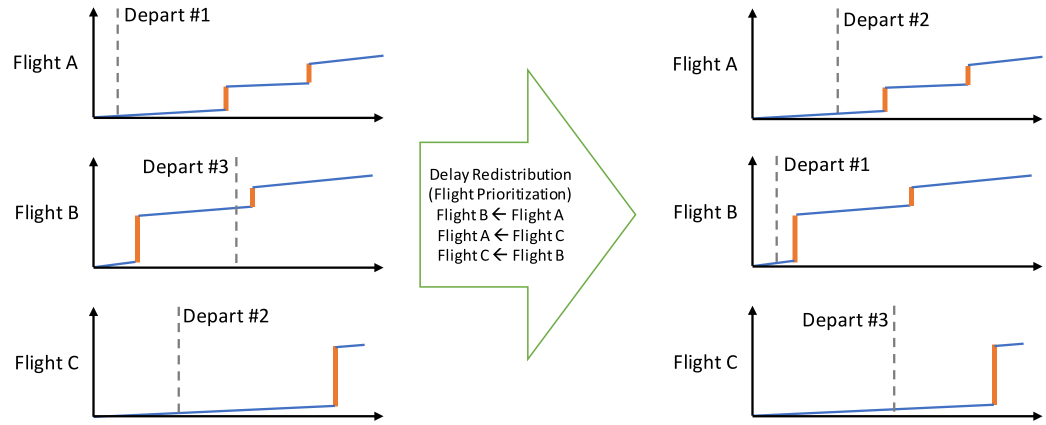

Fig. 2. The flight prioritization problem

with the SFP and FDR features, reflecting the AU's internal constraints and remaining stable when the ATM environment changes. The position of the flights with Margins is automatically optimised while respecting equity with respect to other AUs (i.e. no impact on other AUs' flights).

In the future ATM Network strategic flow management and optimisation activities, the collaborative framework will allow the coordination and collaboration between different ATM processes and actors: Airports, ANSPs, AUs and NM, to ensure the continued stability and performance of the ATM network, and in particular the consolidation at network level of any UDPP input [15].

III. System Design

The SlotMachine system will allow airspace users (airlines) to participate in inter-airline flight prioritization sessions without disclosing confidential information, e.g., the cost of delays for individual flights. Figure 3 illustrates the proposed architecture of the SlotMachine system. The central components of the SlotMachine system are the Heuristic Optimizer and the Privacy Engine, which together conduct flight prioritization in a privacy-preserving manner. A Controller component coordinates the flight prioritization process and the interactions between SlotMachine and external stakeholders, i.e., airspace users, airports, and network management function. A flexible credit system will promote equity and fairness of the prioritizations over time. Airspace users' credit balances are stored in wallets; a blockchain will promote auditability.

The core flight prioritization session consists of three phases: setup, optimization, and confirmation/notification. Figure 4 shows a sequence diagram describing the interactions of the SlotMachine system's components during flight prioritization. If a flexible credit system is in place, a fourth phase – clearing – will update the credit wallets, depending on the employed market mechanism (see Section V); the clearing phase is not shown in Fig. 4. During the setup phase of flight prioritization, the Controller requests the initial flight list from the network management. Furthermore, participating airspace users communicate their preferences regarding the sequence of the flights that are available for swapping. The airspace users communicate their preferences in form of an encrypted weight map for each flight, indicating how suitable a time slot would be for a specific flight. Depending on the market mechanism, airspace users may communicate additional confidential information in encrypted form, e.g., credits to be spent, and possibly non-confidential information, which is not encrypted.

The optimization phase of flight prioritization involves the Heuristic Optimizer and the Privacy Engine along with the MPC nodes. The Heuristic Optimizer initializes an optimization session by sending the encrypted weights to the Privacy Engine. The actual optimization process is a loop of finding possible flight lists by the Heuristic Optimizer and the subsequent evaluation of the fitness of the candidate flight lists by the Privacy Engine. After each iteration, the Heuristic Optimizer decides how to alter the candidate solutions based on the fitness values received for the previous solutions. The Heuristic Optimizer may employ different strategies to find potential flight lists, e.g., a genetic algorithm with different mutation and recombination operators. Likewise, the Heuristic Optimizer may employ different criteria for ending the optimization procedure, e.g., a fitness threshold for a candidate solution or the number of iterations not to provide improvements of the best found solution up to that point. The output of the optimization phase is a choice of optimal flight lists.

After the optimization phase, the airport, airspace users, and network management must confirm which flight lists are acceptable or reject unacceptable flights lists. The network management chooses a flight list from the choice of optimal flight lists found by the Heuristic Optimizer. Finally, the Controller notifies airport and airspace users of the accepted flight list. Airspace users will enter slot preferences of flights manually using a graphical user interface or automatically using analytics to automatically derive the margins for flights from historical data. The preferences are submitted via business-to-business interfaces to the SlotMachine. The necessary components could be customized and adapted for the needs of individual airlines.

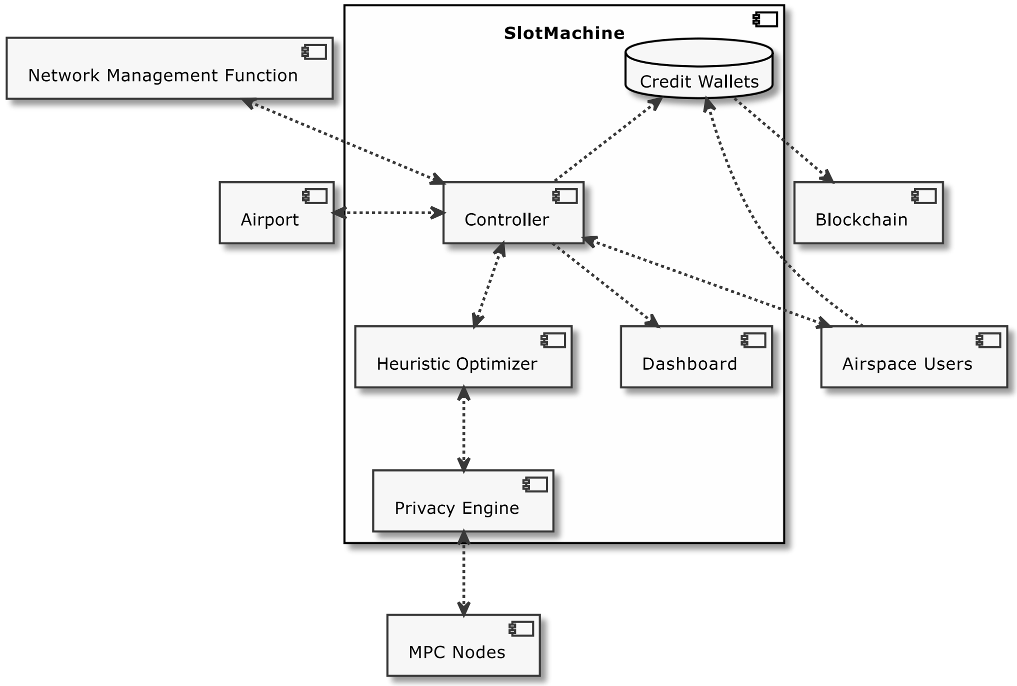

Fig. 3. The architecture of the SlotMachine system

IV. System Components

The SlotMachine system comprises the components for optimizing the flight prioritization at an airport in a privacy-preserving way and controls the fight prioritization. The SlotMachine also maintains a database of credits awarded to airspace users. Airspace users shall interact with the SlotMachine using a client interface. The SlotMachine communicates the optimized flight prioritization to the network management function, airport, and airspace users. In the following, we present more details about the different components of the SlotMachine system.

A. Controller and External Interfaces

The Controller is the central component of the SlotMachine, relaying messages between Airspace User, Network Management Function, Heuristic Optimizer, Airport, and Credit Wallets. The Controller requests a flight list from Network Management and preferences from airspace users. The Controller then initiates the optimization phase.

The airspace users, airport, and network management will require components for communicating with the slot machine. SlotMachine and external components will communicate via REST interfaces (see [6]). The SlotMachine system will also have a Dashboard that shows various key performance indicators related to the flight prioritization sessions conducted via the SlotMachine system.

B. Heuristic Optimizer

The Heuristic Optimizer employs an evolutionary, heuristic algorithm to find an optimal solution for the flight prioritization problem. The employed algorithm could be a genetic algorithm or a local search algorithm, e.g., hill climbing, simulated annealing, or tabu search. Concerning the evaluation of the fitness of a solution, the Heuristic Optimizer calls the Privacy Engine, which computes a fitness value for a solution based on private inputs submitted by the airlines. The private inputs remain encrypted and the SlotMachine system cannot decrypt those private inputs. In order to compute a fitness value over encrypted private inputs, the Privacy Engine employs multi-party computation over encrypted inputs.

Airspace users specify *margins* for each flight, which mirrors the delay targets. Hence, each flight has a time wished – the airline would like the flight to depart at that time. Then a flight has a time the airline does not want the flight to leave after – this would be the delay target. There can also be a time that the airline does not want the flight to leave before. For example, the flight *SWR243*, with a scheduled time of 10am, in case of a congestion, would have an ideal time of 1:30pm, would ideally leave not before 12:30pm and not after 3:30pm (Fig. 5, top). More complex margin specifications could also be devised, incorporating various delay targets. Thus, in order to be flexible, the Heuristic Optimizer will employ weight maps to prioritize flights.

From the margins derive weights for each flight and slot (Fig. 5, middle). The weights could be derived using different functions, varying between airlines and even between different flights. The time wished for a flight would receive the highest weight, which gradually decreases within the margins and would abruptly fall off outside the margins. The Heuristic Optimizer would then try to maximize the sum of the weights of a flight list.

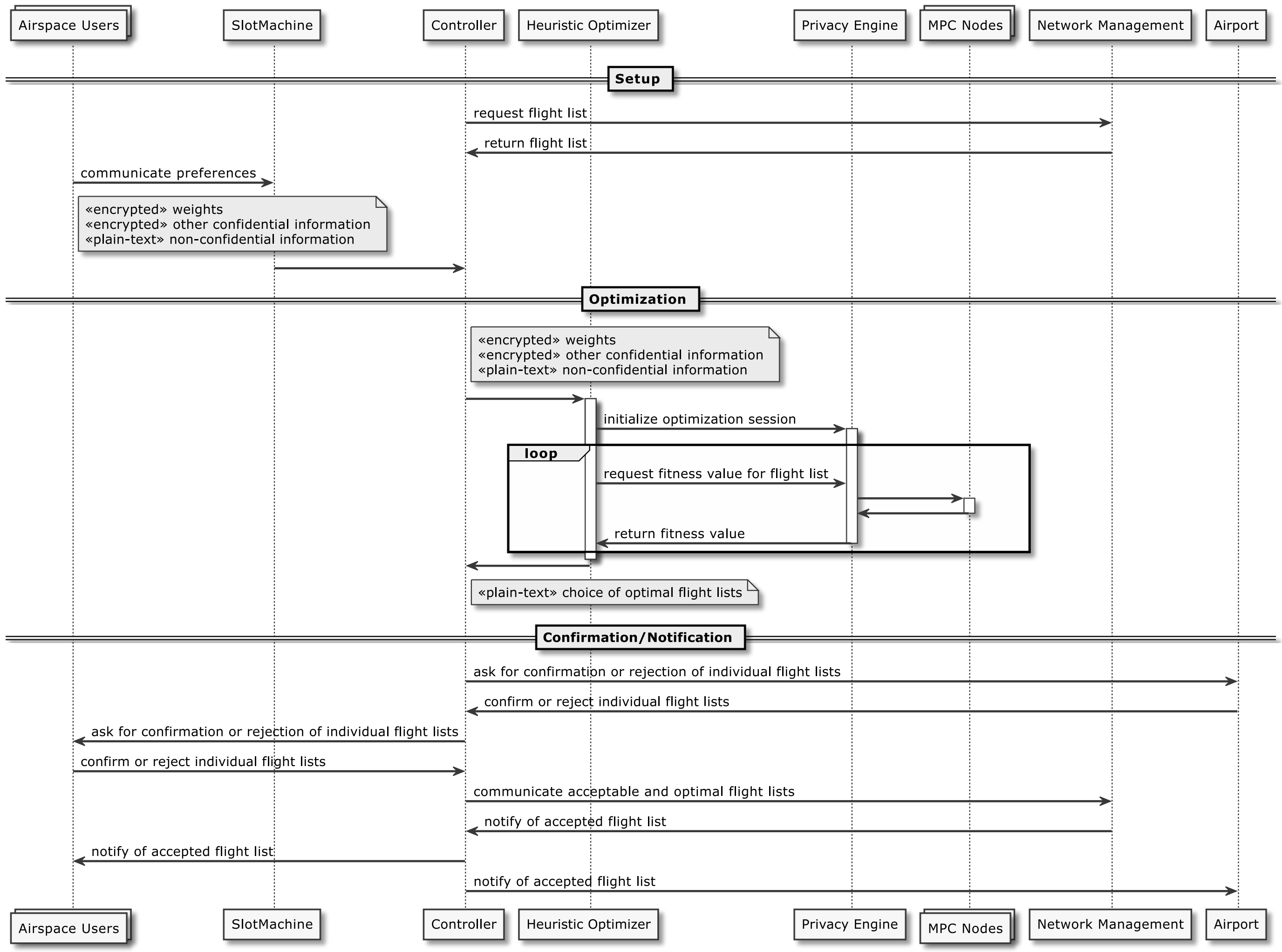

Fig. 4. Sequence diagram of a SlotMachine flight prioritization session

The weight map in Fig. 6 specifies the preferences of Flights A–F. For example, for Flight A, it would be preferable to depart at Slot 3 or Slot 4. For Flight B, it would be preferable to depart at Slot 2. Flight A would prefer not to depart at Slot 5 or Slot 6. Flight B would also prefer not to depart at Slot 5 or Slot 6. While Slot 3 and Slot 4 would not be ideal for Flight B, those slots would still be acceptable. The fitness value of flight list is obtained by summing up the respective weights for the flights. The bottom part of Fig. 6 shows example flight lists and their corresponding fitness value according to the weight map.

The Heuristic Optimizer looks for optimal solutions to the flight prioritization problem in an iterative manner. Figure 7 illustrates the optimization steps, which are conducted in a loop. In each iteration, the Heuristic Optimizer first starts with a set of candidate solutions, which are sent to the Privacy Engine for evaluation of the fitness value. Based on those results, the Heuristic Optimizer alters the candidate solutions and discards certain avenues towards an optimal solution. The Heuristic Optimizer could employ different search strategies. For example, the Heuristic Optimizer could employ a genetic algorithm with partially matched crossover and random mutations for finding new solutions.

Concerning performance, the Heuristic Optimizer can look for multiple solutions in parallel. Furthermore, the optimization process can be aborted at any point while still returning a valid solution. Thus, if the optimization process takes too long, the process will be aborted and still returns a result.

C. Privacy Engine and MPC Nodes

The Privacy Engine manages private inputs from airspace users in encrypted form such that computations on the data is possible without the SlotMachine system being able to know the contents. The main responsibility of the Privacy Engine is to assist the Heuristic Optimizer to find optimal flight lists in a privacy-preserving way, i.e., by not revealing inputs from airspace users.

The Privacy Engine is responsible for the protection of sensitive data provided by airspace users for flight prioritization. The Privacy Engine applies cryptographic techniques from the

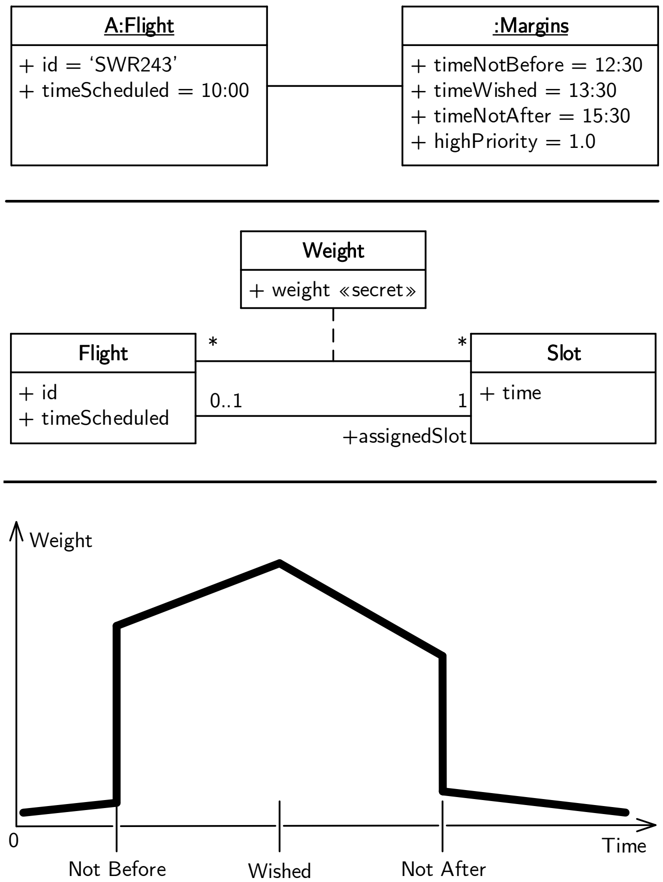

Fig. 5. A flight's margins translate into a weight map

	1	2	3	4	5	6
A	70	90	100	100	0	0
B	0	100	80	70	0	0
C	0	20	80	100	100	0
D	90	100	70	60	0	0
E	0	0	100	90	80	70
F	100	90	80	0	0	0

	1	2	3	4	5	6	
	B	C	A	F	D	E	Fitness: 120
	F	D	A	B	C	E	Fitness: 540
	F	D	B	A	C	E	Fitness: 550

Fig. 6. Weight map for calculation of fitness values for flight lists

domain of multiparty computation (MPC) over encrypted data (see [11]), to assist the Heuristic Optimizer in finding flight prioritization solutions based on airspace user preferences. To this end, the Privacy Engine manages multiple MPC Nodes, which carry out computations and provide an easy-to-use, secure interface for the Heuristic Optimizer to interact with.

For SlotMachine, we rely on MPC and blockchain as core technologies to achieve the highest possible level of security and confidentiality when determining the best flight list given airspace users' preferences, which are confidential information that airlines do not want to disclose to competition. The operator of the SlotMachine platform will not act as auctioneer, i.e., has no insight into the details of the prioritizations, which should run as decentralized as possible. Only after the selection of the best flight lists does the operator become active again in processing the exchange of credits. The combination of MPC and blockchain technology aims to solve problems associated with efficiency, scalability, and transparency. The combination of MPC and blockchain technology also opens up possibilities for the design of scalable privacy-enforcing computation systems with built-in resiliency for mutually distrusted parties [13].

The purpose of privacy-preserving computation is twofold. First, airspace users will be reluctant to share confidential information. Second, even if airspace users trusted the SlotMachine system, with privacy-preserving computation, airspace users' confidential information remains private even in case of security breaches.

D. Credit Wallets and Blockchain

Credit wallets record the credits amassed by the airlines over time in the course of their participation in flight prioritization sessions, which can be spent in future prioritization sessions. A blockchain may be used to make the transactions transparent to the stakeholders in order to build up stakeholders' trust in the system.

Extending MPC with verifiability will increase the transparency and auditability of the flight prioritization process. The combination of succinct zero-knowledge methods and blockchain technology will increase transparency by allowing to manage metadata about prioritization sessions and transactions in the blockchain in privacy-preserving form, e.g., through commitments to bids as well as zero-knowledge proofs for determination of correct credit exchange.

V. Market Mechanism

A digital marketplace allows buyers and sellers to "conduct transactions by electronic means" [5, p. 91], digital marketplaces are differentiated along various dimensions. In this regard, an ATFM slot swapping platform constitutes a vertical many-to-many marketplace of standardized products where participants conduct spot buys. Depending on the airport, power asymmetries between market participants may or may not exist. A vertical marketplace focuses on the requirements of a single industry: The scope of the ATFM slot marketplace is strictly limited to the aviation industry. Typically, ATFM slot swapping will take place on a marketplace with many buyers and sellers although on some airports, certain large airlines may wield quasi-monopoly as predominant airline. Marketplace participants trade ATFM slots, which are highly standardized and regulated.

In order to motivate airspace users to report correct preferences and prevent airspace users to "game" the system, the choice of market mechanism is essential. A flexible credit system can be used to promote equity and fairness over

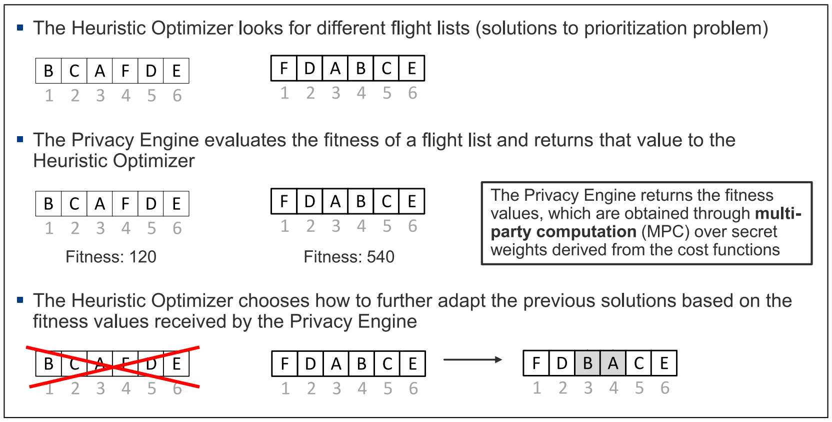

Fig. 7. The general principle of the heuristic optimizer's workings

time. Equity, in this case, may refer to the property of a slot swapping system to evenly distribute the delays among airspace users over time. Fairness, on the other hand, may refer to the property of a system to distribute delay in a way that those flights that can best handle additional delay receive more delay than those flights that are more criticial.

The SlotMachine project investigates two general alternatives for the market mechanism:

- **Credits increase weights.** The weights derive from the margins. Airspace users can only award credits within a lower bound and an upper bound. If airspace users want to prioritize a flight, credits must be spent to go beyond the limits.
- **Weights are credits.** After a flight list has been accepted, airspace users must pay credits or receive credits, the amount of which depends on the weights placed on the received slots.

VI. Related Work

The economic field concerned with designing efficient market mechanisms is mechanism design. The goal of mechanism design is to find a market mechanism that achieves optimal overall outcome for a specific resource allocation problem. Concerning the employed market mechanism for ATFM slot swapping, different alternatives have been proposed in the past. For ATFM slot swapping, exchanges and auctions are the most pertinent market mechanisms [8]. Whereas an exchange marketplace is characterized by real-time bids and asks, an auction platform hosts multiple sessions where participants place bids when requested [5]. A multitude of variants both for exchanges and auctions exists. Most relevant for ATFM slot swapping are double auctions, combinatorial auctions, and combinatorial exchanges. A double auction is characterized by multiple buyers and sellers engaging in trades of a single, homogeneous type of product [1]. A combinatorial auction is characterized by a single seller putting a multitude of heterogeneous products up for sale [2]. Buyers taking part in a combinatorial auction may specify complementarity ("I want A and B") and substitution ("I want A or B") relationships between goods [3]. In this regard, a declarative bidding language often serves buyers to express their preferences. Both double auctions and combinatorial auctions ultimately aim for the efficient allocation of resources, i.e., an allocation with maximum overall benefit. A combinatorial exchange presents characteristics of both double auctions and combinatorial auctions. Secondary trading of airport slots has previously been modelled as a combinatorial exchange problem to improve efficiency of air traffic flow [10].

A plethora of airport and ATFM slot swapping mechanisms have been proposed in the past to more efficiently organize air traffic flow [4]. Yet, none of these market mechanisms have seen widespread adoption in practice, presumably due to a lack of practical implementation as well as concerns about business secrets being disclosed by swapping ATFM slots between airlines [8].

Existing literature on mechanism design has identified privacy as an incentive for market participants to "honestly report information" [4], which is often a requirement to finding globally optimal solutions to allocation problems. Market mechanisms offering privacy are also potentially resistant to collusion [9]. Related work [12] has proposed a privacy-preserving market mechanism for trading airport slots (not ATFM slots), allowing airlines to keep information about the value of a route private.

VII. Summary and Future Work

The ongoing SlotMachine project, funded by the SESAR Joint Undertaking under the EU's Horizon 2020 program, aims to build an online marketplace for flight prioritization. Flight prioritization will be conducted in a privacy-preserving way through the combination of a heuristic optimization algorithm, e.g., a genetic algorithm, with multiparty computation.

Future work will investigate the suitability and scalability of different heuristic optimization options for different scenarios. Likewise, future work will investigate the suitability and scalability of multiparty computation and zero knowledge proofs for computation of fitness values of flight lists and verification of inputs. Of particular importance will also be the choice of market mechanism, which will be based on flexible credits.

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