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Agenda Item 3: Air Navigation System Performance Improvement
3.1: Proposals to improve the efficiency of air navigation services contributing to LTAG

METHODS AND ARCHITECTURE TO FURTHER DISTRIBUTE COLLABORATIVE DECISION-MAKING

(Presented by the United States)

EXECUTIVE SUMMARY

Consistent with ICAO Doc 9971, *Manual on Collaborative Air Traffic Flow Management*, air traffic management in the United States national airspace system is conducted via collaborative decision-making (CDM). To better realize the objectives of existing and emerging airspace users, it is necessary to further distribute this decision-making and further decentralize its supporting architecture. Several new CDM concepts are proposed as part of on-going research into performance improvements as potential candidates for future plans. The concepts are grounded in principles from normative economics. Simulation-based experimentation, including the implementation of some of these concepts as smart contracts on blockchains, revealed benefits enabled by empowering decision-makers with private information about the costs of individual flight delays.

1. INTRODUCTION

1.1 Air traffic management in the United States national airspace system is via collaborative decision-making (CDM), consistent with the principles of ICAO Doc 9971, M*anual on Collaborative Air Traffic Flow Management*. This allows the interests of all airspace users and stakeholders to be represented when addressing system constraints. With the expected emerging diversity of operations, future national airspace system users will have different business objectives to meet their unique needs, requirements and operational priorities. However, there are overarching national airspace system objectives, such as access, capacity, efficiency and equity, that must be agreed upon and met. To manage the complexity of future collaboration scenarios and enable sufficient data sharing between stakeholders, it will be necessary to further distribute CDM and to decentralize its supporting technologies. This will allow users and stakeholders to pursue individual performance goals while still meeting system-level objectives.

1.2 One benefit of further distributing decision-making in CDM is better representation of operators' interests. For traditional flight operators, predictability and flexibility are increasingly important relative to minimization of expected delays. For emerging operators without scheduled service, this is even more true. Further distribution of decision-making would also allow trade of resource access rights, which can improve the Pareto efficiency of allocations.

1.3 The field of normative economics suggests design principles to be adopted in further distributing CDM. One is to use rights rather than directives to coordinate access to resources. A second is to enable trade. Opportunities for trade should be made large by adding dimensions to the trade space and made discoverable by allowing operators to express their preferences richly. The basis of claims to access rights should be clear where appropriate (e.g., ration by schedule) and equal budgets are useful constructs to resolve further allocation fairly.

1.4 A decentralized information sharing architecture will be needed to effectively execute distributed decision-making in the future national airspace system. Due to the anticipated diversity of operations, an appropriate decentralized architecture must be scalable, flexible, and reconfigurable, so that the needs of various stakeholders can be met at every level of the national airspace system. This is more easily achieved within a decentralized architecture where loosely connected components can be reconfigured based on local needs without causing disruptions to the system. Decentralized information sharing supports distributed decision-making by enabling stakeholders to make timely and informed decisions, while relieving the FAA from data and tool provisioning. New technologies, such as blockchain, can facilitate such an architecture in such a way that ensures data transparency, data privacy (when warranted as with proprietary information), and real-time information sharing between stakeholders, while still enabling the FAA to oversee the larger coordination process.

1.5 One type of decentralized architecture – blockchain technology – can provide a secure platform for data sharing among stakeholders through its attributes of transparency, traceability, and immutability. The use of blockchain can also enhance the trustworthiness of the system, as all transactions and data exchanges are verifiable, which promotes cooperative behavior and adherence to regulations. Furthermore, the nature of blockchain as a distributed ledger technology promotes decentralization through transparency, data redundancy, and traceability. Self-executing “smart contracts” can enforce arbitration and negotiation processes in a decentralized CDM system, which could lead to more efficient decision-making and conflict resolution, thereby reducing the need for a centralized authority. Furthermore, smart contracts can play a crucial role in trading mechanisms, allowing airspace users to rapidly adjust their route choices without awaiting central approval. This ensures timely responses to changing conditions, which enhances the overall efficiency and responsiveness of the system. In the context of distributed CDM, smart contracts can be used to automatically execute resource offers or trades when certain conditions are met. Such automation can reduce administrative burdens and increase the efficiency of resource management.

2. DISCUSSION

2.1 A 2023 study explored several mechanisms by which CDM could be further distributed according to design principles from normative economics and leveraging block chain technologies.[1] The remainder of this paper summarizes those mechanisms and results of experimentation. This study is part of on-going research about improving system performance with CDM and is not presently scheduled for implementation.

2.2 The following mechanisms use a generalization of the slot concept called “permits”. Like slots, permits are initially allocated via a traffic management program for a congested resource. A permit grants its holder the right to access the resource during some short time window (e.g., of five-minute duration). There may be multiple permits per time window. When a program revision is necessary, permits persist but may move to other time windows. In this movement – forced if moved later, optional if moved earlier – permits are prioritized by time window and then rank within each window. Figure 1 shows an

[1] P. Kuzminski, “Further Distributing Collaborative Air Traffic Management”, ICAO Air Navigation World 2023, Montréal, Canada, The MITRE Corporation, August 31, 2023.

example of how permits might be defined for a resource suffering an anticipated capacity reduction and how those permits would be initially allocated according to ration by schedule.

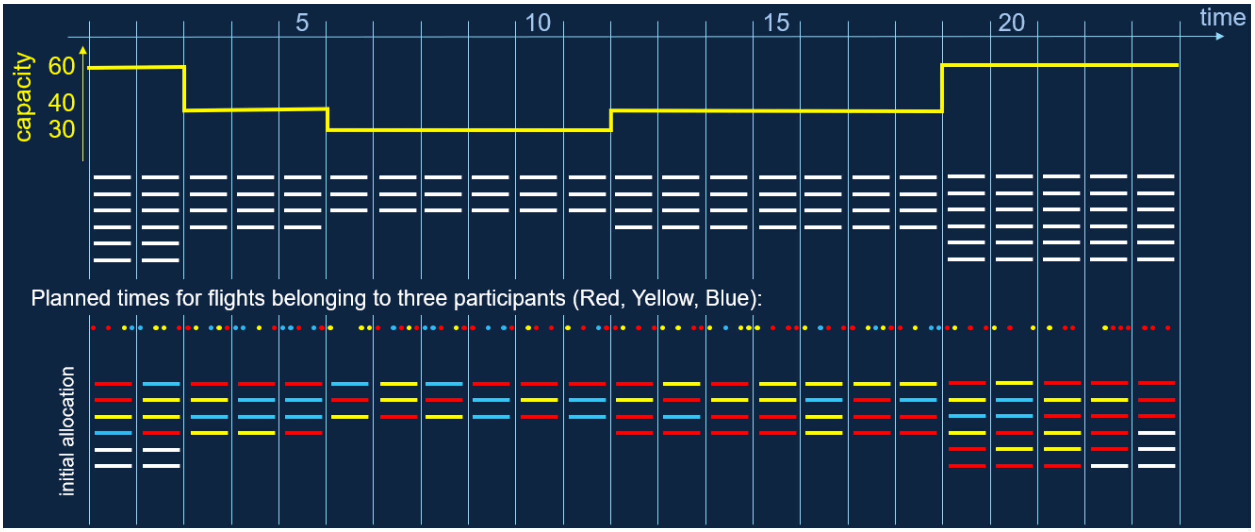

Figure 1. Example of permits defined and allocated for capacity-constrained resource.

2.3 Flagging is a mechanism by which program participants can indicate the importance of some flights, thereby minimizing their delays in an initial ration by schedule allocation of permits. Consistent with the equal budget principle, participants are each given, before initial allocation, a number of flags proportional to the number of flights subject to the program. The participants place one or several flags on flights of particular importance to them. The program then proceeds with ration by schedule in rounds, allocating permits first to those flights with the most flags, then to the next most, etc. Flights with more flags secure earlier permits than they would without flagging.

2.4 Pinning is a mechanism by which permit holders can stabilize the time windows to which a permit grants access to a resource. Again, program participants are given a budget of pins proportional to their number of flights in the program. Any time after initial allocation of permits, pin holders can place one or more pins on their permits, and readjust as they see fit. In the event of a program revision, permit movement would be prioritized first by number of pins, then by time window and rank as without pinning. Permits with more pins are more stable during program revisions.

2.5 Trading allows permit and pin holders to dynamically balance their operational interests and to achieve pareto improvements in the allocation of access. In this mechanism, participants craft and post offers to relinquish packages of held pins and permits conditional on receipt of other packages. A broker identifies and selects compatible trades, which are executed automatically. The intent is that a participant could improve the situation for some of its flights by incurring some sacrifice for others, but only subject itself to net beneficial trades.

2.6 To explore the benefits of flagging, pinning, and trading, some experimentation was done with simulation. The capacity of a single resource was forecast at various moments in the simulation, each time as a function of the average of weather forecasts whose uncertainty decreased over time. Participants' preferences for when their flights could use the resource were modeled as piecewise linearly increasing functions of delay. Participant models identified and posted all net beneficial trade offers for which two permits would be exchanged for two permits. A program model implemented allocations of permits, pins, and flags as above. A broker model identified and selected multilateral trades according to a mathematical program that maximized participants' reported benefits for trade offers.

2.7 Various scenarios were the subjects of experimentation. They represented the use of flagging, pinning, or trading permits individually and multiple trials varied weather and flights' costs of delay.

2.8 The experimental results supported several conclusions. Flagging had the most direct effects, with unflagged flights obviously paying the price in the zero-sum setup. Operators with later flights in a program benefitted more and the effect of flagging was more prominent with smaller flag budgets. The stabilizing effects of pinning were very direct as well. Delay and cost savings turned out to be negligible in most scenarios but were substantial when capacity was reduced dramatically. By design, trading always reduced costs – usually modestly, but again substantially with large capacity reductions. The worse capacity situations also saw more trading activity, suggesting that distributing decision making to participants aware of costs, rather than just delay, becomes more beneficial as problems become more severe.

2.9 In the experiments, a Docker-based blockchain network was created using Hyperledger Besu, an open-source Ethereum client. This network simulated a real-world blockchain environment, with separate containers representing physical nodes for the host (representing the FAA) and each of three flight operators. The host container was tasked with setting up the initial state of the blockchain, generating and distributing public and private keys for operators to join, and deploying two smart contracts. The first contract functioned as an interface for data storage, permitting the host to publish and share information about the current state of the system with operators, who used the information to generate their trade offer sets. The second contract implemented the broker, detecting compatible offers and automatically executing those selected. Altogether, the simulation demonstrated the feasibility of using smart contracts on a blockchain to realize brokered, but decentralized, exchange of permits.

3. **CONCLUSION**

3.1 Modeling and experimentation showed that the flagging, pinning, and brokered trading implementations of normative design principles for distributed decision-making show promise. They exhibited the intended stability effects and, especially in very poor capacity situations, substantially reduced costs relative to baselines without these mechanisms. Despite the very large trade space possible, a simple restriction to two-for-two trade offers proved beneficial as well as manageable for participants and the broker.

3.2 A few variants and refinements on the mechanisms explored by this study are worthy of exploration as well as the sophistication of models used. Two items deserve particular attention. The first is how to limit readjustment of a pin just before its permit's time window. The second is how participants might choose to withhold less beneficial offers. Extensions of the concepts to various applications are also worthy of consideration. Any resource whose demand can be managed via time-based access rights (e.g., arrival and departure runways, vertical touchdown and liftoff areas, airspace, airways, corridors) are possible.

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