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A DIGITAL TWIN FRAMEWORK FOR INTEGRATED AIRLINE RECOVERY

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ABSTRACT

The airline industry provides a critical and connective transportation mode with global economic impact. These movements and connectivity are impaired by disruptions from aircraft maintenance, system delays, weather, and other sources. The integrated airline recovery problem mitigates significant disruptions to an airline's planned schedule. Solution methods require airline operations and passenger itinerary data. Unfortunately, publicly available data are scarce or incomplete. Moreover, these solutions can integrate into a digital twin framework (DT) for airline operations used by an Airline Operations Control Center (AOCC). This study presents a data generation methodology and a DT framework to enable airline recovery.

1 INTRODUCTION

The first solution approach to solve the airline recovery problem utilized a network flow formulation and subsequent literature advanced mathematical programming approaches and integrated the multiple objectives of airline recovery to varying degrees. Recent approaches leverage reinforcement learning (RL) or simulation-based approaches to address scalability and stochasticity (Wu et al. 2025). Moreover, recovery decisions and effectiveness depend on airline network structure (Abdelghany et al. 2004).

2 AIRLINE NETWORKS

An airline's network depends on its operating model, but generally consists of one or a combination of two network types: point-to-point; hub-spoke. Point-to-point networks provide direct travel from an origin to a destination. Hub-spoke networks use hubs that facilitate travel from origin to final destination. The spatial

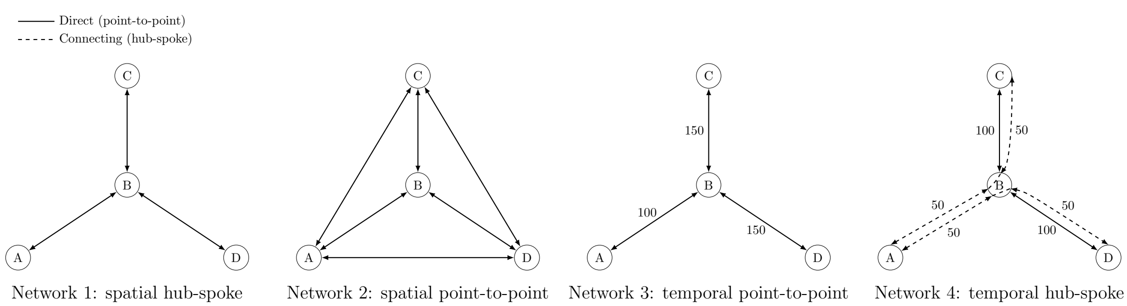

Figure 1: Network configurations adapted from Wu (2016).

configuration of an airline is the concentration of the network around hubs and spokes. Consider Figure 1 where Network 1 implements a hub-spoke approach that requires transit via B to connect A, C, and D while Network 2 directly connects A,B,C, and D for point-to-point travel. Network Connectivity (NC) is a metric computed as a normalized Gini Index that enables comparison of airline networks. Unfortunately, this description of airline networks neglects the spatial and temporal components of airline networks that impact flight scheduling and operations. An airline's temporal network is the configuration of its schedule at airports that result in indirect passenger connections. Consider Network 3 in Figure 1 where aircraft operate only from A, D, or C to B and back. Network 3 operates aircraft arrival and departures without sufficient overlap to enable passenger connections between airports making it point-to-point. Network 4 operates aircraft arrival and departure in a banked structure that enables passengers originating at airport A and connecting through B to travel to their final destination, making it hub-spoke. The Hubbing-Connectivity Index (HCI) metric describes passenger flows and temporal connectivity (Wu 2016). This study presents a data generation methodology for airline schedules and passenger itineraries across a range of NC and HCI values to enable comparison of solution approaches within a DT implementation for various airline configurations.

3 DIGITAL TWIN FRAMEWORK

The simulation and optimization models underpinning AOCC decision support systems can extend to DT systems to improve operations. This study extends the SimAir framework outlined by Rosenberger et al. (2000) as the basis for simulation within a DT framework. A DT ties a physical object and its virtual representation together with two-way information flows. This connection allows realization of insights and decisions generated in the virtual system in the physical object. In addition, DT implementations monitor a system as it evolves over time (Walton et al. 2024). This study presents the DT framework illustrated in

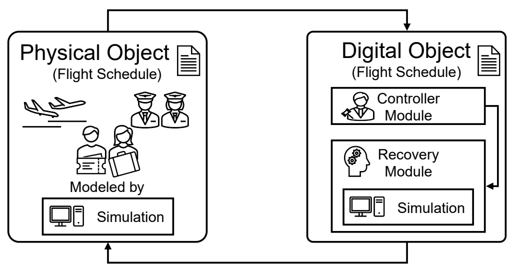

Figure 2: Airline DT Framework.

Figure 3. The physical object is the airline's current and active flight schedule. Schedule changes arising from aircraft arrival and departure as well as long-term disruptions update the DT. The DT's controller module assesses the requirement for recovery and queries its recovery module for solutions over a recovery horizon. The recovery module simulates the schedule forward and updates the physical object's flight schedule. This study utilizes simulation of the physical object that executes a flight schedule generated utilizing the methodology in Section 2. A deterministic recovery solution is implemented to assess the effectiveness of the DT recovery module to enable AOCC operations with the required solution quality and speed.

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