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Terminal Maneuvering Area Design Tool: Translational Research in Aviation

Peter Jackson and Nuno Antunes Ribeiro
Engineering Systems and Design Pillar
Singapore University of Technology and Design
Singapore 487372
nuno_ribeiro@sutd.edu.sg

Abstract

Translational research focuses on bridging the gap between pure research and practical applications, often involving the development of prototypes for real-world use. In this paper, we use a systems engineering process including rapid prototyping, system architecture modeling, and user testing to translate research in optimization-based simulation of terminal airspace traffic from technology readiness level 3 (TRL 3) to TRL 6 (full-scale prototype demonstration). We deliver an analyst-ready tool for conducting design and evaluation studies in response to airspace restriction events. The paper provides a valuable framework for future translational research efforts in academic environments.

Keywords
Translational research, system architecture modeling, airspace design, optimization applications

Introduction
The terminal maneuvering area around an airport is typically defined in terms of Standard Instrument Departure (SID) and Standard Instrument Arrival (STAR) routes which connect the airport to the en-route airspace. The high-level problem statement for this research is on how to re-design the terminal airspace for an airport and evaluate the performance of that design if a portion of the airspace becomes unavailable for some reason. This may happen due to weather systems, or forest fire plumes. Alternatively, even with the full airspace available, traffic volumes may increase to the point of requiring additional or modified routes (SIDs and STARs) to cope with the volume. The importance of this work is two-fold: we provide an analyst-ready tool for conducting such studies and we establish valuable patterns for conducting translational research in academic environments.

Objectives
The objective of this translational research was to take a research concept in airspace design evaluation from technology readiness level 3 ("validate critical properties and predictions using non-integrated software components") to level 6 ("Prototype implementations of the software demonstrated on full-scale realistic problems") (NASA 2017). Our vision was to provide an analyst-ready integrated tool to support the re-design of terminal airspaces by following a structured systems engineering approach.

2. Literature Review
Validating an airspace design typically requires a *high-fidelity* simulation of the design with representative flight schedules, physics-based aircraft trajectories, accurate arrival and departure sequencing, and mimicking of controller decisions to set approach speeds, vector aircraft, or to place aircraft into holding patterns. Commercial software such as AirTOP (AirTOP 2024) is specialized to support the development of such high-fidelity simulations. The challenge is that such development can take weeks of an analyst's time (Odoni et al. 1997). Another approach is to use optimization-based simulation which can quickly evaluate an airspace design. These approaches are often referred to

as low-fidelity, or macroscopic, to acknowledge that they cannot accommodate idiosyncratic arrival and departure sequencing algorithms or controller rules of behavior in the way of a high-fidelity simulation model (Stamatopoulos et al. 2004). Nevertheless, using optimization, aircraft trajectories can be adjusted to accomplish runway sequencing, maintain separation of aircraft at waypoints, and make vectoring and holding decisions. Such an optimization-based simulation approach, therefore, can estimate the general pattern of delays that are likely to occur as a given flight schedule is imposed on a particular airspace design.

Most existing optimization-based literature focuses on runway sequencing (see Ikli et al. 2021 for a detailed review) and extending this to consider constraints in the terminal maneuvering area (TMA) is relatively new. The initial approach, involving a mixed-integer linear programming (MILP) model, was introduced by Capozzi et al. (2009). While effective for small-scale problems, this approach faced computational challenges with larger flight numbers. Subsequently, Samà et al. (2015) introduced a novel, efficient MILP formulation using generalized disjunctive graphs, later extended to include departures and taxi operations (2018). More recently to handle more realistic instances, simulated annealing and tabu search have been employed in several studies aiming at optimizing aircraft speeds and runway sequencing (Samà et al. (2017), Ma et al. (2019), Huo (2022)). Our recent work (Ng et al. 2024) proposed a novel matheuristic algorithm (TMAOpt) that expands decision-making beyond speeds and sequencing to include holding patterns, vectoring, and point merges, approaching the detail level of an AirTOP model.

Despite advances in the development of optimization algorithms for rapid analysis of terminal maneuvering area scenarios, the transition from these algorithms to an analyst-ready tool for conducting such studies has remained unexplored. More generally, the step of translating pure research into practical applications is often overlooked in the literature, despite its considerable importance. This concept, known as translational research, is predominantly associated with biomedical sciences (see Woolf, 2008). However, the principles and ideas of translational research are applicable across various fields. This paper aims to contribute to the broader application of translational research principles to aviation, specifically by leveraging the TMAOpt algorithm developed by Ng et al. (2024).

3. Methods

3.1 System Architecture

Figure 1 is a context diagram sketching the basic capability of the proposed tool. It takes as input a given flight schedule, the flight characteristics of different equipment types (to establish speed profiles), and the required separation times at runways and waypoints. The analyst presents a scenario of available runways, waypoints, and runway direction, and a particular design of SIDs, STARs, and holding areas. The output is similar to the output that could be produced by a comparable AirTOP model, with bar charts summarizing arrival and departure delays and holding area usage. The algorithm would be TMAOpt, the optimization model provided by the methodological research group (Ng et al. 2024).

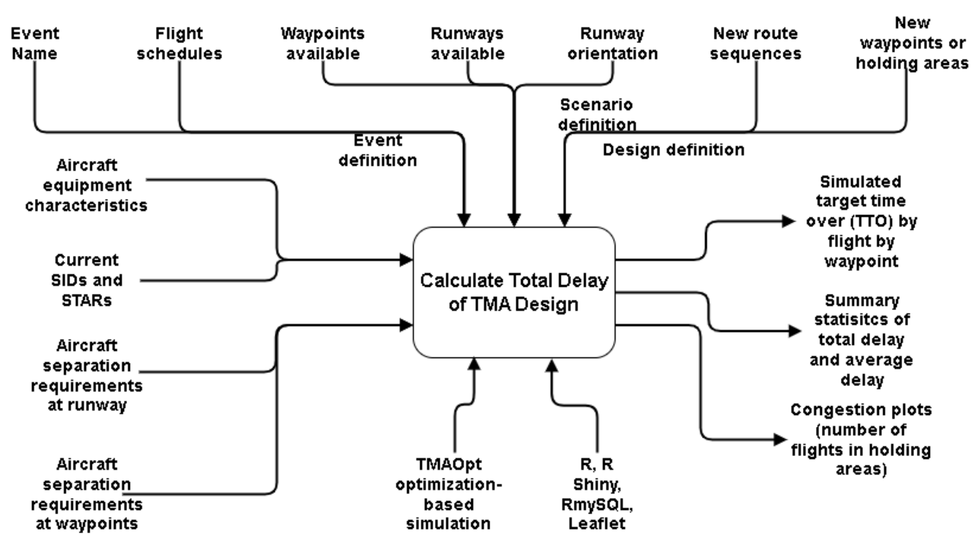

Figure 1. Context for Terminal Maneuvering Area Design Tool

Following Arikan and Jackson (2023), we used the open-source Capella System Architecting software to document the use cases, functions, processes, responsibilities, and database design of the proposed TMA Design Tool. Figure 2 describes the use case capturing two stakeholders: the TMA Manager who identifies the need for a new airspace design and who selects a particular design for approval, and the TMA Designer who is responsible for generating designs, estimating their performance, and submitting comparison studies to the TMA Manager for selection and approval. We imagined that the hosting platform would provide ancillary services and the TMA Design Tool would provide a service to the hosting platform by publishing airspace designs for further analysis. We planned for the development of our own database to provide the "ancillary services". In the spirit of supporting a platform approach, however, we planned to house all functions accessing this database in a separate interface module.

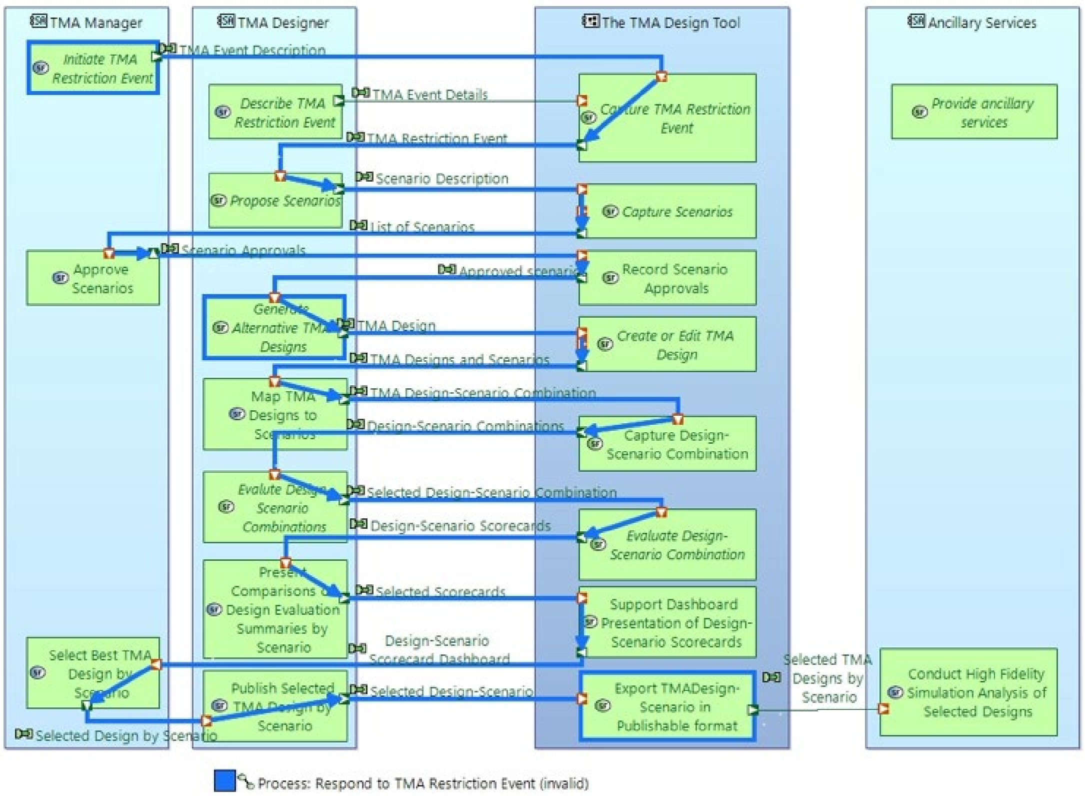

Figure 2. Use Case Analysis for Terminal Maneuvering Area Design Tool

Starting from this use case, we developed a functional hierarchy and a logical architecture for the TMA Design Tool. That enabled us to have a clear plan for the data requirements which we documented in the form of a database design. Figure 3 is a class diagram which represents our initial database design for capturing the concept of terminal airspace restriction events and scenarios. Figure 4 is a class diagram for capturing the concept of a terminal airspace design, specific to a scenario. Figure 5 is a class diagram for capturing the concept of a trajectory which the simulation will update and use to estimate system delays.

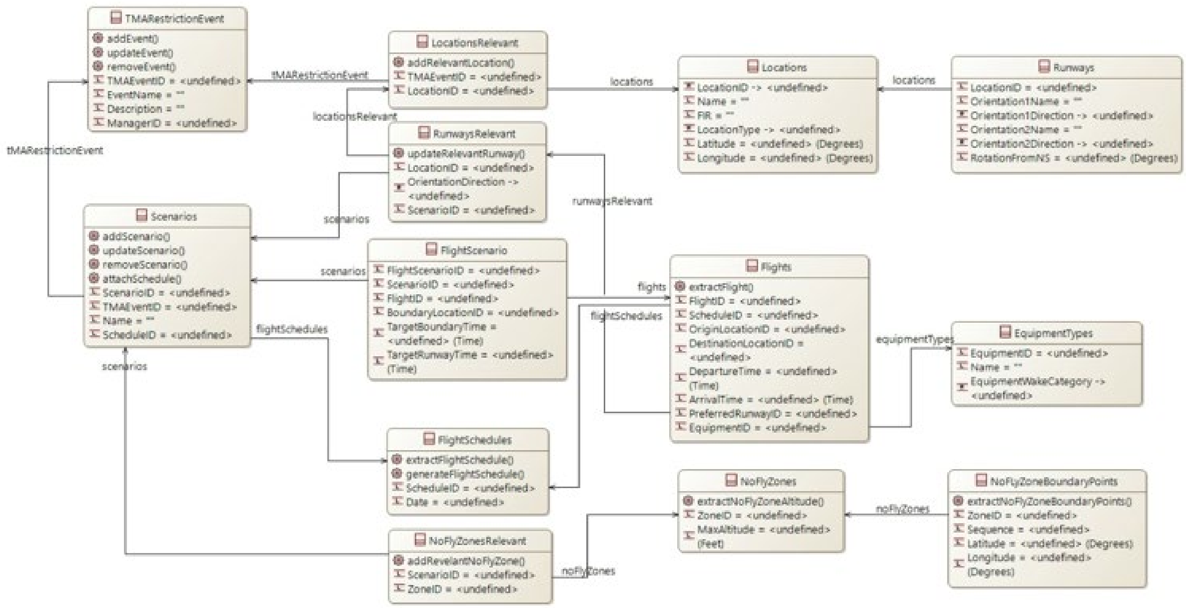

Figure 3. Initial Database Design for TMA Design Tool: Scenarios

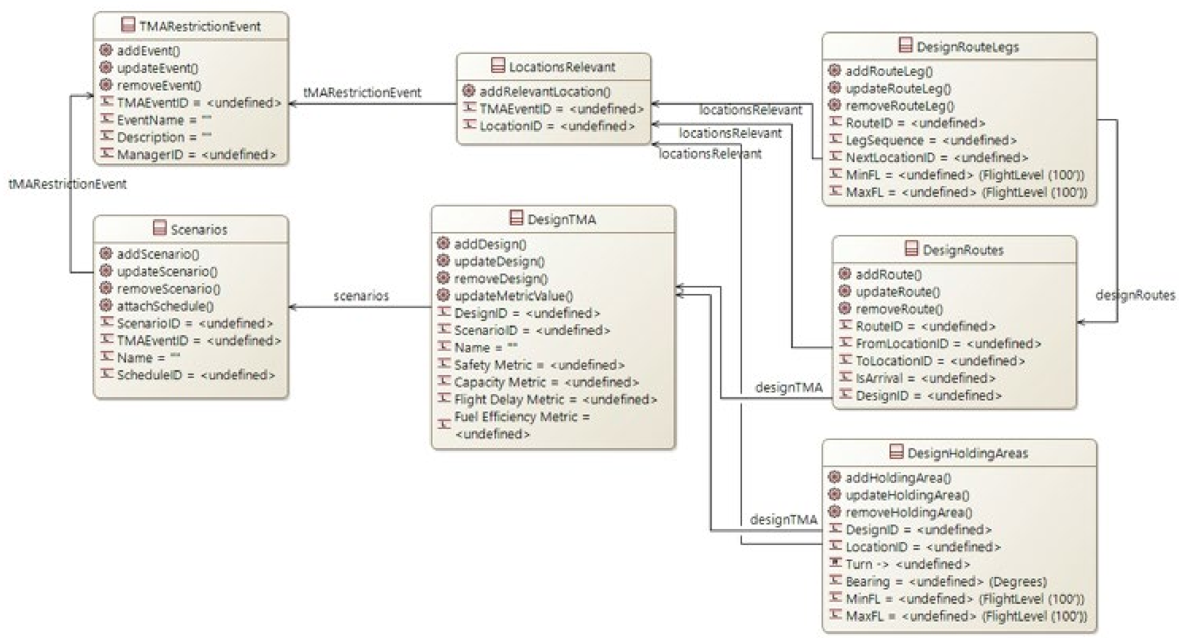

Figure 4. Initial Database Design for TMA Design Tool: Designs

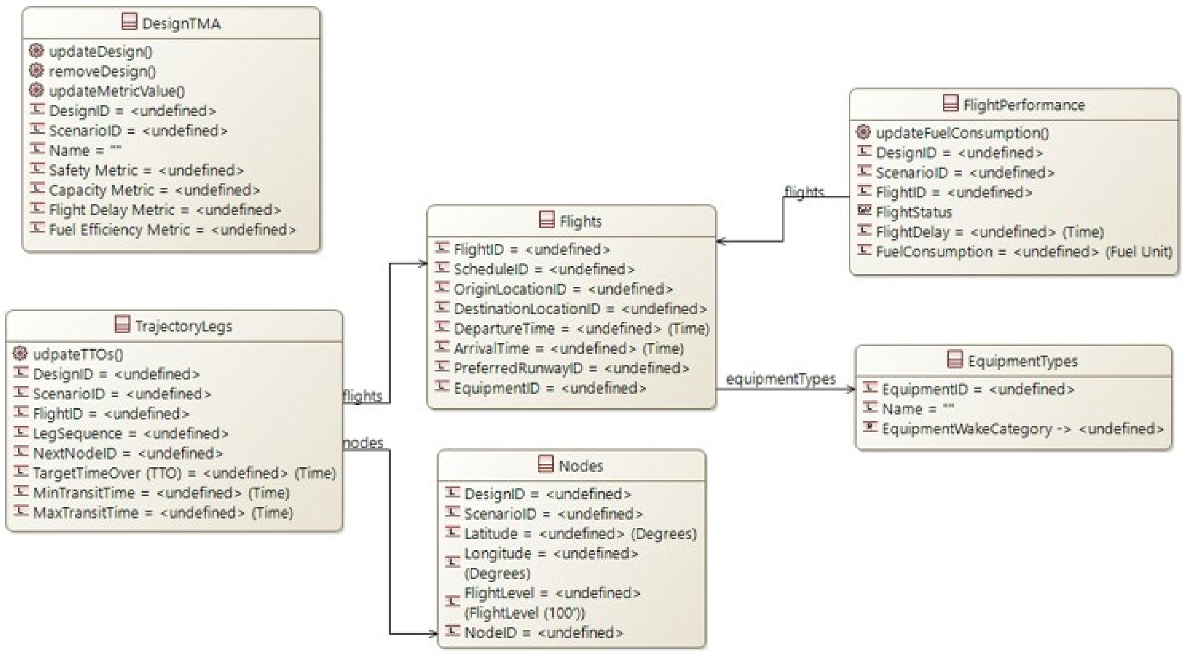

Figure 5. Initial Database Design for TMA Design Tool: Trajectories

An interactive version of the system architecture document is available online (Aviation Studies Institute system architecture documents 2024).

3.2 Application Framework Decisions

The TMA Design Tool has been constructed using R Shiny with a MySQL database. Except for SQL files to initialize the database, virtually all the code is written in the R scripting language. The code makes extensive use of packages obtained from public sources. The code is highly modularized and resides in structured subdirectories of a single file folder. The user interface is innovative in that many individual data objects such as airspace restriction events, scenarios, waypoints, no-fly zones, airspace designs, and routes are displayed on the webpage as individual control blocks with their own visual editing components. Installing the code on a workstation is simply installing the supporting software (R, R Studio, and MySQL) and launching the app scripts. Database operations are conducted using a separate interface module to be conducive to integrating with a platform or other applications.

3.3 Structured Workflow

As per the system architecture, the workflow for the analyst starts with the identification of an Airspace Restriction Event (e.g., due to convective weather). This is a folder to capture design and simulation studies around a particular event. As an example, we imagine the need to avoid waypoint GGGG which lies on several STARs into Singapore Changi Airport. The database we use pre-dates important changes which occurred on 21 Mar 2024. All diagrams and results use generic terms and are for illustrative purposes only. Within the event folder, the analyst can create multiple scenarios. The analyst uses a scenario to specify which runways are in use and their orientation (Figure 6), the flight schedule of arrivals and departures, and no-fly zones which mark which waypoints are inaccessible (Figure 7). Then, for each scenario, the analyst can create multiple designs for evaluation. Each design will specify a revised set of SIDs and STARs which avoid the restricted waypoints. For example, Figure 8 shows that the route from CCCC currently passes through waypoint GGGG. The waypoint is shown in red indicating that the analyst must delete it from the STAR and find an alternative route. As an example, the analyst may re-route to the north (Design A) or to the south (Design B). The next step in the workflow, after completing the route designs, is to evaluate each design using the TMAOpt optimization-based simulation. When the simulations are complete the analyst can compare the results. For example, Figure 9 displays summary statistics on average and total delays between the two designs for this scenario. The lower bars reflect the simulation for Design A (Workshop Design 02A) routing aircraft to the north of GGGG with arrival delays in yellow and departure delays in blue. Total delays are shown on the left and average per flight on the right. The upper bars reflect the simulation for Design B (Workshop Design 02B) routing aircraft to the south. Design A, routing to the north, has slightly lower delay for this scenario. This is likely just a consequence of the additional distance for the southern routes and not any congestion effects. Other plots, such as Figure 10 which shows usage of the holding areas, allow a deeper dive into the simulation results. Thus, with a largely point and click interface, the analyst can explore a wide variety of design challenges and run quick simulations to identify the best candidates for implementation.

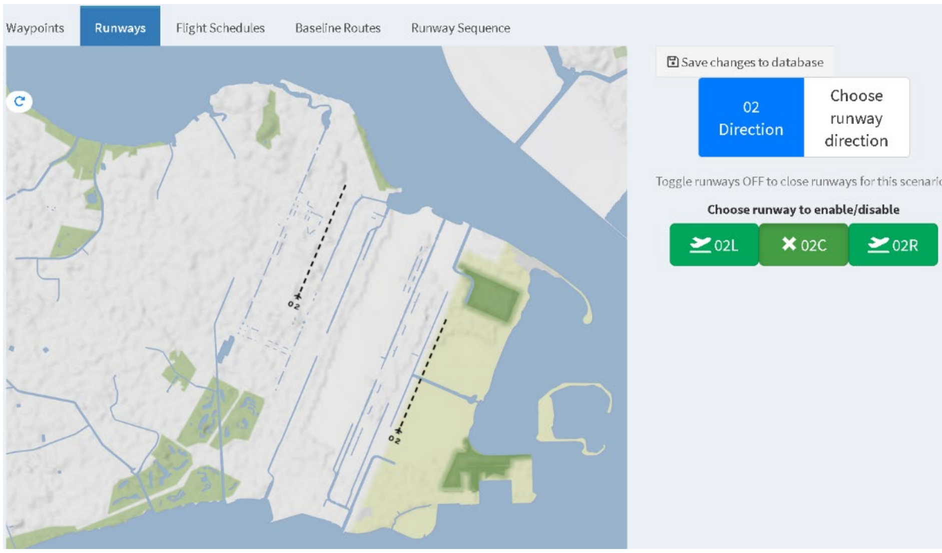

Figure 6. Interface to select runways and runway direction.

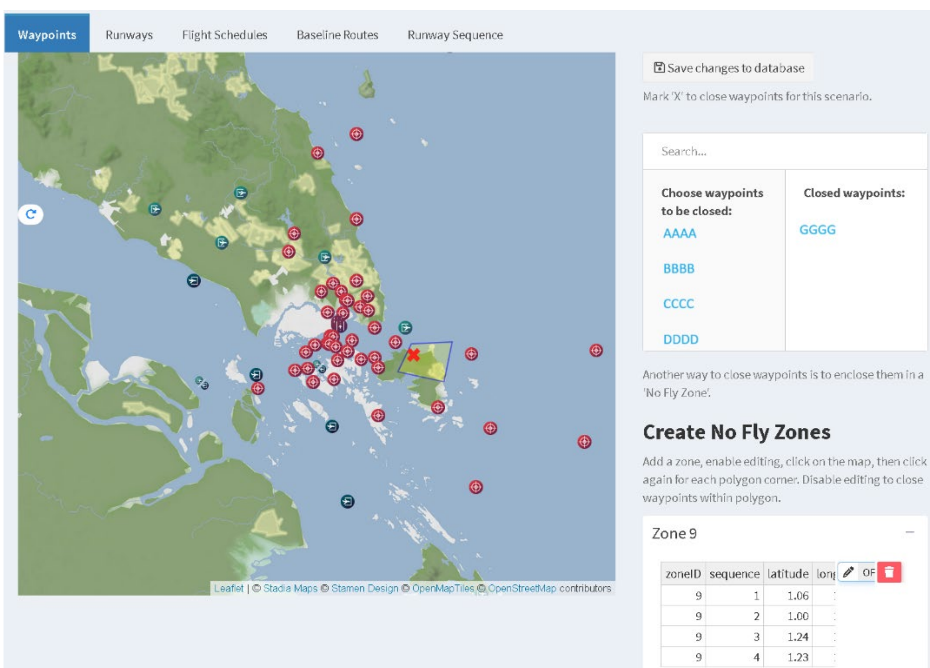

Figure 7. Interface to create no-fly zones.

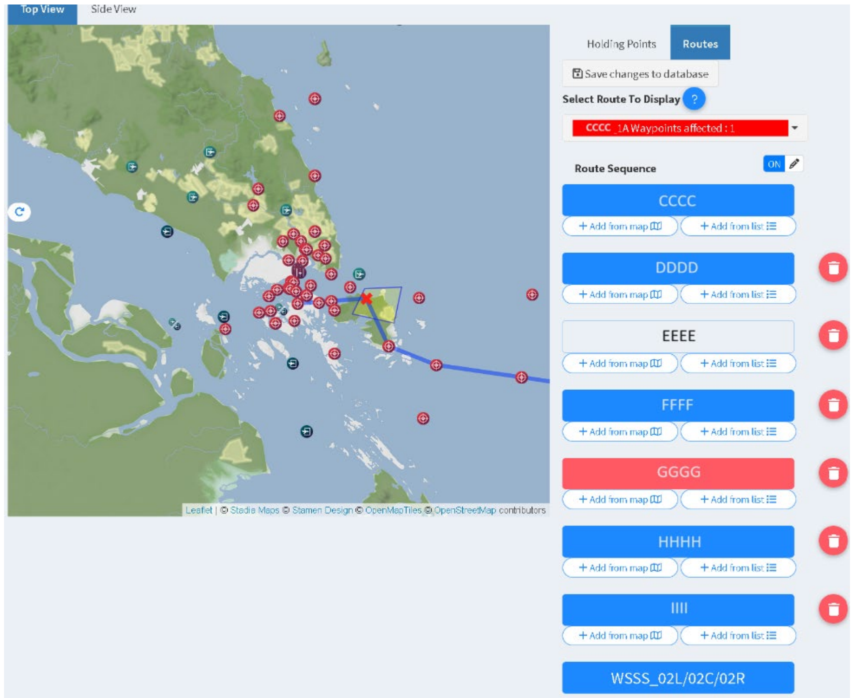

Figure 8. Interface to modify routes.

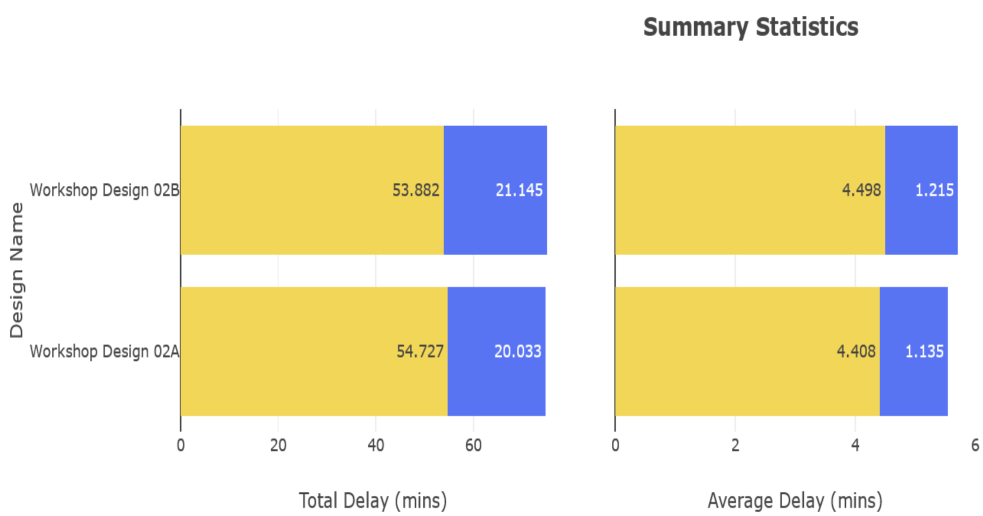

Figure 9. Summary statistics for arrivals (yellow) and departures (blue) comparing two designs, A and B, for the given scenario.

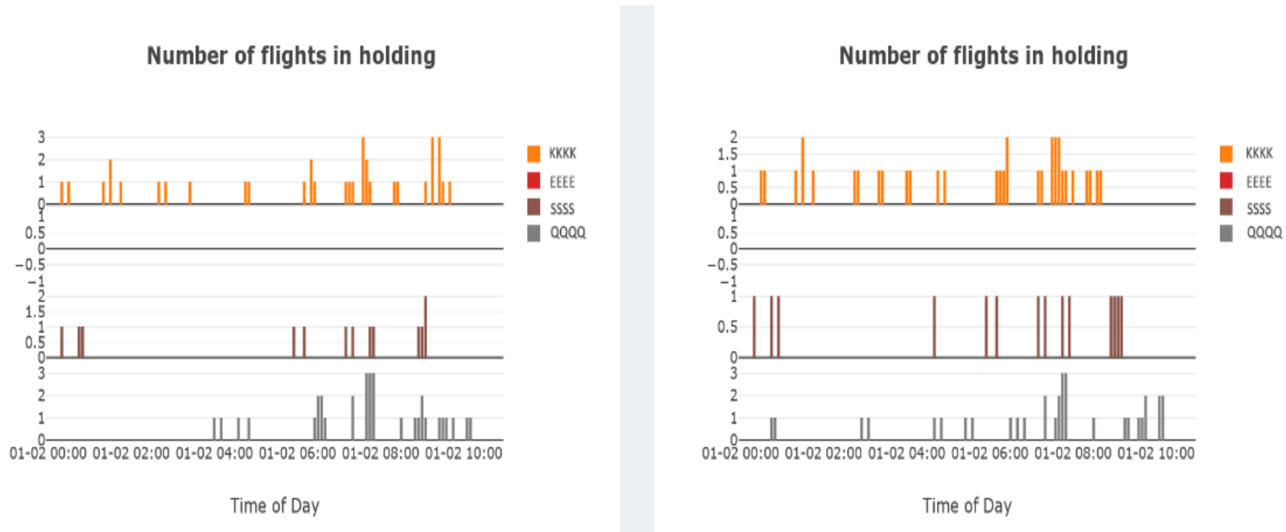

Figure 10. Simulation details (flights in holding areas) for comparison of two designs, A (left) and B (right). Time is represented as MM-DD HH:mm (UTC).

3.4 Rapid Prototyping

During the process of developing the system architecture for the TMA Design Tool, we employed the design process known as rapid prototyping. We developed a game, called the Airspace Design Game, to capture our understanding of the airspace design problem as we understood it from our discussions with subject matter experts.
We mention it here because of its strong influence on the development of the TMA Design Tool.
In the Airspace Design Game, participants are given an initial airspace design (SIDs and STARs) that are flawed. These flaws are flagged as 'safety issues':

- Flight paths must not have sharp turning angles,
- Flight paths must not enter holding patterns at sharp angles, and
- Flight paths must not cross each other except at waypoints (where vertical separations can be applied).

Participants are given the task of revising the routes (through a drag and drop interface) to eliminate all the safety issues. They then proceed to a side view of the airspace and adjust the flight levels for each route at each waypoint to optimize a fuel efficiency score. Finally, the participants are presented with a trade-off between throughput and queueing delay, and they choose a flight acceptance rate to optimize this trade-off. An overall score is computed (with 100% safety being required) and participants compete for the highest score. As a further reward of their efforts, the game automatically runs an optimization-based simulation of the flight schedule and presents the participant with a 3D Cesium (2023) animation of all arriving and departing flights, including their use of holding areas, as shown in Figure 11.. Participants leave the game after a one-hour workshop with the understanding that airspace design is a fascinating multi-dimensional challenge.

Figure 11. Cesium animation of flights for a particular design of Auckland airport airspace design (The Airspace Design Game**).**

We also supplemented the game to present a holographic view of the 3D animation using the Looking Glass (2024) display for demonstration purposes. These displays do not require headsets and are suitable for public events.
We used the Airspace Design Game to check our understanding of the issues with subject matter experts. We have also run multiple workshops and public demonstrations as outreach events to interest prospective students in pursuing aviation studies.

4. Data Collection

We hosted a workshop in February 2024 attended by ten air traffic controllers and operation analysts in which they exercised the tool on pre-generated test cases. Feedback for the workshop was positive and we collected numerous suggestions for improvements to the user interface. One of the chief requirements which emerged was the need to extract a spreadsheet file of the results of the analysis to permit the users to combine, explore and publish the results using other media. Another discovered requirement was the need to allow the users to add new waypoints. The tool now features both these capabilities.

5. Results and Discussion

Academic research is often not product focused. It seeks to solve what is perceived as the fundamental technical challenge, but it leaves to others the challenges of delivering solutions in usable form. A typical research project will often stop at technology readiness level 3 (“Proof of Concept”). At the Aviation Studies Institute (ASI) at the Singapore University of Technology and Design (SUTD), we have taken on the challenge of carrying several of these proofs of concept to technology readiness level 6 (“Prototype demonstration in a relevant environment”). On the one hand, we claim success in delivering the tool for this project at TRL 6 while, on the other hand, we acknowledge the difficulties universities experience in these translational research efforts. In particular, we underestimated the difficulty of converting the algorithmic research into the modularized and generic form of code required for integration into the TMA Design Tool. In future efforts, we would recommend early engagement with researchers on both the front end and back end of tool development projects to agree on data flows and functional hierarchies.

6. Conclusion

This paper documents the successful translation of a sophisticated algorithm for the estimation of delays in terminal maneuvering areas into an analyst-friendly tool for evaluation of alternative airspace designs. The use of system engineering techniques such as rapid prototyping, system architecture modeling, and user testing contributed to the success of the implementation. The online system architecture document is useful for case studies in systems engineering: it features the progression of analysis for this tool from Operational Analysis, through System Analysis, to Logical Architecture and includes database design as well.

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Biographies

Peter Jackson is a Professor in the Engineering Systems and Design pillar in the Singapore University of Technology and Design where he serves as Director of the Aviation Studies Institute. He also served as Head of Pillar at SUTD from 2016-2022 and is a Professor Emeritus of Cornell University. He currently leads research in air traffic regional collaboration within the Southeast Asia context, but he has numerous papers in production planning, multi-echelon inventory planning, and supply chain management. As the former Director of the Cornell University Systems Engineering Program, he led the introduction of its online M. Eng. degree program in systems engineering. He is the author of an introductory text on systems engineering, *Getting Design Right: A Systems Approach*. He is also a celebrated instructor of industrial engineering and the creator of dozens of experiential learning games and tools.

Nuno Ribeiro is an Assistant Professor in the Engineering Systems and Design Pillar at the Singapore University of Technology and Design (SUTD). Before joining SUTD, he earned his Ph.D. in Transport Systems from the University of Coimbra in Portugal (2019). During his doctoral studies, he gained valuable insights through visiting research positions at prestigious institutions such as MIT (2016) and Carnegie Mellon University (2017). His specialization in the field of Operations Research methods applied to aviation studies has garnered recognition from both academia and industry. His contributions have been honored with several awards, such as: (i) the Ana Valicek Silver Medal from the AGIFORS in 2018 for his work on Airport Slot Scheduling ; (ii) the Best Paper Runner-Up award from the ATRS in 2022 for his work on Passenger Demand Modeling in Air Transportation; (iii) the Best PhD dissertation (2019), Best Research Paper (2021), and Best Presentation (2023) awards from INFORMS-AAS for his work on Airport Capacity Management and Optimization of Terminal Airspace Operations. Nuno is currently the Secretary/Treasurer of the Aviation Application Section of INFORMS and an Editorial Board Member of the Journal Transp. Research Part C: Emerging Technologies.