Advanced Air Mobility as an Electric Grid Demand Response Asset

Purdue University

Team Members

Nick Gunady
MS Aerospace Engineering

Seejay Patel
BS Aerospace Engineering

Sai Mudumba
MS Aerospace Engineering

Akshay Rao
MS, Mechanical Engineering

Ethan Wright
BS, Aerospace Engineering

Faculty & Industry Advisors

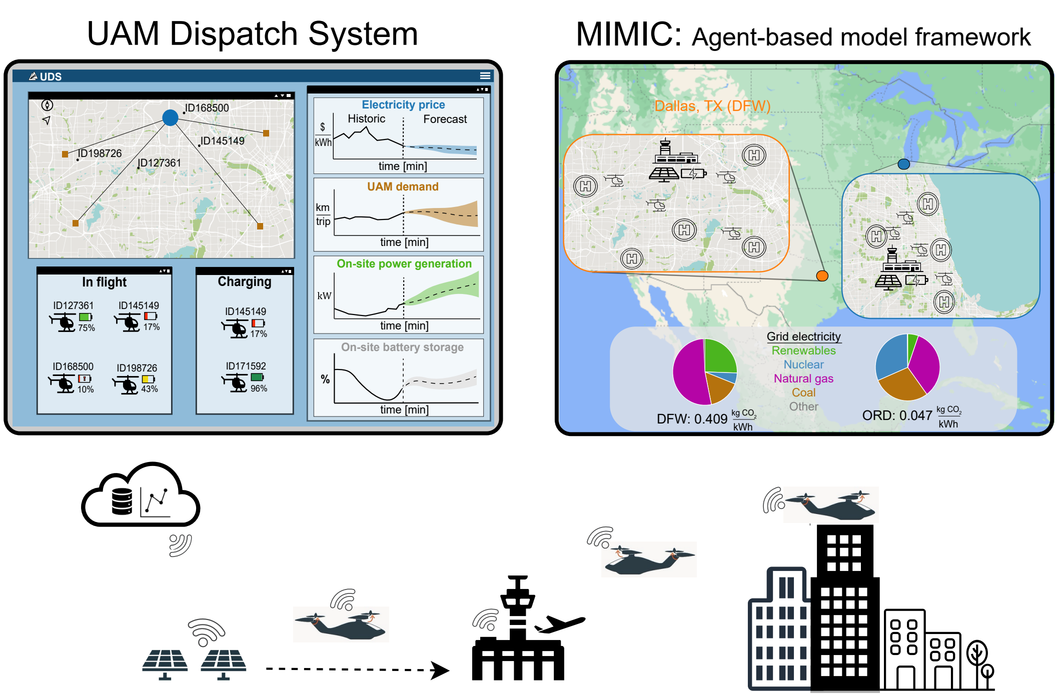
Daniel DeLaurentis
Distinguished Professor
Purdue University

Heather Salah Wood
Senior Engineer
American Airlines

Ana Del Amo
Research Engineer
GE Aviation Systems

Shaoshuai Mou
Associate Professor
Purdue University

Dale Miller
Chief Consulting Engineer
GE Aviation Systems



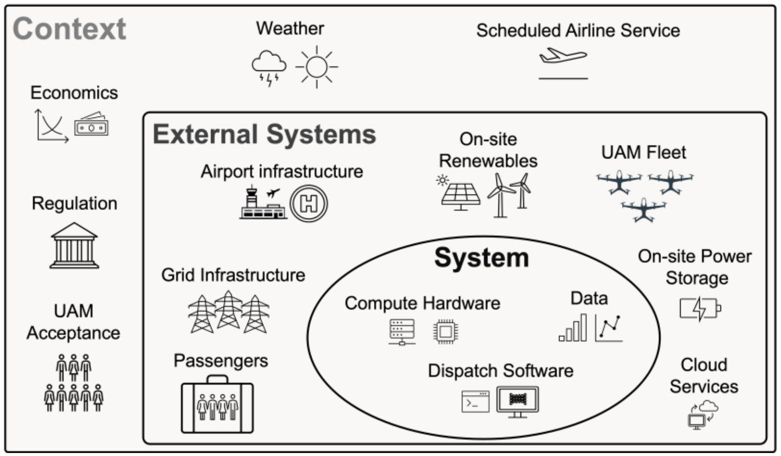
Advanced Air Mobility as an Electric Grid Demand Response Asset

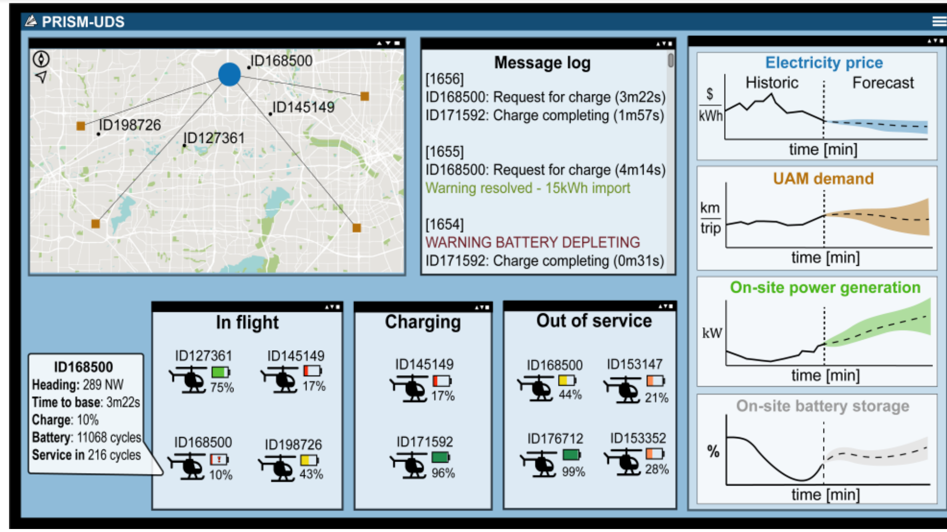
A system-of-systems approach for decarbonization and electric grid services

PURDUE UNIVERSITY

Objective & Approach

We aim to address future energy in advanced air mobility (AAM) operations through UDS -- a software product for optimal resource management, and MIMIC – a simulation platform scientific study.





UDS aids operators in making decisions by processing, analyzing, and visualizing available data resources. The software may be implemented with varying levels of autonomy and customized to help reduce operating costs and emissions, without sacrificing passenger throughput.

Project Team & Support

Nick Gunady
MS Aerospace

Akshay Rao
MS Mechanical

Ethan Wright
BS Aerospace

Sai Mudumba
MS Aerospace & Electrical

Seejay Patel
BS Aerospace

Dr. Daniel Delaurentis
Professor of Aerospace Engineering, Director of i-GSDI, Chief Scientist of the DoD SERC

Dr. Shaoshuai Mou
Associate Professor of Aerospace Engineering, Director of the Center for ICON

SAN DIEGO INTERNATIONAL AIRPORT. GE Aviation American Airlines

Schedule & Cost

Q2 '22 – Q2 '25	Q3 '25 – Q1 '28	Q2 '28 – Q4 '31	Q1 '32 – Onward
Phase 1 Development Product iteration, technical development, and certification	**Phase 2 Deployment I** Beta testing and deployment with early customers	**Phase 3 Deployment II** Product roll out, expand functionality, and enhance analytics	**Phase 4 Expansion** Explore emerging AAM operations, including RAM and cargo

UDS for solar may cost from $5,000 to $500,000 based on the deployment complexity. Software development costs may be lower when considering other energy sources. Cost estimates for external systems infrastructure are further described in the report.

Onsite solar power	Beta version	Full functionality
100 kW	$4,800	$165,500
200 kW	$9,500	$331,100
300 kW	$14,300	$496,600

Executive Summary

Advanced Air Mobility (AAM) and Urban Air Mobility (UAM) are a multi-billion dollar industry that is expected to disrupt passenger and cargo transportation with electrified air vehicles. Current energy infrastructure is not prepared to handle the significant load increases of UAM on-demand mobility operations. Yet, UAM operations will likely commence far sooner than major energy infrastructure upgrades can be implemented. To practically deploy UAM operations, new systems and infrastructure must be put in place to support the energy requirements and logistics of fleet operations.

Our approach, "Advanced Air Mobility as an Electric Grid Demand Response Asset", aims to extend the functionality of UAM vehicles as a grid-scale battery by strategically charging based on predicted energy supply and trip demand. We aim to provide our customers, UAM operators, with the ability to safely and cost-effectively manage dispatching vehicles and interfacing with grid and on-site energy sources. With MIMIC - our novel modeling framework - we can answer questions about network design and system sizing for UAM vehicle manufacturers and airlines. UDS - our proprietary dispatch software - is built and tested with MIMIC to optimize vehicle operations and power allocation.

Stakeholder conversations with Supernal, GE Aviation Systems, and American Airlines, informed design features for MIMIC and UDS. Key features and qualities include the ability to generalize to diverse energy sources, reliability and backup modes, and reduced dependence with the local grid.

Unlike competitors that focus on optimizing the energy systems or the vehicle operations, we take an integrated approach to consider both sets of systems. Initial studies show that implementing our system with solar energy could result in energy cost and emissions savings of up to 50% when compared to an uncontrolled baseline.

With widespread adoption of UAM in North America, we estimate a market value of $80M for just power allocation tools for passenger transport service. We estimate the total available market, considering power allocation support for global passenger and cargo operations, to be over $7.6B.

Future work will first involve product development and beta testing with early customers. Initial deployment will be tailored to large airports markets with highly intermittent electricity pricing structures. Expansion will involve developing extensions and modules to handle larger UAM networks and newer forms of on-site energy generation.

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1 Introduction

Advanced Air Mobility (AAM) has inspired significant interest in exploring the possible use cases of future air mobility in missions or communities not currently served with today's aircraft such as NASA's AAM National Campaign [1]. Future AAM missions include Urban Air Mobility (UAM), a segment of AAM which seeks to transport goods and passengers in urban settings with novel airborne technologies. Examples of UAM missions include airport shuttle trips, air-taxi missions, package delivery, etc. [2]. Figure 1 shows two examples of UAM vehicles currently in development: the Joby S4 and the Archer Maker. Presently, over 200 UAM vehicles are in various stages of development, many of which are electric vertical takeoff and landing (eVTOL) vehicles [3]. Much of the industry's current focus is on the development and certification (Part 135) of future UAM aircraft. However, with the imminent expected launch of UAM services, further investigations into the optimal operation and infrastructure are required for the successful long-term implementation of UAM.

(a) Joby S4 **(b) Archer Maker**

Figure 1. Examples of Electric UAM Vehicles. Retrieved from Vertical Flight Society [3]

1.1 Background

Current infrastructure, particularly energy infrastructure such as the grid, is simply not prepared for electrified AAM operations. Passenger-carrying UAM presents one of the greatest challenges, as the industry's vision for UAM is on-demand mobility, where passengers request flights on their mobile devices and expect short wait times and near-immediate transport [4]. This means charging of UAM vehicles will likely be highly irregular, causing significant load demands on the grid without warning. The state of infrastructure development to support this vision of future UAM operations remains in low technical readiness levels. Companies developing UAM vehicles are developing concepts of operations for infrastructure and implementation, but details are largely proprietary. The UAM ecosystem will rely on vertiports, takeoff and landing ports which will facilitate vertical takeoff and landing (VTOL) operations of future UAM services. Early adaptations for vertiports may be integrated into existing airports and heliports to minimize the initial costs of entry into service [5]. Significant research on the analysis of future UAM operations identified future roadblocks and critical milestones of development. Implementing UAM operations with current energy infrastructure conditions would cause significant adverse effects, primarily due to the fact that electric grid systems are not designed to handle the significant increase in charging demand [6].

An analysis done by Black & Veath [7], on a notional vertiport in Houston, TX concluded that advanced implementation of UAM operations is expected to require upwards of 50 MWh of additional electricity per day. That is equivalent to the estimated energy required by an American household over a 5 year time period according to the U.S Energy Information Administration [8]. Methods to supply such power demands for UAM vertiports are not well defined. Furthermore, aviation systems were responsible for approximately 1.04 billion tons of greenhouse gas emissions in 2018 [9]. Significant efforts toward "clean aviation" have focused on electrifying systems and increasing energy efficiency. However, these pursuits only reduce emissions if clean energy is used to power the electric aircraft.

1.2 Motivation

With the rapid development of UAM vehicles and supporting technologies, the multi-billion dollar industry is expected to disrupt the status quo of passenger and cargo transportation. Existing research on UAM is primarily focused on aircraft technology such as propulsion, aerodynamics, design, autonomy, operations, etc. Garrow et al. [2] found that out of over 500 UAM-focused research papers from AIAA, only 12 contained infrastructure themes. UAM infrastructure and the electric demand caused by UAM operations pose a large barrier for manufacturers and operators to implement this emerging technology into the transportation system.

Renewable energy generation methods have been identified as a method to reduce the carbon footprint and grid reliance of UAM operations. Efforts to incorporate solar photovoltaics (PV) and wind power for current energy needs are ongoing in many municipalities around the United States. Airports have particularly increased solar PV infrastructure to reduce carbon emissions. However, due to the intermittency of solar energy because of its reliance on daylight hours, solar has not been seen in the past as a viable means for powering UAM. In addition, to maintain the stability of an electric grid, the new flow of power (generation and consumption) must be balanced, with a slight lee-way with energy storage. Too much supply may cause over-current and poses fire risks, while too much demand can cause spikes in energy draw, resulting in blackouts or heavy reliance on non-renewable backup power systems.

Future UAM operations will be hindered by current energy infrastructure's ability to consistently supply enough electricity to meet the load increases associated with UAM. Additionally, if UAM operators simply connected to the grid to power on-demand mobility, they would be at the mercy of grid pricing, which can change drastically within a single day. This is exemplified by the Texas winter storm event in early 2021, where the price of energy soared to 7500% of typical levels of $0.12 to $9 per kilowatt-hour [10].

On-site power systems, demand response, and economic-optimal control are technologies that provide an untouched opportunity to mitigate the power and pricing issue that limit the long-term viability of UAM services. From literature and market studies, it is clear that a solution which reduces future UAM operators' dependence to the grid is required to ensure the reliability of UAM on-demand services, and minimization of energy costs.

1.3 Problem Statement & Overall Approach

For future UAM services to achieve long-term viability and profitability, solutions that detach UAM operators' dependence on current energy infrastructure are required. With the lack of research and development in energy infrastructure for UAM, in industry and academia alike, the path to practical UAM implementation remains unclear.

Our research aims to identify a path to supplying future UAM energy demands through studying the emergent behaviors of future UAM energy operations with systems engineering methodologies. We introduce a novel clean energy-based concept for UAM energy demand response. Our solution minimizes UAM operators' direct operating cost and carbon footprint while maximizing passenger throughput and profit.

Our project is guided by two main methodologies: the Definition, Abstraction, and Implementation (DAI) approach, for modeling and analysis of systems-of-systems (SoS), and the systems engineering V-Model for system design.

2 Project Description

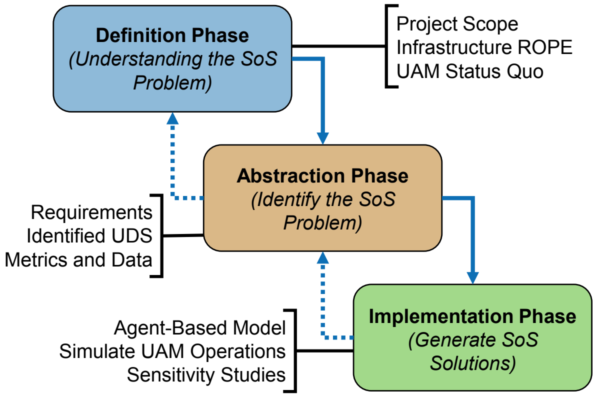
In our effort to develop a system to manage the future energy demands of UAM, we designed a software-based system to facilitate optimal resource management called UAM Dispatch System (UDS). In doing so, we identified the need to perform verification and validation of the performance of such system. Thus, we developed a second product called MIMIC– a high fidelity, agent-based model for simulating future UAM operations and the energy associated with such missions. The following sections introduce our two deliverables: UDS for UAM resource management and MIMIC for high-fidelity operations and energy modeling.

2.1 Systems Engineering Approach

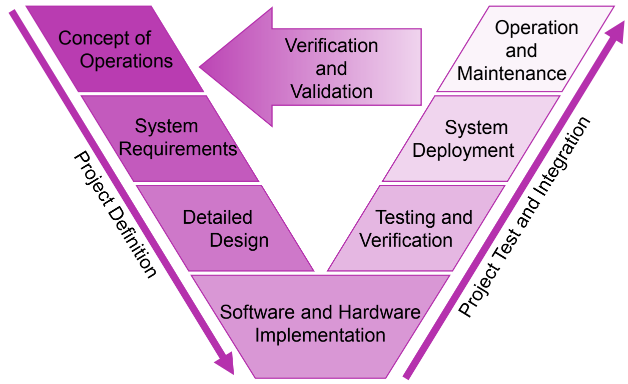
To best describe our concept, we first present the methodologies utilized in developing UDS. UAM is a system-of-systems (SoS), a complex system comprised of managerial and operational independent systems which work together to accomplish a common goal [11]. We use SoS methodologies such as the Definition, Abstraction, and Implementation (DAI) process developed by DeLaurentis [12] to effectively model the UAM SoS and generate the design parameters for UDS, shown in Fig. 2a. With the outputs of the DAI process, UDS was developed utilizing the systems engineering V-Model, described by The International Council on Systems Engineering (INCOSE) [13], shown in Fig. 2b. Details of the DAI process and simulation development are further described in Sec. 2.1.1, and the process of developing UDS with the Systems Engineering V-Model is introduced in Sec. 2.1.3.

2.1.1 Systems-of-Systems Modeling and Analysis

The DAI methodology is a 3-phase modeling and analysis approach utilized to efficiently analyze and model the major systems involved in complex SoS such as UAM to better understand the SoS dynamics and emergent behavior.



(a) The DAI Methodology



(b) The Systems Engineering V-Model

Figure 2. The Systems Engineering Methodologies used to Model and Analyze UAM Infrastructure (a) and design the UAM Dispatch System (b)

Extensive literature review and stakeholder interviews drove the development of the major outcomes of the Definition Phase. The Resources, Operations, Policies, and Economics (ROPE) method helps identify and categorize the various resources, operations, policies, and economics hierarchically depicted by levels α, β, and γ. The major ROPE elements are displayed in Table 1.

Using the ROPE elements, project scope, and operational context generated from the Definition Phase, the Abstraction Phase further breaks down each system identifying the main classes of actors, effectors, disruptors, and networks of the SoS. A major outcome of the Abstraction phase is the network diagram, shown in Fig. 3, which shows major systems in UAM infrastructure and their interactions with one another through the flow of information, energy, or physical connections. The network diagram serves as a guide for future modeling development in the implementation phase. Early in the SoS abstraction process, we identified the need for a system controller or dispatch authority, seen in Fig. 3, to optimize the allocation of SoS resources based on system states. The dispatch system must facilitate the execution of demand response methods to minimize grid usage without sacrificing UAM throughput.

Lastly, the Implementation Phase aims to utilize the major outcomes of the previous two phases to create a model that simulates the problem being analyzed. To model and analyze UAM infrastructure with high fidelity, an agent-based model (ABM) was chosen as the best method for simulation, which uses autonomous decision-making entities called agents [14]. Analysis of the behaviors of agents allow for the study of emergent, or unexpected system-level, behaviors of the SoS. Understanding such behaviors allow for the generation of engineering parameters for UDS development. This model, MIMIC is further developed in Section 3.3.

2.1.2 Stakeholder Interviews

To robustly perform stakeholder analysis beyond the outputs of the DAI process, we conducted (and continue to conduct) many interviews with possible stakeholders. Stakeholder groups interviewed included aerospace system manufacturers, UAM manufacturers,

Table 1. Hierarchical Resources, Operations, Policies, and Economics of UAM Infrastructure

Hierarchy	Resources	Operations	Policies	Economics
α	Energy Subsystems, UAM Vehicle Subsystems, Passengers, Airport Subsystems	Operations of energy subsystems, UAM vehicle subsystems, airport subsystems	Policies of operating energy subsystems, UAM vehicle subsystems, airport subsystems	Economics of operating, acquiring, and utilizing energy subsystems, UAM vehicle subsystems, airport subsystems
β	Energy Systems, UAM Vehicles, Airport Systems	Operations of energy systems, UAM vehicles, airport systems	Policies of operating energy systems, UAM vehicles, airport systems	Economics of operating, acquiring, and utilizing energy systems, UAM vehicle systems, airport systems
γ	Networks of Energy Systems, UAM Fleet, Network of Airports	Operations of energy networks, UAM fleets, airport networks	Policies of operating energy networks, UAM Fleets, networks of airports	Economics of operating, acquiring, and utilizing energy networks, UAM fleets, airport networks

operators, and airports. A comprehensive discussion of interviews conducted is presented in Section 3.1. Stakeholder interviews yielded a key discovery – through discussions with the San Diego Airport Authority and officials from San Jose Airport, we realized investing in infrastructure upgrades to accommodate future UAM operations is not in scope of most airports. Rather, many airports expect future UAM operators to bear the cost of ensuring infrastructure is prepared for UAM services. This finding was confirmed through conversations with Supernal, a UAM manufacturer and future operator.

2.1.3 Concept Development Using the Systems Engineering V-Model

The systems engineering V-Model developed by INCOSE, seen in Fig. 2b, represents the development cycle of engineered systems. To efficiently manage and organize the steps in system development, we used Model Based Systems Engineering (MBSE) using CORE9 software provided by ViTech. The insights generated in Section 2.1.1 identified the key design parameters which serve as inputs to applying the V-Model for UDS development. The agent-based model allowed for several operating scenarios to be simulated for a high-fidelity derivation of Concept of Operations (ConOps). The Definition phase of DAI aided our determination of key stakeholders, stakeholder needs, and engineering requirements.

Using Quality Functional Deployment (QFD) in the form of a House of Quality (HoQ), we related and weighted stakeholder needs to requirements for guiding design decisions. This

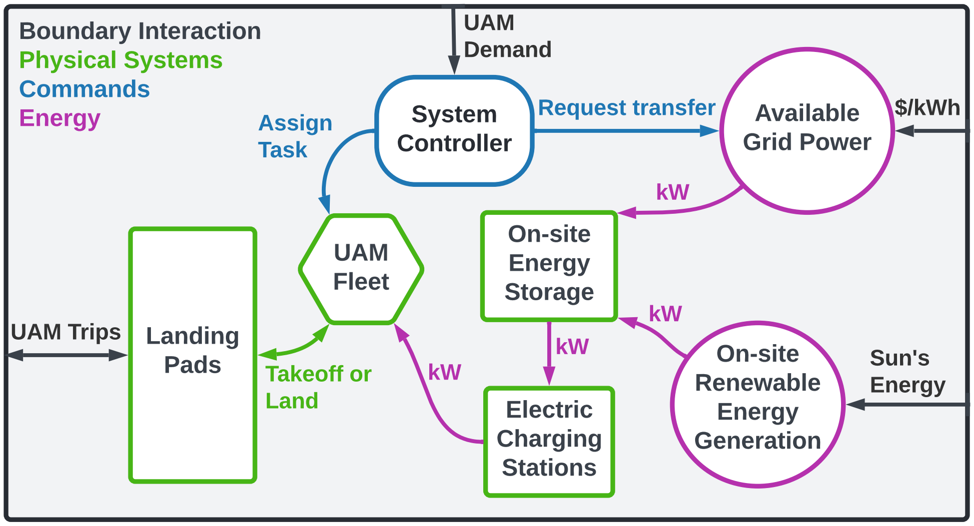


Figure 3. Directed Network Diagram of UAM Infrastructure Systems

led to functional analysis, where we developed the functional decomposition found in Fig. 5 and a functional flow block diagram (FFBD). Once the major functions of the UDS were determined, the concept generation phase commenced, where we developed a morphological chart to generate concepts which could fulfill system functions. Several ”solutions”, or combination of functional concepts, were generated through the morphological chart, which then guided the concept selection phase.

To avoid design fixation, we used two concept selection methods - Weighted Objectives, and Pugh's Method. Both methods involve highlighting the key stakeholder needs from the QFD process, and scoring each solution's ability to fulfill each need. The weighted objectives method uses weights on each need to determine a solution, while Pugh's method develops a matrix which compares each solution to a baseline iteratively, until the final solution is determined. Figures from the V-Model development cycle were omitted from this report.

The final outcome of the systems engineering V-Model is a comprehensive design of the UDS. This system is a combined energy and aircraft dispatch system that merges operator data with cutting edge optimization and systems engineering tools. The ABM described in Section 2.1.1 is used to both test the effectiveness of UDS as well as provide a platform to perform case studies that can assist various relevant stakeholders. We are working closely with industry partners to tailor our simulation to represent the best estimates of real UAM operation, while distilling their knowledge and customer needs into the dispatch system.

2.2 Concept Overview

Our concept, UAM Dispatch System (UDS), is an resource management system for UAM operations which leverages internet-of-things capabilities and robust optimization techniques for supporting the future of connected national airspace systems. Using real-time systems data, UDS dynamically manages energy consuming and energy supplying systems to minimize operating cost and emissions while maximizing fulfillment of passenger demand and

Table 2. Stakeholder categories and gruops considered in further stakeholder analysis.

Stakeholder Category	Example Stakeholder
Passenger	Businesspeople, Children, Families, Adults including mobility, visually, and hearing challenged individuals
Airport Authority	Decision Makers, Dispatch
UAM Operators	Ground Crew, Engineering, Aircraft Maintenance, Technicians, Dispatch
Airside Operations	Aircraft Ground Crew, Aircraft Charging Crew
Air Traffic Control	Departure Controllers, Flight Data Controllers, Arrival Controllers
Regulatory Agencies	FAA, EASA, etc.
Local Communities	Local government, community organizers, citizens
Equipment Suppliers and Manufacturers	Renewable Energy Companies, Aircraft Acquisition Suppliers
Electricity Providers	Independent System Operators (ISOs), Mechanical and Electrical Contractors, Construction Entities

revenue. UDS is highly modular – though this paper focuses on applying this deployment system to UAM on-demand mobility, any mission included in AAM may be managed by a similar deployment system. Future iterations may develop other mission-specific deployment systems. In addition, UDS supports a wide range of energy supplying systems, including power from the grid, and renewable energy sources such as solar arrays, wind power, nuclear, and hydrogen, among others.

These features are highlighted in the external systems diagram in Fig. 4, which depicts the various subsystems, external systems, and context of UDS. Subsystems of UDS include localized compute hardware, data, and dispatch software which work to accomplish the functions of UDS. External systems are systems that are not included within the bounds of our system, but have the ability to affect (and be affected by) our system. Context are aspects of the operating conditions which affect UDS, but are not affected by UDS.

Figure 5 depicts the functional decomposition for the UDS. Main functions of UDS can be boiled down to four sub-functions: 1) Gather System Inputs, 2) Perform Predictions, 3) Dispatch System Commands, and 4) Monitor System Health. UDS actively takes input of UAM operator system states and performs predictions on future states using advanced optimization and machine learning algorithms. System states include vehicle position and charge in addition to passenger demand and energy parameters such as cost of grid energy and state of charge of on-site batteries. The system states and predictions of such states allow UDS to generate real-time suggestions for optimal operations.

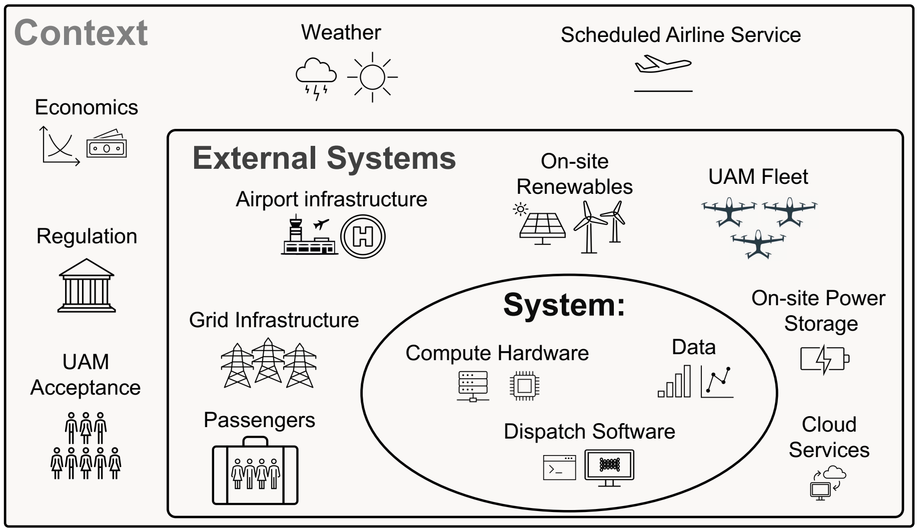


Figure 4. The external systems diagram describes the system boundary and relationships with external entities and services that enable successful operation

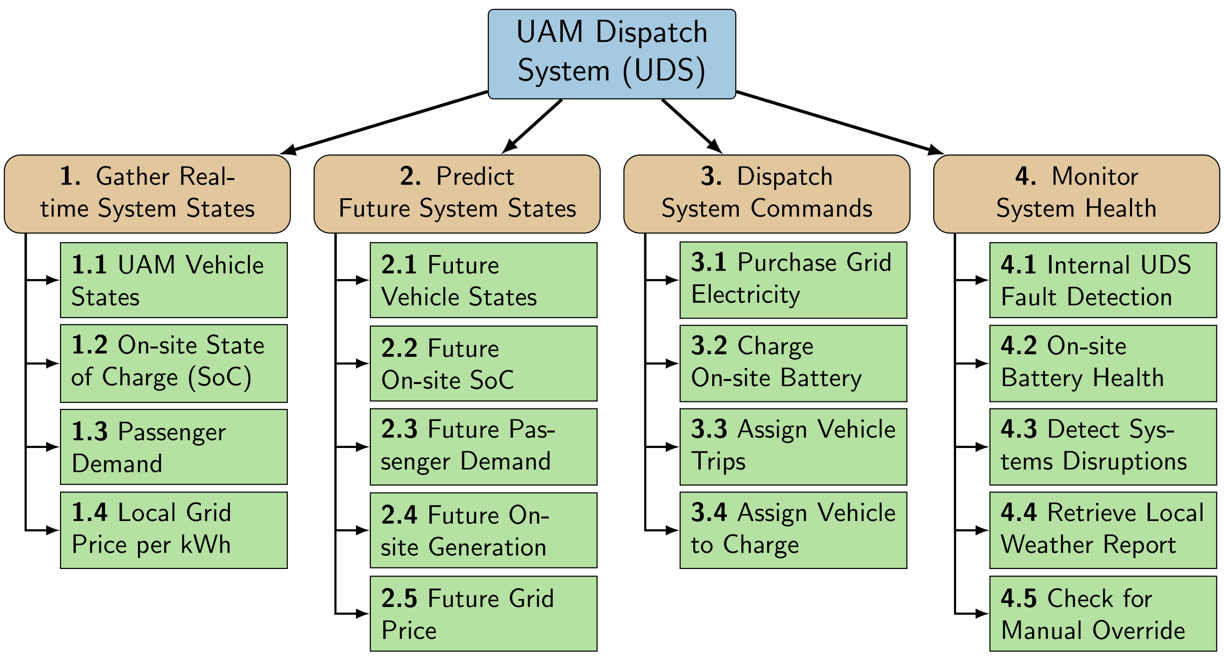


Figure 5. Functional Decomposition of the UAM Dispatch System

By monitoring system health, the UDS will be able to identify disruptions or failures and mitigate their effects to UAM operations. The failure analysis described in Section 2.3.3 was used to identify major internal and external failure modes, their potential causes, effects, and mitigation strategies.

2.3 Life Cycle Analysis

We consider the product life cycle from software development, to deployment, certification, and risk. Life cycle analysis informs the business strategy and cost breakdown, which in turn helps us provide the most value for our customers and passengers.

UDS is currently is within TRL 3 to 4, due to a clear formulation and functional breakdown and the demonstration of key features in simulation, as shown by sections 2.2 and 3.3. The approach is based on high-fidelity methods in the system-of-systems and operations research fields. Tangential technologies and dependencies are much lower risk (TRL 5 to 9) and include established areas such as renewable energy systems, embedded systems, UAM vehicles, and dispatch software. TRL convention is defined by [15].

2.3.1 Regulation and Certification

UDS is a dispatch software that is not in control of airborne avionics or any airborne safety-critical systems. The large body of software assurance certification processes that exist are for airborne and ground systems software. Processes RTCA/DO-178C [16] and RTCA/DO-278A [17] cover airborne systems and non-airborne communication, navigation, surveillance, and air traffic management systems, respectively. Using the DO-330 is a tool qualification consideration that is commonly used to remove gray areas in DO-178C and DO-278A. Our future efforts will aim to certify UDS as an FAA acceptable management software for ground-based systems involved in aircraft operations. While a simple recommendation software may not need this rigorous certification for basic low-autonomy applications, we aim to comply with the most tested, rigorous and operationally successful processes of DO-178/DO-278 to prepare for future potential with high levels of autonomy.

2.3.2 FAA 2025 & 2035

For 2025, the FAA outlined five pillars [18] for implementing aviation systems that enhance: (1) safety, (2) reliability, (3) efficiency, (4) capacity, and (5) environmental performance. UDS aims to enhance our customer's efficacy in all five areas through the lens of dispatching aircraft and energy resources. By integrating large amounts of data resources, UDS brings sophisticated data aggregation, analysis, and visualization to alert operators in the case of unsafe operations, enhance the effective storage capacity and resiliency of energy management, and ensure high throughput of electric vehicles powered by low-carbon energy sources. Our product additionally fulfills the FAA's needs for innovative technologies, new equipment, advanced system oversight.

FAA 2035 report [19] outlines how the NAS will evolve to address changes in three fundamental areas: (1) Operations, (2) Infrastructure, (3) Safety Assurance. Along the way, AAM and UAM operations ushers in an information era, where operations data analytics, collection, and visualization are becoming immensely valuable decision making tools. Our goal of having AAM as an electric grid demand response asset is an initiation step towards the 2035 vision. As data becomes ubiquitous, UDS seamlessly bridges the gap between infrastructure and operations by intelligently and efficiently allocating energy from the grid and renewables that is CO_2, SO_2, NO_X emissions friendly and cost effective for the operators. Sustainable growth involves a sustainable ground infrastructure.

In summary, UDS uses data-rich information of hourly grid energy prices, renewable resources for compatible land-use energy generation, passenger demand distributions to reduce (a) significant loads on the grid, (b) electricity usage costs, (c) greenhouse gases released from charging from unclean grids, and (d) adverse health impacts on communities living on or near the flight paths.

2.3.3 Systems Safety, Reliability, and Inherent Risks

As with any complex system, especially in aerospace applications, systems safety and reliability is paramount. Risk assessment of the UDS was performed to identify the possible failure modes and likelihoods of occurrence of such scenarios. Using the Failure Modes and Effects Analysis (FMEA), we generated an extensive matrix of possible failure modes based on UDS subsystem. Though the FMEA is far too large to present in its entirety in this report, we highlight several failure modes in Table 3.

Another key activity performed of analyzing the inherent risks is life cycle analysis in the context of reliability. Since our concept relies heavily on software systems integrated with hardware for nominal operations, we expect the reliability of UDS to follow a modified bathtub curve of reliability [20]. Hardware systems will likely follow the traditional bathtub curve of failure rate, including three phases - wear-in (infant mortality), useful life (random failures), wear out. Software will influence this curve with a similar wear-in period for debugging and testing in implementation before steadying to useful life. Wear-out for software is not like hardware in that failures emerge over time; rather, software becomes obsolete over time. Therefore, the need for software upgrades periodically throughout the UDS life cycle is required. Throughout the hardware useful life, we expect small wear-in periods after each software upgrade.

Through this analysis, we determined that UDS presents very few safety-critical risks (outcomes of failure modes that result in serious injury or death). A conscious design decision the team made was to clearly define the scope of UDS to not include overriding control authority of Safety Critical Systems (SCS) such as aircraft or power systems. We intentionally designed UDS as a recommendation system to manage resources in highly-constrained environments, with a staged roll-out of autonomy. This ensures the ability for UAM operators to have a human-in-the-loop, either to constantly monitor, or simply serve as a final override in emergency situations.

UDS closely monitors systems states and issues commands based on optimal conditions, but does not have the authority to control the specific dynamics of how each system must perform the task. For example, a fire due to battery overload is unlikely since UDS does not force charge to the batteries. Instead, UDS issues charge or discharge commands to the battery system controller, which determines if conditions of the battery system are suitable to carry out directives from UDS.

A major risk of UDS exists in cyber and physical security. Though UDS does not have overarching control over SCS, it does have access to data from each system included in the UAM Operator's SoS. This means UDS may be a target to cyber and physical attacks which aim to steal possibly sensitive data. An attack may come in the form of a hack, where bad actors attempt to breach security protocols remotely, or a physical attack where bad actors may attempt a breach through physical interface with the centralized UDS command.

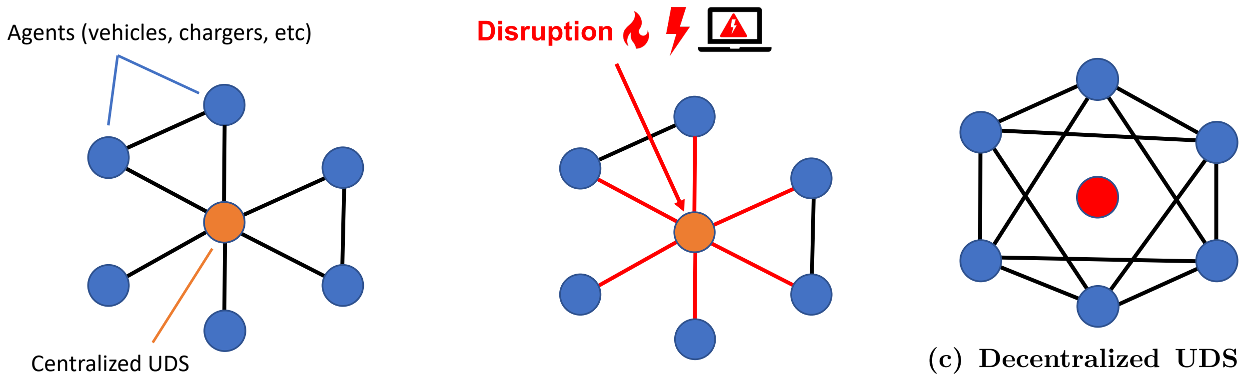
Table 3. An abridged sample of the FMEA table developed for failure mode analysis.

Scope	Failure Mode	Causes	Effects	Mitigation
Internal	Unexpected system shutdown	Cyber-attack, Physical system failure, Server failure	Long-term operation disruption, Revenue loss	Decentralized control mode, Secure and robust software
	Communications failure	Server delays, Physical system failure	Unintended predictions and dispatches	Regular maintenance, Redundant systems
	...	...	...	...
External	Loss of Power	On-site power failure, Grid blackout	Loss of control, Operational delays, Revenue loss	Localized computing
	Inaccurate data transmitted	Abnormal system operation, communication disruption	Unintended predictions and dispatches, loss of optimal control	Regular maintenance, Nominal operation monitoring
	...	...	...	...

Several defenses exist for such attack, beyond typical firewalls and security protocols we assume to be integrated with UDS. Integrating both multiple local machines and cloud computational resources serves as layers of redundancy when one of the local systems or the cloud is unavailable or communications are disrupted. Cloud attack is unlikely, as we expect to utilize secure services such as Amazon Web Services (AWS) GovCloud. However, in the case of a cloud failure or communication disruption with the cloud, UDS will switch to local hardware for full computational functionality.

In development of UDS, we considered possible operating modes for safe and secure continued operation under disruption. Several backup modes and a safe mode were developed to address possible off-nominal conditions. Safe mode operation is an operating condition where all non-essential systems are turned off, to focus service on working components when issues arise. Backup modes were designed based on FMEA as defenses to possible failure modes. One such backup mode is shown in Fig. 6 which depicts the network graphs of a notional strategy developed to mitigate the effects of a debilitating attack on the centralized UDS.

Figure 6(a) shows the nominal operating mode, where agents of the UAM SoS (in blue) interact with the centralized UDS (in orange) to send system states and receive commands, shown in the edges of the graph. Note several edges exist between non-UDS nodes as a precaution to monitor the accuracy and trustworthiness of the UDS. When a severe disruption occurs which takes the centralized UDS offline, as shown in Fig. 6(b), a decentralized backup mode will be initiated. Figure 6(c) shows this decentralized backup mode, which uses a block-chain style distributed computing policy and multi-agent control to fulfill the operations of UDS without the need for the centralized node.



(a) **Nominal operating mode with centralized UDS.**

(b) **Disruption on UDS – e.g. cyber attack, physical damage.**

(c) **Decentralized UDS protocol via distributed computation when central UDS is inactive.**

Figure 6. A notional strategy via Multi-Agent, distributed computation to mitigate a central UDS failure.

2.4 Path to Commercialization

We analyzed the future economic viability and possible paths to commercialization of UDS through performing market research, developing a clear strategy of commercialization to parallel UAM development progress, and performed a cost analysis of UDS. We also utilized the Business Model Canvas (BMC) (omitted from this report) to highlight the considerations of a possible business venture launching UDS and MIMIC.

Market studies were performed to understand current industry issues. Several solutions exist on the market which manage aircraft fleets and other non-aerospace systems that perform energy demand response. To our knowledge, no system currently exists which solves the energy demand issues of AAM through dynamically optimizing around passenger demand. This is largely due to the state of AAM development as an industry, where companies are largely focused on building and certifying aircraft rather than optimizing future operations. We expect the emerging market of managing energy for future AAM operations to grow to a massive scale, outlined in the next section.

2.4.1 Commercialization Strategy

The commercialization strategy is planned in four distinct phases, as described in Fig. 7. Each phase is planned in accordance with a market size and in parallel with the UAM maturity levels (UML) [21].

A preliminary market sizing analysis was conducted to understand the key players in the segment UDS intends to disrupt. From our findings, no system exists which dynamically links fulfillment of passenger demand to energy demand response. Therefore, market sizing estimates maximum possible industry-wide yearly revenue calculations. We identify, in Fig. 7 the Target Market (TM) size to be $500K, the Serviceable Available Market (SAM) to be $ 80M, and the Total Available Market (TAM) to be $7.6B. The go-to market strategy aims to service the TM, an initial roll-out at 10 major US airports at UML 2 or 3.

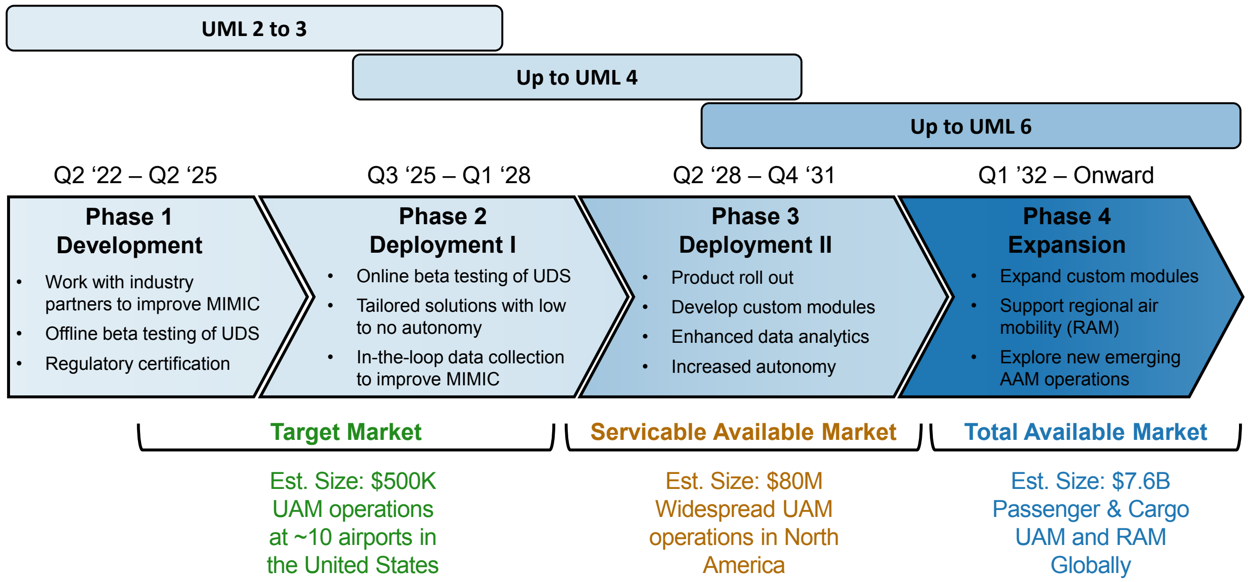


Figure 7. Phases of commercialization are planned in parallel with expected developments in UAM and in accordance with market phases.

2.4.2 Cost Analysis

We estimate the costs for our product and separate, but related, infrastructure using literature for microgrid deployments [22], solar panels [23], and projected costs of UAM infrastructure [7]. The cost of our system, the UDS, are solely based on software development and deployment. This includes the costs associated with engineering overhead and computing infrastructure. Similar features of this product are included in the controller cost on a robust study of prior microgrid deployments [22]. The UDS cost for a baseline controller with minimal features may be as low as $5,000. However, employing a more sophisticated product may require as much as $165,000 to $500,000 based on the scale of the project, as shown by Table 4.

Table 4. Software implementation cost

	Controller Complexity	
Solar	**Simple**	**Advanced**
100 kW	$4800	$165500
200 kW	$9500	$331100
300 kW	$14300	$496600

Associated costs are costs that may be covered or shared among airlines, UAM operators, manufacturers, energy providers, and the United States Government. This can be split between the costs of power systems and the cost for implemneting UAM. To provide a perspective on these costs, we estimate that an implementation of a 100-300kW solar farm with a 1MWh on-site battery and 10 vehicles may require on the order of $150,000 to $250,000 in power infrastructure. Infrastructure needed for this implementation of UAM may require anywhere from $4.7M to $5.8M [7].

It should be noted that the associated UAM costs are prerequisite for the implementation of UAM vehicles, but not included in our recommendation software system. Stakeholder interviews with SJC and SAN airports suggested that the integration of associated power costs may be supported by the airport in accordance with clean energy initiatives, the United States Government through subsidies, or through airlines and operators.

2.5 Customer and Passenger Experience

UDS is built to enhance both the passenger and operator experience by leveraging large and diverse sets of data to make informed decisions with tailored communication and visualization approaches.

Passengers may see a more reliable UAM service, as UDS aims to improve the efficiency of the vehicle and energy network. This means passengers' wait times will be minimized, as vehicles are more likely to be charged and ready, while minimizing users' personal carbon footprints through clean energy for UAM.

Operators will make use of a sophisticated recommendation software with a graphical user interface (GUI) that is tailored their needs. Shown in Figure 8, the GUI displays the state of vehicles within the network and allows focus on specific vehicles of interest. A message log creates alerts that assist an operator's ability to make high-level decisions. Along with text alerts, a graphical read-out of current and future parameters of interest (e.g., UAM demand, battery state-of-charge, etc.) allows users to apply human reason in case of a warning or failure.

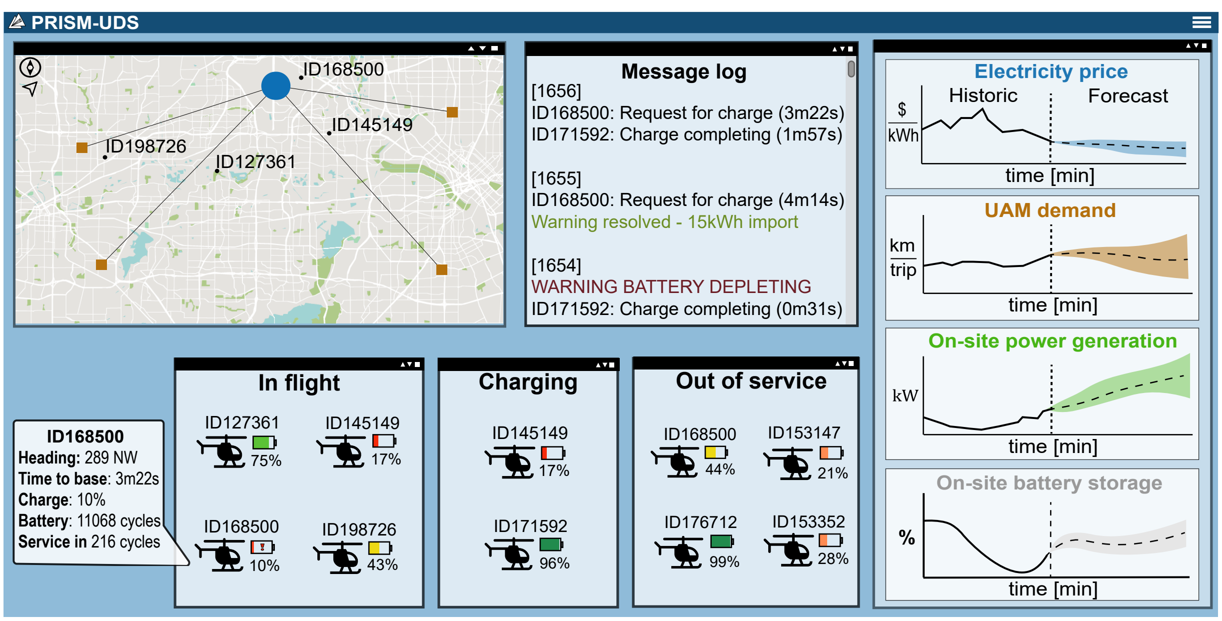


Figure 8. An example graphical user interface (GUI) through which a operator may interact with the UDS software.

3 Research & Testing

To robustly analyze and iterate upon the efficacy of UDS, we developed testing methods rooted in research. The following sections present our research which informed all aspects of the project, the MIMIC simulation platform, testing strategy employed, and challenges the team faced along with design changes from the proposal.

3.1 Market Research & Industry Interviews

To best understand the design space and parameters of developing UDS and MIMIC, we performed extensive research through literature review and industry interviews. Interviews were organized through identifying relevant real-world stakeholders and leveraging the team's network of industry connections to schedule discussions via Microsoft Teams. Interviews conducted gave us insight into the perspectives and needs of three major industry groups:

- **Future UAM Operators**
  We held discussions with American Airlines and Supernal to better understand the inner-workings of UAM operators. American recently demonstrated interest in UAM, announcing a partnership with Vertical Aerospace, another UAM manufacturer [24]. Further discussions with Supernal guided the development of MIMIC and UDS, as we learned of Supernal and Hyundai's vision for the future of aerial mobility with UAM. These discussions highlighted several key findings from literature review. The expected entry into service for UAM is far sooner than infrastructure will be ready for on-demand UAM services. Current infrastructure is severely ill-equipped to handle the future load increases of even early stage UAM operations. This represents a major concern for future UAM operators, as their operations will be curtailed by the limitations of infrastructure unless a solution is determined. In addition, few high-fidelity models exist which model the energy dynamics of conducting UAM operations. **These operators expressed the need for a system to give insight into detailed operating parameters and costs as well as a solution to avoid the restrictions of current infrastructure limits.**

- **Airports**
  We interviewed representatives from two airports - San Diego International Airport, and Mineta San Jose International Airport. Here, we learned of the varying managerial structures of airports in the US, and discovered that UAM operators will likely bear the brunt of infrastructure cost for future operations. San Diego was particularly helpful, sharing high-fidelity solar generation data and real-time grid cost from their power systems and insights from passenger dynamics data. **A key question that arose from this discussion was presented by the airports, which sought a robust method for sizing on-site UAM infrastructure assets for better clarity in planning.**

- **Aerospace OEM**
  We identified the need for discussions with aerospace system Original Equipment Manufacturers (OEMs) to better understand the design process of aviation equipment and

seek guidance for the development process of UDS. Therefore, we held discussions with the Chief Consulting Engineer and other technical professionals from GE Aviation Systems. These discussions significantly aided our understanding of the bottom line in product development and manufacturing from the perspective of an OEM and leadership within such corporation, refining the technical details and pitch of UDS and MIMIC. **We determined that OEMs hope to enter the UAM space, but lack the insights required to design for operations that have yet to be fully defined.**

These interviews provided valuable insight into the expected UAM operating conditions and deficiencies of existing infrastructure and modeling methods. Through identifying stakeholder needs, we determined a system with robust modeling of future UAM operations and energy dynamics is sorely needed by future UAM operators, as well as an optimized tool for managing UAM resources.

3.2 MIMIC: Simulation as a Product

As a byproduct of developing UDS, we developed a secondary product in the form of a simulation. Through the DAI process, we developed MIMIC - an agent-based model which a robustly models future UAM energy needs and operations. MIMIC uses real data provided through industry partners and publicly available datasets as a foundation for a robust simulation platform.

MIMIC serves as a testing platform for UDS and as a tool to study UAM integration and power system dynamics. The model is built in Python using the Mesa simulation framework. It provides a modular architecture to test new algorithms and data sets, as well as the generality to consider all locations within the US with a flexible parameter space (vehicle data, energy sources, capacity requirements, etc.). The following sections outline how we used MIMIC in the testing and validation process of UDS.

3.3 Testing Process

In this version of MIMIC, we consider a network of vertiports with anywhere from 10-100 vehicles. Here, trips originate from the airport (ORD or DFW) and take passengers to predetermined locations according to a passenger demand model [25]. The vehicles may be charged with electricity that is generated by on-site solar panels and stored in an on-site battery, or via a connection to the local electric grid.

MIMIC considers historical data for weather (solar energy) using the NASA MERRA2 project and electricity price from the ERCOT and PJM regions. Solar irradiance has a spatial resolution of $0.5^\circ \times 0.625^\circ$. UAM demand is modeled notionally based on prior literature and considers real case studies in networks centered about airports in Chicago, IL (ORD), and Dallas, TX (DFW). UAM demand has a temporal resolution of one minute, while irradiance and price use a one hour temporal resolution. The information flow through the model is visualized by Figure 9.

Specifications of vehicles and assumptions about specific process parameters are informed by manufacturers, prior literature, and conversations with industry partners. The baseline

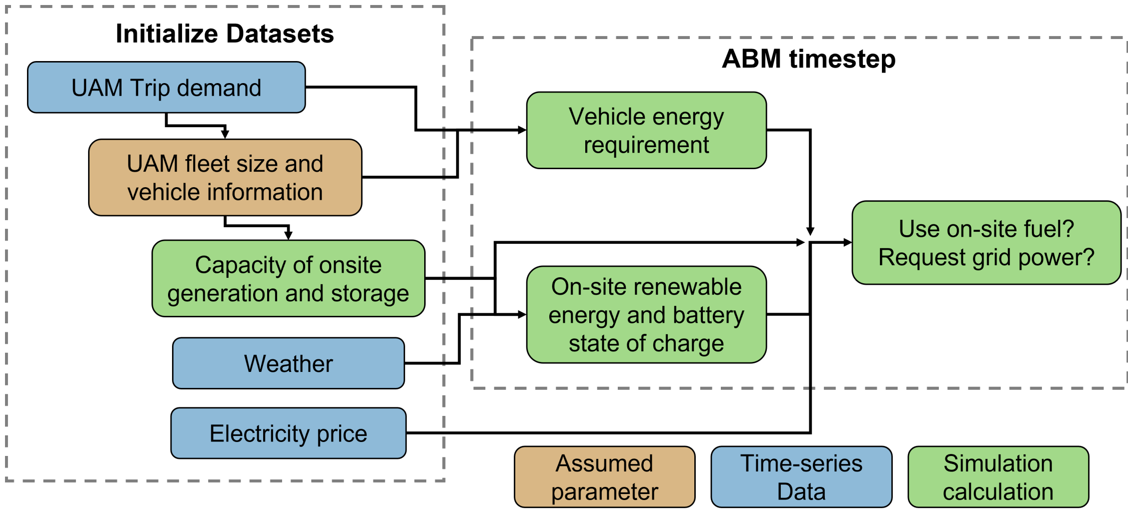


Figure 9. Information flow through the ABM simulation.

study uses notional information for the Archer-like vehicle [26]. Assumptions with on-site power systems include a total battery size of 1MWh and solar panel efficiency of 22%. Solar panel area is computed by calculating the average power needed to satisfy charging all vehicles in one day, using the peak daylight hours for each.

The optimization approach breaks the dispatch problem into three distinct sub-problems: (1) purchasing electricity from the grid, (2) allocating vehicles for charging, and (3) dispatching vehicles for passenger trips. Grid electricity is purchased at the lowest grid price but constrained to not allow the on-site battery reserves to be depleted. When a charging station opens, the dispatcher chooses the vehicles that are closest to the needed charge. The acceptable charge may be the charge needed to satisfy 90% of trips. When a take-off or landing zone is open, the vehicles with the lowest charge that can still accomplish the trip is assigned to the request. Using a proprietary algorithm, we perform an uncertainty-aware prediction of the future state of charge, price, and demand. Then, using techniques in robust optimization, we solve the three sub-problems to provide a robust recommendation at each time-step.

3.4 Simulation Case Studies

Incorporating solar energy into the system reduces both carbon emissions and the cost that the operator must pay to purchase electricity from the grid, as shown by Fig. 11. The improvement may result in nearly a 60% decrease in weekly electricity cost, in the extreme case of adding 300kW of on-site solar power at DFW. Texas sees a larger benefit from using on-site solar, as opposed to Chicago, due to higher nominal grid prices, higher grid carbon intensity (natural gas systems), and abundant natural solar resources.

3.5 Challenges and Justification of Design Changes

A major challenge we experienced in this project was the vast unknown surrounding future UAM operations. Though conversations with stakeholders were highly helpful in

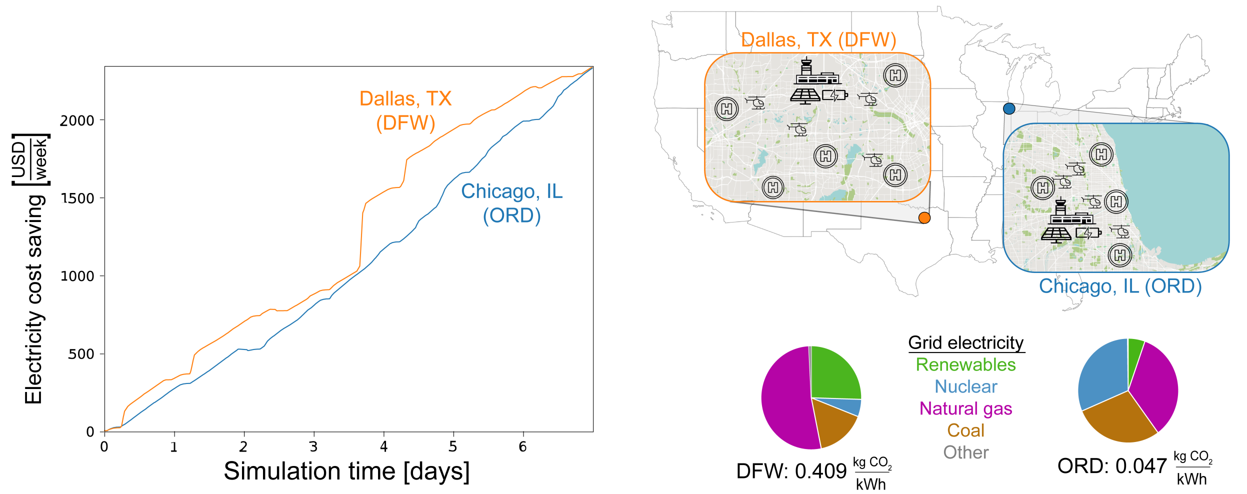


Figure 10. (a) Electricity cost savings due to adding a pricing-based control policy for grid electricity purchasing. (b) a visualization of case study networks with the the energy generation and embedded carbon intensity of each local grid.

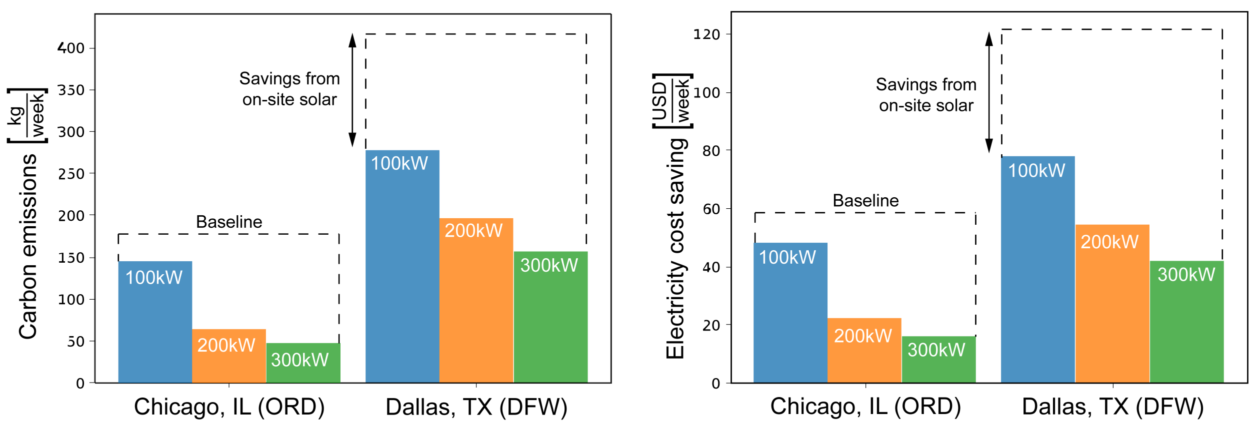


Figure 11. Savings in terms of (a) carbon emissions and (b) electricity cost from using on-site solar power in increments of 100, 200, and 300 kW, when compared to a baseline of 0kW on-site solar.

elucidating our assumptions and questions, the fact that UAM operations do not exist yet meant our background research in expected future operations of UAM had to be very robust. In the same vein, our project set out to design a complex system to optimize the performance of an SoS. This proved challenging, as we had to balance the development methodologies of both the DAI and V-Models.

From the project proposal, two project changes occurred. From stakeholder conversations, we realized that our assumption that airports would bear the brunt of UAM infrastructure cost was false. Rather, as we mentioned in previous sections, UAM operators will likely be responsible for UAM infrastructure cost. This was more of a scope change than a design change but influenced further design through the adjustment of the problem statement to focus on aiding UAM operators rather than airports as the main customer.

The second change we made from the concept proposed was a design change which broadened the portfolio of energy sources UDS can support. In the proposal, we suggested that the UDS would only consider solar, as a part of our system. This version of UDS was built under a conscious decision to generalize the possible energy sources. As an input to MIMIC, we use a python script to initialize the possible renewable and non-renewable energy systems in the SoS, which include systems such as solar, wind, nuclear, hydrogen, and diesel. This report still focuses on solar implementation, since solar energy boasts the lowest cost per unit energy with the most difficult implementation due to the intermittency of solar generation.

4 Conclusions & Key Findings

UDS helps UAM operators reduce reliance on under-prepared energy infrastructure, minimize operational expense, and cut down on operational carbon emissions by suggesting the best times to charge and dispatch vehicles around fluctuating grid pricing. The product does this by aggregating large amounts of available airport data and applying risk-averse optimization techniques to make robust recommendations. UDS does not interfere with existing operations or protocols and acts as a force multiplier to guide operators in making complex decisions with minimal latency.

UDS has the ability to significantly disrupt future UAM operations in a smart airport environment, alleviating the barriers that current infrastructure present. Through intelligently managing resources of UAM operations, UDS maximizes passenger throughput and operator revenue while minimizing carbon footprint and operating cost. A key focus for future iterations of the software is refining the algorithm to best balance multiple-objectives in throughput, cost savings, and emissions savings.

Near-term efforts to advance technology readiness will involve further validation and testing, inclusion of secure communication protocols, and formalization of the underlying mathematics. Validation will involve testing algorithms in a hardware-in-the-loop configuration with low-risk autonomous vehicles (roomba-like products). In parallel with development, close partnerships and feedback from operators will help tailor the data visualization and read out to maximize usability. Future efforts to improve the software will involve the development of more sophisticated prediction algorithms that can then be coupled with our robust optimal framework.

5 Project planning

The technical demonstration will require equipment for displaying a PowerPoint presentation and an mp4 video, with sound.

A timeline of project development is shown in Figure 12.

6 Budget

We expect to spend $5,500 in total. $1,000 is needed for travel costs associated with a three-day car rental. $2,500 will be used for lodging for three nights. This was purchased as soon as the finalists were announced at a location separate from the venue. $1,000 is

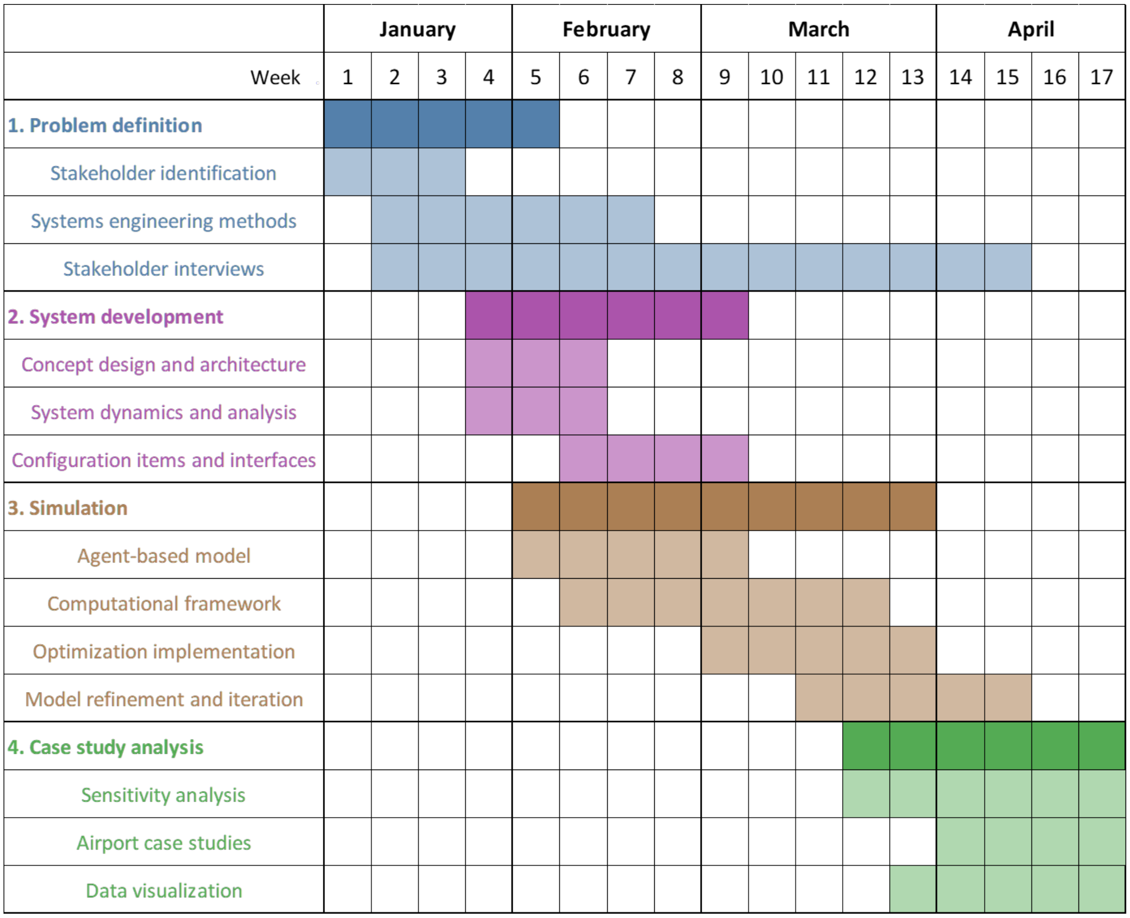


Figure 12. Project timeline.

budgeted for food and coffee expenses for the team. Flights are contributed by our project partner, American Airlines. In development, we did not incur added cost and thank Purdue University for access to state-of-the-art facilities.

6.1 Academic and Industry Partners

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