ORNL/TM-2025/3999

Airport Ground Support Equipment Infrastructure & Logistics Electrification Assessment Tool: 2025 Data Development, Modeling and Analysis for DFW

FINAL REPORT

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July 9, 2025

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Buildings and Transportation Science Division

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This report is developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy. It develops and implements the *Airport GSE Infrastructure & Logistics Electrification Assessment Tool (Agile@)*–a strategic tool to model electricity demand for ground support equipment (GSE) at the Dallas-Fort Worth (DFW) International Airport and assess its potential grid impact for GSE and drayage operations. The analysis draws on Agile@ modeling iterations and 2025 inbound/outbound freight data compiled by ORNL.

ORNL Task Team Contributions:

- Ranjan Kumar Bose (Principal Investigator): Led the study, developed the methodological framework, authored the report, presented findings, and analyzed Agile@ modeling iterations.
- Praveen Kumar: Supervised Agile@ development, conducted data analysis, and performed review/editing.
- Ingrid Busch: Managed data collection, performed freight data analysis, supported the investigation, and performed review/editing.
- Wan Li: Delivered Agile@ iterations, conducted Python-based analysis, and performed review editing.
- Michael O. Rodgers: Provided strategic guidance, ensured quality control, and performed review/editing.

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ABBREVIATIONS

ASIF	Activity Structure Intensity Fuel
Agile@	Airport GSE Infrastructure & Logistics Electrification Assessment Tool
Athena	Advanced Transportation Hub Efficiency Using Novel Analysis
AGV	Autonomous Guided Vehicle
C#	Pronounced as “C-sharp” – an object-oriented programming language from Microsoft
DFW	Dallas-Fort Worth International Airport
DOE	Department of Energy
eGSE	Electric Ground Support Equipment
FAA	Federal Aviation Administration
FedEX	Federal Express—a global freight and logistics company
FFM	Freight Facility Model
ft	Feet
GPU	Ground Power Unit
GSE	Ground Support Equipment
IEWO	Inter-Entity Work Order
ICE	Internal Combustion Engine
IoT	Internet of Things
km	Kilometer
kWh	kilowatt-hour
lb	Pound
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
SQL	Structured Query Language
tkm	Ton-Kilometer
ULD	Unit Load Device
UPS	United Parcel Service—a global freight and logistics company
VTO	Vehicle Technology Office
ZEV	Zero Emission Vehicles

1. INTRODUCTION

1.1 ELECTRIFYING AIRPORT OPERATIONS FOR ENHANCED EFFICIENCY

The aviation industry is increasingly turning to modernize freight facilities by integrating electric Ground Support Equipment (eGSE) to enhance operational efficiency of freight facility moving vehicles and equipment. Airports worldwide are adopting eGSE to streamline cargo movement, reduce fuel and maintenance costs, and improve logistics coordination.[1] North America, with its advanced aviation infrastructure, leads this transition, leveraging Internet of things (IoT)-enabled automation and zero emission technologies to boost reliability and reduce human errors.[2] Electrification of freight facility moving vehicles and equipment boosts turnaround times, improves equipment reliability, and optimizes logistics coordination, giving operators a competitive advantage. With rising fuel price volatility and the pressure to meet stringent performance benchmarks, airports are focusing on cost-effective, scalable solutions for long-term financial and operational gains.

To further accelerate electrification, airports are integrating Zero Emission Vehicles (ZEVs) into rental car fleets and deploying electric baggage carts, requiring strategic investments in charging infrastructure**.**[3] The shift, however, presents challenges, such as limited technical expertise, high capital costs, and complex procurement processes. By forging strategic partnerships, leveraging advanced technologies, and optimizing infrastructure investments, airports can create a resilient, future-ready ecosystem that enhances the movement of people and goods through electrification-driven efficiency.

Supported by the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO), this electrification effort provides a scalable, cost-effective solution to improve airport freight operations. Through targeted investments and innovation, airports enhance efficiency, reduce costs, and meet performance benchmarks while advancing toward a resilient, electrified future.

1.1.1 ORNL's Role in the Athena ZEV Project at DFW

The U.S. DOE VTO initiated a multiyear Advanced Transportation Hub Efficiency Using Novel Analysis (Athena) ZEV project[4] in August 2023 centered at Dallas Fort Worth International Airport (DFW), focusing on airport electrification and identifying barriers to widespread vehicle electrification. Led by the National Renewable Energy Laboratory (NREL) with Oak Ridge National Laboratory (ORNL) as a key subcontractor**,** the project focuses on developing tools and planning guidance to electrify various airport transportation sectors, including rental cars, transport network companies, freight, airline ground service equipment (GSE), shuttle buses, and aviation operations**.**

While Athena ZEV's initial phase by NREL prioritized rental car fleet electrification, its broader vision includes transitioning multiple airport transport modes to ZEV technology. A key area gaining

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[1]Airport Ecosystem Study Report: *Electrifying Airport Ecosystems – Act Now to Meet a Growing Demand.* Prepared jointly by Enterprise Mobility, Excel Energy and Jacobs. January 22, 2024. https://www.enterprisemobility.com/content/dam/enterpriseholdings/marketing/innovation-in-mobility/vehicle-innovation/airport-electrification-study-full-report-2024.pdf
[2]Aircraft Ground Support Equipment Market Overview. Credence Research, February 17, 2025. https://www.credenceresearch.com/report/aircraft-ground-support-equipment-market
[3]Airports build for electric vehicles, even as car rental companies pump the brakes. Travel Weekly, February 19, 2024. https://www.travelweekly.com/Travel-News/Car-Rental-News/Airports-build-for-electric-vehicles
[4]Athena ZEV. https://www.athena-mobility.org/.

momentum is the electrification of Ground Support Equipment (eGSE)[5]—a strategic shift as airlines grapple with rising costs, compliance demands, and operational challenges.

Airports provide ideal conditions for eGSE, with predictable routes, flat terrain, low-speed limits, and strict safety standards. Early adopters have reported enhanced reliability, cost stability, and improved local air quality, underscoring the need for robust charging infrastructure.

Replacing diesel-powered GSE with eGSE reduces fuel dependency, delivers instant torque, and enhances efficiency in stop-and-go operations. Unlike internal combustion engine (ICE) powered GSE, eGSE optimally supports auxiliary loads like hydraulic lifts, refrigeration, and pumps, while enabling safer, more flexible charging locations, minimizing congestion and non-productive travel.

With centralized procurement and maintenance, airlines, contractors, and airport operators are well-positioned to drive this transition. By adopting eGSE, airport authorities stabilize costs, mitigate fuel price volatility, boost efficiency, and create a healthier environment making electrification the definitive path forward for efficient operations.

In this backdrop, NREL subcontracted this study to ORNL to leverage its expertise in transportation electrification and energy systems modeling, aiming to develop a strategic tool for modeling electricity demand and assessing grid impacts of freight GSE and drayage operations at DFW Airport freight facility.

1.2 MAXIMIZING EFFICIENCY WITH ELECTRIC GSE AT AIRPORTS

Airports provide a controlled and predictable environment where eGSE can operate with minimal range concerns. With charging stations always within proximity, EVs at airports can maintain high uptime, reduce refueling delays, and streamline ground operations. As the aviation industry embraces electric GSE to enhance efficiency and safety, advanced technologies are redefining how ground operations are managed.[6]

1.2.1 Enhancing Operational Performance with Electric GSE

- **Optimizing Aircraft Handling with Electric Tugs**
  - Modern electric aircraft tugs improve precision and reduce manpower needs through remote control capabilities and advanced obstacle detection systems.
  - Their instant torque delivery, reduced maintenance, and enhanced maneuverability lead to faster turnaround times and lower operational costs.

- **Improving Logistics with Electric Baggage and Utility Tugs**
  - ZEV baggage tugs accelerate cargo movement with responsive acceleration and seamless operation.
  - ZEV's quiet operations with no exhausts make them ideal for indoor use in Maintenance, Repair, and Overhaul facilities and warehouses, ensuring a safer and more efficient working environment.

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[5]Electric Ground Support Equipment at Airports, NREL, December 2017.
https://afdc.energy.gov/files/u/publication/egse_airports.pdf
[6]The Best Electric Ground Support Equipment at Airports for Efficiency. January 13, 2025.
https://www.governmentprocurement.com/news/the-best-electric-ground-support-equipment-at-airports-for-efficiency

- **Automating Ground Operations with AGVs**
  - Autonomous Guided Vehicles (AGVs) increase reliability and precision in handling heavy airframe components such as engines and wings.
  - Programmed for specific routes and speeds, AGVs enhance efficiency and consistency in large-scale logistics and aircraft assembly.

1.2.2 Role of Ground Support Equipment in airport operations

Electric GSE plays a critical role in ensuring efficient freight and passenger movement at airports. Such freight facility equipment facilitates aircraft servicing between flights, including refueling, towing, luggage and freight handling, passenger transport, de-icing, catering, sewage removal, and firefighting.

According to NREL, eGSE is increasingly being adopted due to its operational benefits, including high torque, and lower maintenance costs.[7] Airlines, contractors, and airports benefit from centralized procurement and maintenance, making eGSE a viable alternative to traditional diesel-powered equipment. Electric-powered auxiliary functions such as hydraulic lifts, refrigeration, and pumps improve efficiency while reducing idle fuel consumption. Additionally, electric chargers can be more widely distributed across airports compared to diesel refueling stations, minimizing unnecessary equipment movement.

Airports have been transitioning to eGSE since early deployments in the 2000s, with major projects at airports like Seattle-Tacoma, Philadelphia, and DFW. According to a 2013 survey of Ground Support Worldwide readers, 10% of the existing GSE was electric.[8] Programs such as the FAA's Voluntary Airport Low Emissions Program have supported this shift, with airlines like Delta already converting a significant portion of their fleets. Delta Airlines reported that it had converted 15% (or 15,000 pieces) of its GSE fleet to eGSE as of early 2016.[9] The continued expansion of eGSE contributes to more sustainable and efficient airport operations.

Global Snapshot: Key Statistics on Ground Support Equipment Worldwide

- The total number of operational GSE worldwide is estimated to be around 38,000 to 40,000 units in 2024. These are freight facility GSEs.
- This number will be approximately 44,700 units by 2029 as the aviation industry continues to expand.
- The GSE are expected to grow at a compound annual growth rate of 3.9%.
- The global GSE market is currently valued at $6.1 billion in 2024 and is expected to grow significantly, reaching $7.4 billion by 2029.
- 5 to 10 Ground Support Equipment (GSE) units per 10,000 metric tons of cargo

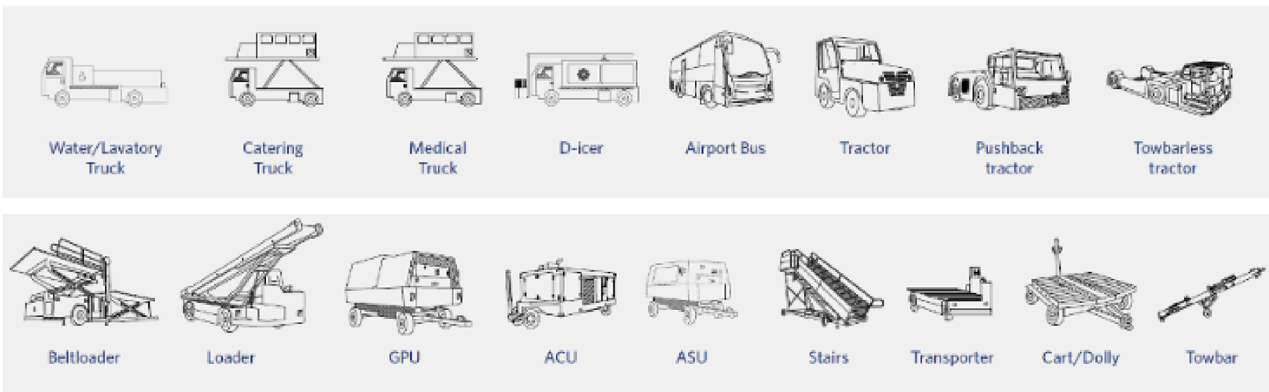
Sources:
1. *https://www.marketsandmarkets.com/Market-Reports/aircraft-ground-handling-system-market-264041553.html*
2. *https://www.globenewswire.com/news-release/2024/06/04/2893280/0/en/Global-Ground-Support-Equipment-Industry-Research-2024-2029-Electric-GSE-Sector-s-Expected-Ascendance-North-American-Market-Leadership.html*
3. *https://www.researchandmarkets.com/reports/4805013/ground-support-equipment-gse-global*

[7] National Renewable Energy Laboratory (NREL), Report on Electric Ground Support Equipment at U.S. Airports. NREL/FS-5400-70359 | December 2017. https://www.nrel.gov/docs/fy18osti/70359.pdf.
[8] Electric GSE Buying Trends Report. March 18, 2013. https://www.aviationpros.com/gse/gse-technology/green-alternative-energy-gse/article/10889496/electric-ground-support-equipment-buying-trends-report.
[9] Delta's Other Fleet: The Science Behind Ground Equipment. March 17, 2016. https://www.aviationpros.com/gse/article/12177348/deltas-other-fleet-the-science-behind-ground-equipment

1.2.3 Categories of GSE and their functions

GSE plays a vital role in ensuring efficient airport operations.

Figure 1-1 provides a visual representation of key GSE types based on their function. GSE supports, services, and maintains aircraft operations on the ground, ensuring efficiency, safety, and timely departures. It facilitates cargo handling, passenger boarding, and aircraft maintenance, while minimizing turnaround times and operational delays. GSE enhances safety through baggage handling, emergency response, and protocol compliance.



Source: Adapted from Overview of Ground Support Equipment (GSE at airports). Airport Suppliers (2023) https://www.airport-suppliers.com/supplier/tcr-international-nv/

Figure 0-1. Different types of GSEs used at airports

GSE enables seamless ground operations, including refueling, deicing, and aircraft positioning, ensuring flights stay on schedule. GSE can be classified into five categories:

I. **Aircraft Handling Equipment**
- Ground Power Units (GPUs): Supply electrical power to aircraft when engines are off, maintaining onboard systems.
- Dolly Tugs and Tractors: Move aircraft safely within the airport, ensuring precise positioning for maintenance and gate operations.
- Pushback Tractors: Assist in maneuvering aircraft away from the gate for departure.

II. **Cargo and Baggage Handling Equipment**
- Container/Pallet Dollies: Transport Unit Load Devices (ULDs), containers, or pallets across the airport using non-motorized, flatbed carts. Towed by tugs or tractors to move cargo between locations efficiently.
- Flatbed Trucks: Carry multiple pallets or ULDs over longer distances within the airport grounds for larger or more distant transfer operations.
- Forklifts: Load and unload cargo from dollies, trucks, or flatbeds, playing a crucial role in moving pallets or containers within the cargo handling area.
- Conveyor Belt Loaders: Facilitate efficient baggage and cargo loading/unloading.
- Cargo Loaders: Handle large or oversized freight, ensuring secure loading.

III. **Passenger Handling Equipment**
- Passenger Boarding Bridges (Jet Bridges): Connect the terminal to aircraft for seamless boarding.

- Stair Trucks: Provide mobile stairs for boarding when jet bridges are unavailable.
- Passenger Buses: Transport passengers between remote aircraft parking areas and terminals.

IV. Aircraft Servicing Equipment

- Fuel Trucks: Deliver fuel to aircraft for departure readiness.
- Lavatory & Water Service Trucks: Maintain onboard lavatories and water supply.
- Deicing Trucks: Remove ice and snow from aircraft for safe operation in cold weather.

V. Maintenance and Safety Equipment

- Maintenance Stands: Provide a stable platform for aircraft inspections and repairs.
- Fire and Rescue Vehicles: Ensure rapid emergency response.
- Aircraft Jacks & Towbars: Aid in lifting and repositioning aircraft for maintenance.

This classification enables airports to optimize GSE deployment, ensuring operational efficiency, safety, and timely departures.

1.3 SCOPE OF STUDY

Under the Athena ZEV project, ORNL analyzes GSE movement at an air freight facility and assesses the grid impact of electrifying GSE and drayage[10] operations within DFW's controlled areas ("behind the fence"). While NREL evaluates freight movements between aircraft and passenger terminals, ORNL focuses on freight movements between aircraft and cargo terminals, working closely with DFW representatives nominated by NREL.

To support this, ORNL developed the *Airport GSE Infrastructure & Logistics Electrification Assessment Tool (Agile@)*—a platform integrating the Freight Facility Model (FFM), the Activity-Structure-Intensity-Fuel (A-S-I-F) framework, and Monte Carlo Simulations. Agile model's electricity demand as ICE-based GSE transition to electric. This freight analysis study exclusively focuses on cargo movement and key freight facility GSE, while excluding GSE used for passenger services and aircraft maintenance. The study primarily focuses only on the following four of the most common pieces of GSE, namely, forklifts, cargo loaders, pushback tractors, and tug tractors as they have the electric options available, as shown in **Figure 1-2**.

ORNL's study team concentrates on two primary tasks:

1. **Bridging Data Gaps** – Collaborates with NREL and DFW to gather and refine data for FFM, analyzing ICE-powered GSE movements and quantifying cargo flow and operational needs at DFW's cargo terminals.
2. **Modeling Electricity Demand** – Integrates FFM outputs into Agile@ to estimate electricity demand, simulating the transition from ICE-powered GSE to eGSE and evaluating grid impacts.

[10]Drayage is a key component of modern logistics, responsible for the short-distance transportation of goods between aircraft, warehouses, and distribution centers, ensuring seamless connectivity within the supply chain.

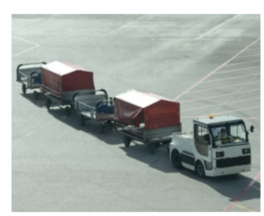
GSE Type	Description	Picture of the GSE
Forklift	A forklift is a heavy-duty vehicle designed for handling air cargo containers and pallets at airports. These forklifts are built to operate on the airport on a paved surface where aircraft are parked, equipped with large tires and a powerful lifting mechanism to transport heavy loads efficiently. They play a crucial role in loading and unloading cargo from aircraft, ensuring smooth logistics operations.	
Cargo Loader	A cargo loader is a specialized vehicle designed for loading and unloading air cargo containers and pallets into aircraft. It features a scissor lift mechanism that allows it to raise and lower Unit Load Devices (ULDs) to match the aircraft's cargo door height. These loaders are essential for efficiently handling heavy cargo, ensuring safe and smooth operations at airports.	
Pushback Tractor	A pushback tractor is used in airport freight and passenger operations. It is designed to move aircraft in and out of parking positions by pushing or towing them, particularly when they need to be reversed from the gate but cannot move backward on their own. These vehicles are crucial for maintaining efficient airport logistics, ensuring timely departures, and maneuvering aircraft safely in congested areas.	
Tug Tractor	A tug tractor, also known as a baggage tug or cargo tractor, is used in airport freight and passenger operations. It is a compact, yet powerful vehicle designed to tow cargo containers, baggage carts, and other ground equipment across the airport tarmac.	

Figure 0-2. Common GSE with electric alternatives analyzed in this study

1.4 ORGANIZATION OF THE REPORT

This technical report evaluates the energy demands, charging requirements, and operational impacts of electrifying GSE fleets to service loading/unloading airplanes between flights and cargo terminals. It assesses the transition's implications on the DFW grid using data-driven modeling and analysis of results. The report comprises six chapters, each structured to ensure clarity in understanding the analysis, methodologies, and outcomes of GSE electrification at DFW air freight facility.

1. **Establishes Context –** Defines the Athena ZEV initiative, project scope, study area, boundaries, and key tasks.
2. **Introduces Modeling Framework –** Presents the assessment tool for estimating electricity demand and grid impacts of GSE and drayage operations.
3. **Analyzes Study Area** – Examines energy needs for GSE and drayage operations between freight aircraft and cargo terminals (and not the passenger terminals) within airport premises.
4. **Details Data Collection & Analysis –** Investigates freight facility movements between aircraft and dedicated cargo terminals, excluding passenger terminal operations.
5. **Presents Results & Discussion** – Interprets key findings from the modeling toolkit and scenario assessments.
6. **Conclusion –** Demonstrates the feasibility and strategic benefits of GSE electrification at airports, highlighting energy impact assessment, guiding infrastructure planning, and showcasing the scalability of the Agile@ tool for data-driven decision-making.

2. FRAMEWORK FOR ANALYSIS

2.1 AGILE@ PLATFORM: A STRUCTURED FRAMEWORK FOR ANALYSIS

This section introduces an analytical framework for estimating freight demand at DFW and assessing the impact of freight electrification on the airport's grid. Utilizing a structured three-step process as illustrated the flowchart in **Figure 2-1**, the Agile@ Platform integrates the FFM, A-S-I-F framework, and Monte Carlo Simulations to generate critical insights into freight electrification. This platform enables users to analyze current and future GSE electrification, supporting infrastructure planning and operational strategies at airports.

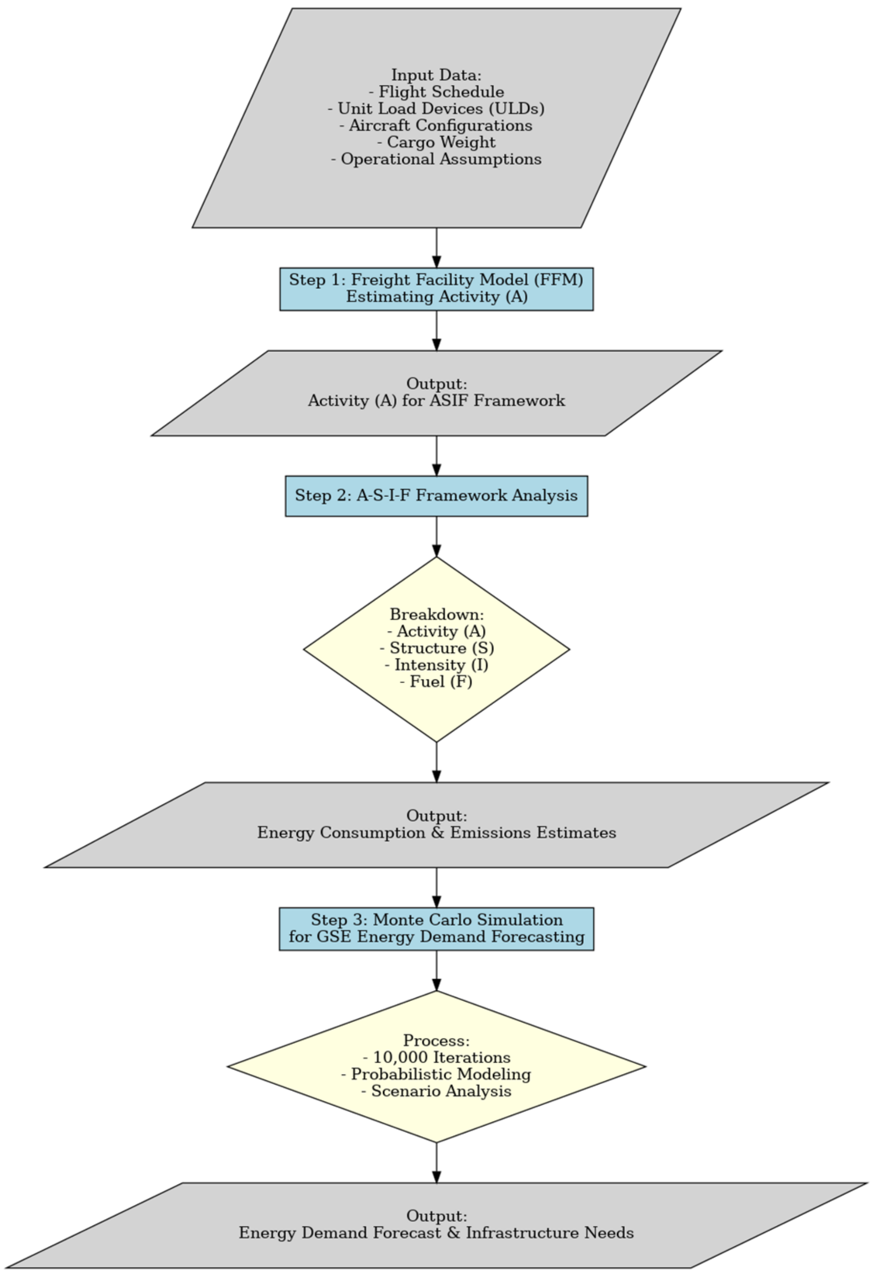


Figure 2-1. Flowchart of the Agile@ Platform

The Agile@ Platform shown in **Figure 2-1** has three main steps, each with key components and interactions:

Step 1: Freight Facility Model (FFM) - Estimating Activity (A)

- **Input Data:**
  - Flight schedule (cargo flights per day)
  - Unit Load Devices (ULDs) and aircraft configurations
  - Cargo weight (monthly tonnage)
  - Operational assumptions (e.g., refueling time, pushback distance)
- **Process:**
  - Compile flight turnarounds
  - Determine ULDs and cargo configurations
  - Estimate (A) value for ASIF framework
- **Output:**
  - Activity (A) for ASIF framework

Step 2: A-S-I-F Framework – Estimating Energy Demand and Environmental Impact

- **Input Data:**
  - Activity (A): Aircraft-GSE logistics (daily distance, hours, ton-km)
  - Structure (S): GSE Fleet composition by category of the freight facility equipment
  - Intensity (I): Energy consumption per unit operation (kWh/km, kWh/ton-km)
  - Fuel (F): Environmental impact factors based on fuel type used (g of pollutants per liter)
- **Process:**
  - Decomposes transportation energy demand into A, S, I, and F components.
  - Quantifies the impact of each factor on total energy consumption.
  - Identify key drivers of changes in energy demand within the transport sector.
  - Analyzes interactions between operational activity, fleet composition, energy intensity, and fuel type.
  - Supports policy and technology assessments for improving energy efficiency and minimizing environmental footprint.
- **Output:**
  - Calculating total energy consumption by multiplying A, S, I, and F.
  - Identifies the primary drivers of energy consumption changes in transportation modes and regions.
  - Quantifies the contribution of each factor to overall energy demand variations.
  - Facilitates comparative analysis across different regions or time periods by examining changes in the ASIF components.
  - Supports policy design by highlighting key areas for Promoting energy efficiency.

Step 3: Monte Carlo Simulation – GSE Energy Demand Forecasting

- **Input Data:**
  - Leverage results from ASIF framework to model uncertainty in GSE energy consumption
  - Use probabilistic distributions (like a normal distribution) to capture variability in:
    - Energy patterns
    - Fleet growth
    - Operational efficiencies
  - Incorporate key assumptions:
    - Freight growth
    - GSE fleet growth
    - Battery capacities
    - Specific energy consumption

    - Explore multiple scenarios (e.g., high growth, phased electrification)
    - Project energy demand and infrastructure needs for future planning
  - **Process:**
    - 10,000 iterations to model uncertainties
    - Probabilistic modeling of energy demand
    - Scenario analysis (fleet growth, electrification pathways)
  - **Output:**
    - Energy demand forecast
    - Infrastructure needs for electrification

2.1.1 Agile@ Analytical Framework

This section explains the operation of the Freight Facility Model (FFM), Activity-Structure-Intensity-Fuel (ASIF) framework, and Monte Carlo Simulations within Agile@. It outlines their key components, interactions, and their role in estimating electricity demand for the transition of GSE from ICE to electric power.

a. Freight Facility Model

The Freight Facility Model (FFM) employs event-based simulation to analyze ground support equipment (GSE) movement between aircraft and cargo terminals. It generates data-driven insights into airside freight handling and provides outputs to Agile@ for assessing electrical demand during the transition from ICE-based to electric GSEs. As more data are integrated, FFM enhances simulation accuracy and improves representation of real-world operations. Key components of FFM are summarized below together with assumptions due to lack of real-world data.

Structure
- **Developed** in C# with a SQL Server database for data storage.
- **Provides** a user interface for selecting analysis periods and carriers.

Input
- **Processes** flight turnaround schedules from cargo operators or airport authorities.
- **Defines** Unit Load Device (ULD) requirements based on aircraft configurations.
- **Accounts** for cargo weight using historical tonnage data.
- **Incorporates** the following operational assumptions, including refueling, towing, pushback, and electric GSE charging primarily due to lack of real-world data.
  - *Allocates* 60-minutes for aircraft refueling.
  - *Covers* the following GSEs: fuel truck, loader, pushback tractor, and dolly tug.
  - *Limits* tug tractor to towing a maximum of 5 dollies.
  - *Adds* 5 minutes to travel time for paperwork and tie-downs.
  - *Sets* aircraft pushback distance at 200 feet and duration at 10 minutes for traffic and paperwork.
  - *Connects* GSE to charger when battery falls below 20%, charges to 80%, then returns to the equipment pool.
  - *Sets* air cargo density at 10 lb/ft^3.
  - *Assigns* a single loader for cargo operations per aircraft, pending data on multi-loader feasibility.
  - *Excludes* bulk cargo (non-ULD) from consideration.

Model Execution
- **Simulates** aircraft arrivals, cargo handling, and turnaround operations.
- **Estimates** ULD needs using flight schedules and cargo density factors.

- **Calculates** freight capacity utilization for each aircraft.

Output

- **Generates** Excel-based summaries of equipment usage, energy consumption, and key operational metrics.

By integrating FFM outputs, Agile@ enables a comprehensive assessment of freight electrification and its grid impact at DFW. The next sections detail the framework's implementation and findings.

b. ASIF Framework[11]

The ASIF framework breaks down GSE operations in an airport into four key components:

- **Activity (A): Evaluates** GSE operational characteristics (daily distance, hours, usage frequency in ton-km) using FFM, leveraging freight data collected from logistic companies operating at the airport to analyze aircraft-cargo terminal logistics.
- **Structure (S): Examines** fleet composition and ownership across airlines and logistics firms (units expressed in percentage)
- **Intensity of Energy Use (I): Calculates** energy consumption per unit of operation (units expressed in kWh/km, kWh/ton-km, KWh/hour).
- **Fuel (F):** Evaluates exhaust emissions based on the type of fossil fuel used (units expressed in grams of exhaust emissions per unit energy burned by ICE-powered GSEs).

The ASIF framework uses Equation 1 to estimate total exhaust emissions loading from ICE-powered GSEs in airport cargo handling, with the first three terms in Equation 1 providing energy demand estimates.[12] Furthermore, total freight facility movement by GSE (A) in Equation (1) is generated by the event-based simulation model FFM described earlier.

$$G = \sum_{k,f}(A \times S \times I \times F) \qquad \ldots(1)$$

where

G = exhaust emissions from cargo handling using GSEs (tones of emissions)
A = total freight movement by GSE (tkm)
S = modal share of GSE composition (percent)
I = energy intensity of GSE by type (liters/tkm or kWh/tkm)
F = fuel mix and emission characteristics (grams of pollutant/liter)
k = fuel type
f = GSE mode type

The types of data available across large airports like DFW vary widely and there are deficiencies and inconsistencies in the available data. Expanding the knowledge base is essential to use ASIF framework effectively. For most airports, data is often either nonexistent or inaccurate. Under such a situation, the ASIF method helps to provide a common measure across these diverse airports and begins to provide an understanding of their unique circumstances. Estimating the GSE fleet size in operation and its composition, the average distance traveled and occupancy or load factor in each type of vehicle is the

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[11] Bose, Ranjan K. 2007. Urban Transport Scenarios in South Asia | Energy and Environmental Impact of Enhanced Public Transport Systems. *Transportation Research Record: Journal of the Transportation Research Board, No. 2011,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 116–126. https://journals.sagepub.com/doi/epdf/10.3141/2011-13

[12] While the ASIF Framework provides both energy demand and exhaust emissions, the Athena ZEV Freight analytical work focuses solely on assessing the impact of transitioning ICE-powered GSEs to eGSEs. This study analyzes the electricity demand implications of GSE electrification for freight movement between aircraft and cargo operations at DFW, informing its potential impact on the local grid on electricity load.

starting point for implementing the ASIF method. Yet this proves to be a major challenge because of the deficiencies and inconsistencies in the available data, and several past studies have been based on estimates that are highly questionable.

c. Monte Carlo Simulations for GSE Energy Demand Forecasting

The Athena ZEV Freight study models GSE energy consumption uncertainty using 10,000 Monte Carlo simulations in Agile@, leveraging probabilistic distributions to capture energy patterns, fleet growth, and operational efficiencies. Given limited data, it explores scenarios from high growth to phased electrification to project energy demand and infrastructure needs. Key assumptions include freight and fleet growth, battery capacities, and energy consumption, ensuring a robust foundation for future planning.

Key Assumptions

In the absence of actual data on several fronts for the study area, the study incorporates key assumptions to model the impact of electrification,

- *Freight Growth Rate:* Annual increase of 1.25–1.5% in air freight volume.
- *GSE Fleet Growth Rate:* Compound annual growth rate of 3.9%, leading to approximately 475–570 units by 2029.
- *Battery Capacities:* Ranges from 50–350 kWh depending on the type of GSE.
- *Specific Energy Consumption:* Varies from 0.5–2.5 kWh/km based on GSE characteristics (see Table 2-1).

Why Monte Carlo Simulation for GSE Energy Forecasting?

Monte Carlo simulations model complex, variable-driven systems like airport GSE operations, ensuring accurate energy demand forecasts and supporting electrification strategies.

Key Advantages:

- **Handle Uncertainty & Variability:**
  - Capture real-world fluctuations in GSE energy consumption, fleet composition, and operational distances.
  - Account for unpredictable freight volumes and efficiency changes.
- **Enable Comprehensive Scenario Analysis:**
  - Run 10,000+ iterations to identify best-case, worst-case, and most-likely energy demand scenarios.
  - Support strategic load management and infrastructure planning.
- **Conduct Sensitivity Analysis:**
  - Determine key factors (e.g., fleet growth, distance traveled) influencing energy demand.
  - Guide decision-makers in optimizing critical variables for efficiency.
- **Optimize Infrastructure & Investment:**
  - Identify peak demand periods to inform charging infrastructure placement.
  - Plan for future growth and prevent unnecessary grid overloads.
- **Enhance Forecasting Accuracy for Electrification:**
  - Project energy impacts of GSE electrification at DFW.
  - Ensure grid reliability and sustainability with data-driven insights.

Monte Carlo simulations equip planners with actionable, probabilistic forecasts, enabling efficient, future-proof electrification strategies.

Source: Monte Carlo Simulation: What It Is, How It Works, History, 4 Key Steps. In Investopedia. Accessed on 21 February 2025 from https://www.investopedia.com/terms/m/montecarlosimulation.asp

The Monte Carlo technique is a statistical simulation method used in this code to analyze the uncertainties in energy consumption for ground support equipment (GSE) in an airport or logistics setting. Given the inherent variability in operational conditions, such as fluctuating energy usage, changing loads, and unpredictable external factors, Monte Carlo simulations provide a way to model these uncertainties and generate probabilistic insights.

In this approach, random values are generated within predefined minimum and maximum energy consumption ranges for each type of equipment, assuming a uniform distribution. By running 10,000 simulations per scenario, the code produces multiple confidence levels, including the 1%-99% range to capture extreme possibilities, the 5%-95% range for high-confidence estimates, the 25%-75% range for typical variations, and the 50% median estimate for a balanced central value. These confidence intervals offer a more comprehensive view of possible energy outcomes, helping stakeholders prepare for best-case and worst-case scenarios.

To make the results more accessible, the code visualizes the simulated data through various plots, such as hourly energy trends with uncertainty bands, total daily and weekly energy distributions, and equipment-specific energy profiles using box plots and violin plots. These visualizations highlight the range and distribution of energy consumption, allowing for better decision-making and risk assessment in operational planning.

Monte Carlo simulations are particularly beneficial because they account for variability, making predictions more realistic than fixed estimates. They also support risk management by identifying potential energy shortages or inefficiencies, helping planners optimize equipment usage and charging schedules. By incorporating a probabilistic approach to energy forecasting, this analysis enables more efficient resource allocation and strategic planning, ensuring smooth and energy-efficient GSE operations in airport ground support activities.

The energy calculation for pushback tractors, cargo loaders, tugs, and forklifts begin with applying first principles of physics—calculating the kinetic energy ($\frac{1}{2} mv^2$) and the work done against resistive forces such as friction and gravitational gradients. In an idealized scenario, one would use these basic equations to determine the energy required for acceleration, deceleration, and steady motion. However, real-world conditions introduce inefficiencies such as mechanical losses, variable surface friction, aerodynamic drag, and the dynamic nature of the loads being moved. To bridge the gap between theory and practice, correction factors are applied to account for these deviations, ensuring that the calculated energy more accurately reflects the actual performance. Based on these calculations the values used in the Monte Carlo Simulation are given in **Table 2-1**.

Table 2-1. Energy Consumption Pattern of GSEs

Pushback Tractor (kWh/pushback)		Loader (kWh/kg/hour)		Tug (kWh/km/kg)		Forklift (kWh/Kg)	
Min	Max	Min	Max	Min	Max	Min	Max
7	10	0.0003	0.0005	0.001	0.003	0.002	0.003

The values given in **Table 2.1** are derived from Newtonian mechanics using first principles of motion. Detailed calculations for each GSE type are provided in **APPENDIX A**.

Simulation Outputs

Monte Carlo simulation generates:

- Hourly energy demand profiles for each GSE type
- Total daily energy consumption estimates for current and future scenarios

3. THE STUDY AREA

3.1 DALLAS-FORT WORTH INTERNATIONAL AIRPORT

DFW International Airport is one of the world's largest and busiest airports, covering 18,076 acres—making it the largest in Texas, second-busiest airport in the world. In 2022, according to the reports from Airports Council International (ACI), DFW handled 73.4 million passengers and 901,502 tons[13] of cargo.[14]

Strategically positioned between Dallas and Fort Worth, DFW serves as a major domestic and international hub. The airport comprises five terminals (A–E), with A, B, and C dedicated to domestic flights, while D and E accommodate both domestic and international travel (see **Figure 3-1**). A high-speed Skylink train connects all terminals within the secure area for seamless passenger transfers.

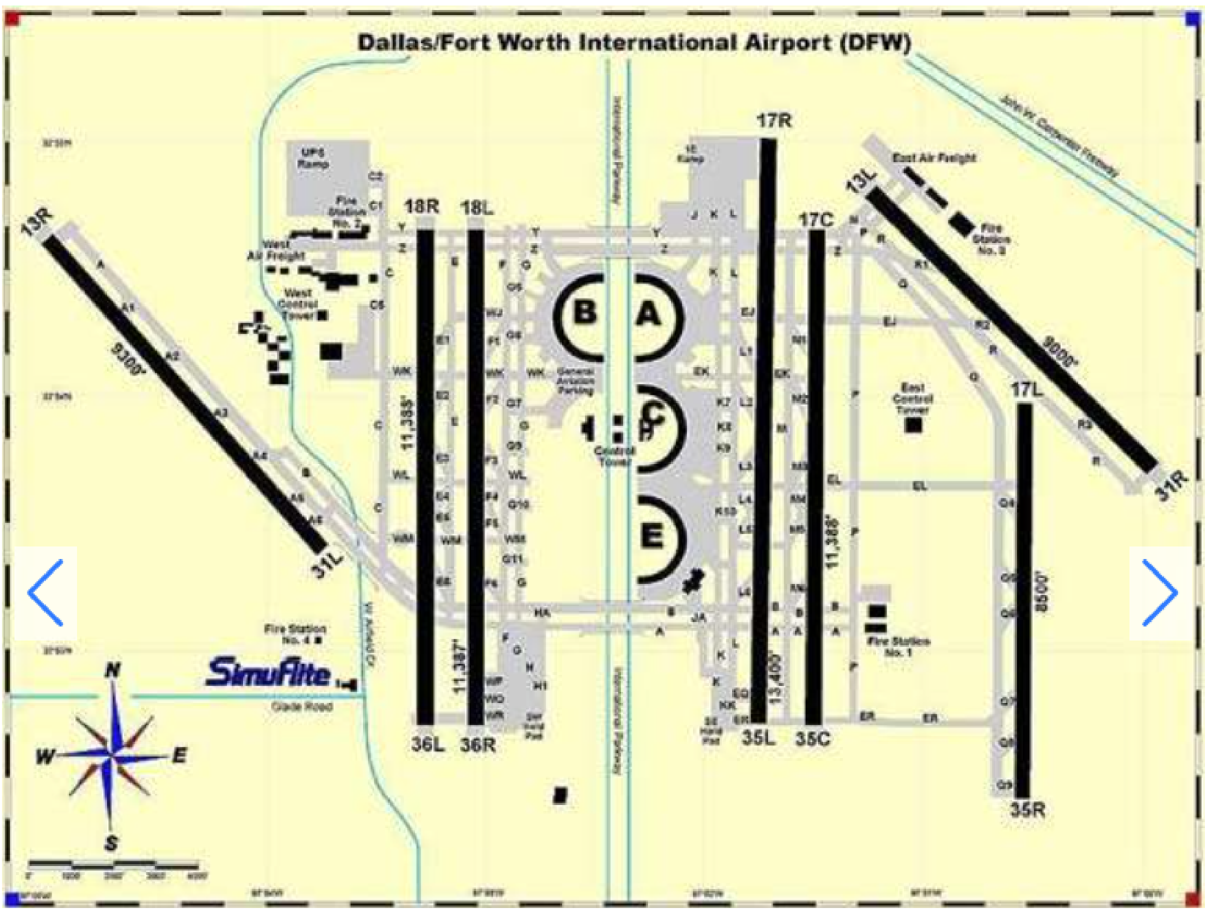

Figure 3-1. Layout of Dallas / Fort Worth International Airport

Source: Extracted from Dallas / Fort Worth International Airport, April 24, 2017. https://www.airport-technology.com/projects/dallas-fort-worth-international-airport/?cf-view

[13] The unit is short tons (U.S. tons). 1 short ton = 2,000 lbs (907.1847 kg).

[14] Dallas/Fort Worth ranks as the second-busiest airport in the world. April 17, 2023. https://www.aviacionline.com/dallas-fort-worth-ranks-as-the-second-busiest-airport-in-the-world.

For this freight analysis study confined to cargo terminals only, the task team used a Google Earth screenshot to highlight three key cargo operations areas at DFW, shown in **Figure 3-2**. The UPS facility is in the northwest**,** the FedEx facility in the northeast, and all other freighters and integrators operate west of the airport. The list of carriers considered in this study is based on data provided by DFW and terminal-carrier connections were identified using Google Earth views and blue square signs marking buildings in the cargo handling area.

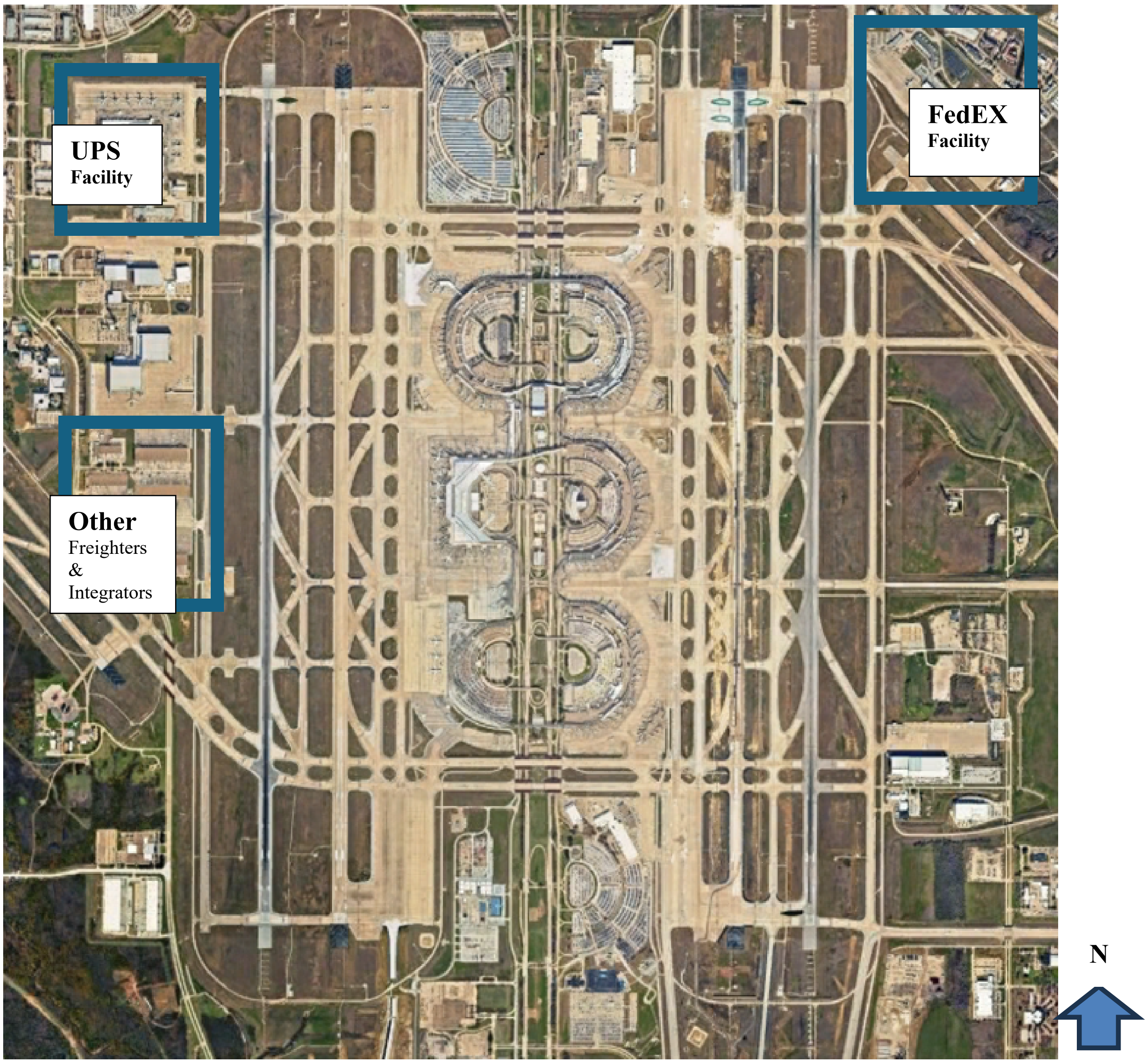

Figure 3-2. Location of the cargo operations areas in blue at DFW (screenshot of Google Earth)

3.2 ORNL'S ROLE IN GSE ELECTRIFICATION AND GRID IMPACT AT DFW

ORNL and NREL defined ORNL's role as a collaborating partner in the September 9, 2024, virtual meeting, focusing on energy demand analysis for electric GSE and drayage operations at DFW's controlled freight facilities ("behind the fence"). ORNL contributions to the study include:

- Developing a conceptual framework and model for GSE electrification using the latest DFW freight data.
- Focusing on freight-dedicated GSEs and drayage operations, while NREL estimates GSE energy use at passenger gates.
- Analyzing cargo transport within the airport perimeter to map GSE movement from aircraft to transfer points to cargo handling areas.
- Assessing the grid impact of electrified GSEs by analyzing cargo transfer operations between aircraft and freight terminals.

Four of the most common pieces of GSEs used at DFW at air freight facilities are considered in this analysis. These include cargo loader, forklift, push back tractor and tug tractor.

3.2.1 A Generic DFW airport layout map to illustrate cargo movement

The schematic diagram in **Figure 3-3** illustrates the typical movement of freight between aircraft and the cargo terminal in a large airport, using various types of GSEs. It highlights the key components involved in cargo handling, including the cargo and passenger terminals, transfer points, and the specific equipment used in different stages of freight movement. Most large airports intentionally segregate passenger activities from freight facilities meaning that any "belly freight" carried by passenger aircraft requires movement to a freight facility for final disposition and delivery. In the schematic, the "cargo transfer point" represents the location where the "chain of custody" of this belly freight transfers from passenger terminal personnel to those of a freight facility. Depending on the airport and airline, this point can be near the passenger terminal, the freight facility, or some intermediate point. Once this transfer is completed, the remaining cargo movements are typically limited to storage, transfer to another aircraft, or customer/agent pickup.

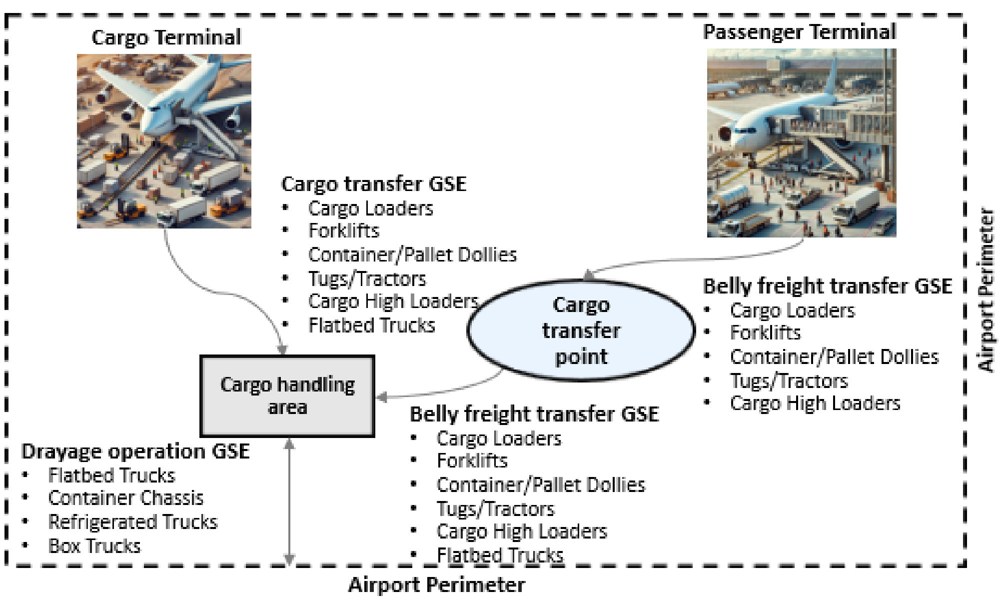

Figure 3-3. Conceptual Airport Layout for Cargo Operations and GSE Energy Analysis

3.2.2 Key Elements of the Conceptual Airport Layout

1. **Cargo Terminals**
   - This is the designated area for handling dedicated cargo aircraft operations.
   - Freight from cargo planes is transferred using Cargo Transfer GSE, which includes:

        - Cargo Loaders
        - Forklifts
        - Container/Pallet Dollies
        - Tugs/Tractors
        - Cargo High Loaders
        - Flatbed Trucks
2. **Passenger Terminal (Belly Freight Handling)**
    - DFW Airport handles cargo primarily through its dedicated Cargo and Logistics Center, while belly cargo on passenger flights may be processed at passenger terminals before transfer to freight facilities.
    - It utilizes Belly Freight Transfer GSE, including:
        - Cargo Loaders
        - Forklifts
        - Container/Pallet Dollies
        - Tugs/Tractors
        - Cargo High Loaders
3. **Cargo Handling Area & Cargo Transfer Point**
    - This is the intermediary location where cargo is transferred between aircraft and ground transportation.
    - It acts as a hub where different types of GSE operate to facilitate the movement of freight efficiently.
4. **Drayage Operation GSE** (Transporting Cargo within the Airport Perimeter)
    - After cargo is offloaded from the aircraft, it is moved between the terminals or outside the airport using:
        - Flatbed Trucks
        - Container Chassis
        - Refrigerated Trucks
        - Box Trucks

3.2.3 Process Flow

1. Cargo from aircraft (either cargo aircraft or passenger belly freight) is unloaded using Cargo Loaders and transferred via Forklifts, Dollies, and Tugs/Tractors to the cargo handling area.
2. In the Cargo Handling Area, freight is either sorted for further airport distribution or transferred to the Drayage Operation for movement outside the airport.
3. If cargo is meant for another aircraft, it is transported between the Cargo Terminal and Passenger Terminal via the Cargo Transfer Point, ensuring smooth transition using designated GSE.

This structured approach ensures efficient cargo movement while maintaining operational efficiency within the airport perimeter.

GSEs are used to transfer cargo from the transfer point to the cargo handling area as shown in **Figure 3-3** typically include the following:

3.2.4 GSE Used for Cargo Transfer and Handling

The GSEs typically include the following:

- **Tugs/Tractors:** Tow cargo dollies or carts from the transfer point to the cargo handling area.
- **Container/Pallet Dollies:** Transport Unit Load Devices (ULDs), containers, or pallets between locations within the airport when towed by tugs or tractors.

- **Flatbed Trucks:** Carry multiple pallets or ULDs over longer distances within the airport grounds.
- **Forklifts:** Load and unload cargo from dollies, trucks, or flatbeds, and move pallets or containers within the cargo handling area.
- **High-Loaders (Cargo Loaders):** Lift cargo to the appropriate height when transferring between different levels, such as from a flatbed to a higher cargo bay.
- **Roller Beds:** Facilitate the smooth transfer of containers and pallets from tugs or trucks to the handling area, reducing manual effort and accelerating the process.

3.2.5 GSE for Loading/Unloading Cargo Aircraft and Transferring Cargo

For loading and unloading cargo aircraft, the following GSE is typically used:

- **Cargo Loaders (High-Loaders):** Lift large containers or pallets into the cargo hold of an aircraft, with adjustable heights to match the cargo door and capable of handling heavy loads.
- **Belt Loaders:** Extend into the cargo hold to *allow* workers to *load* or *unload* smaller items, loose cargo, or baggage manually.
- **Forklifts:** Lift heavy or bulk items directly into or out of the aircraft cargo hold, especially for irregular-sized cargo or on smaller planes without automated loading equipment.
- **Conveyor Systems:** Transfer smaller cargo or baggage to/from the aircraft, reducing manual labor and speeding up the process.

3.2.6 GSE for Transferring Cargo to the Cargo Handling Area

For transferring cargo to the cargo handling area, the following GSE is typically used:

- **Tugs/Tractors:** Pull loaded carts from the aircraft to the cargo handling area.
- **Container/Pallet Dollies:** Transport ULDs, containers, or pallets between the aircraft and cargo handling areas, often hitched together and *pulled* in a train by a tug.
- **Flatbed Trucks:** Transfer larger quantities of cargo or containers over longer distances between the unloading point and the cargo handling area.
- **Roller Beds:** Assist in efficiently moving containers and pallets from dollies or loaders into warehouses or cargo processing areas.

4. FFM SIMULATION: DATABASE COMPILATION AND OUTPUTS

This chapter defines the process of compiling the database and preparing inputs for the FFM simulation. It first details the data sources, assumptions, and key considerations to ensure model accuracy and adaptability. Next, it presents the model run and simulation results for aircraft scheduling. Finally, it outlines the FFM outputs in an Excel worksheet for Agile@ to predict electricity demand for GSE movements.

4.1 DATA INPUTS AND ASSUMPTIONS

The FFM simulates the movement of GSE at an air freight facility, tracking cargo movement between aircraft and cargo terminals. The model uses several types of input data to simulate realistic freight operations at the DFW Airport. These inputs are compiled and processed into structured databases to ensure accurate and effective simulations.

4.1.1 Flight Schedule

The flight schedule—*to determine aircraft arrivals and departures*—is a crucial component of FFM since it dictates the timing and frequency of aircraft turnarounds—when an aircraft arrives and departs from DFW.

- **Retrieve flight schedules from DFW**: DFW Airport provided the proposed freighter schedules for the Summer 2024 and Winter 2024-2025 seasons. These schedules include all relevant details about arrival and departure times, flight numbers, and carrier information for freighter aircraft.

- **Supplement missing data for UPS, FedEx, and DHL**: Most cargo flights at DFW are flown by UPS, FedEx, and DHL. However, these schedules were not available from DFW. To fill this gap, the FlightRadar24 website (https://www.flightradar24.com) was used to gather flight data for these carriers during January 2025, focusing on turnarounds of UPS, FedEx, and DHL flights. The additional flight data were compiled into the database for more comprehensive coverage.

- **Calculate daily flight turnarounds**: With the schedule information in hand, the number of turnarounds by day of the week was computed, as shown in **Figure 4-1**. A turnaround is the time taken from an aircraft's arrival until its next departure. This data is key for FFM as it helps to simulate the required GSE movements and timing.

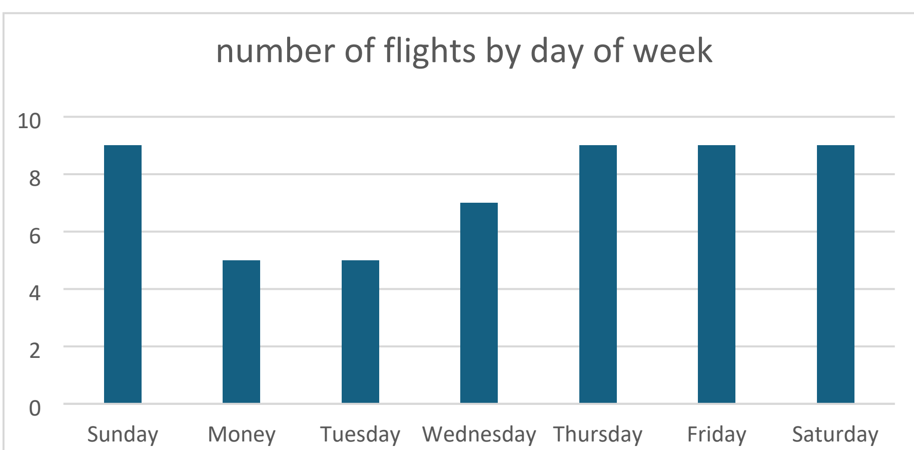

Figure 4-1. Number of Flights by Day of Week

- **Integrate turnarounds data for UPS, FedEx, and DHL**: The data collected from FlightRadar24 was analyzed to determine the turnaround times for UPS, FedEx, and DHL flights in January 2025. This supplementary data is presented in **Figure 4-2** and incorporated into the flight schedule database, ensuring that the FFM reflects the movements of these major cargo carriers.

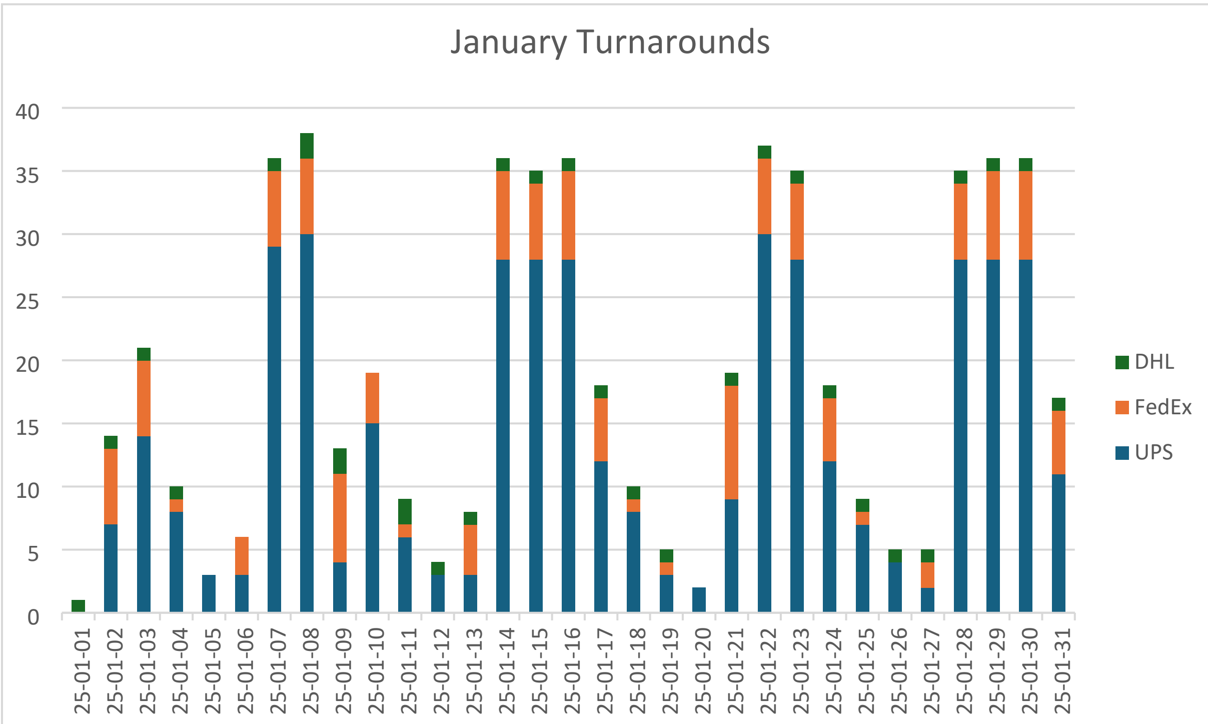

Figure 4-2. Turnarounds in January 2025 for UPS, FedEX, and DHL

- **Provide schedule-based triggers for GSE movement**: The flight schedules and turnaround times are then used by the FFM to trigger GSE movement operations. The simulation uses these data to determine when GSE needs to be deployed, how long it should operate, and when it will return to the equipment pool for recharging or maintenance.

4.1.2 Unit Load Devices

Unit Load Devices (ULDs)—*to define cargo handling requirements*—are standardized containers used for shipping cargo. These are essential for efficient cargo handling, and their characteristics must be accurately represented in the FFM.

- **Categorize ULDs by size, type, and aircraft compatibility**: ULDs come in various shapes and sizes. The FFM categorizes the different types of ULDs used at DFW. The ULDs included in the simulation are selected based on the most common ones used for freighter operations, as outlined by DFW and available data.

- **Reference representative ULDs for modeling**: The ULDs that are chosen for use in FFM are those that most closely reflect the range of ULDs typically found in cargo operations. Table **4-1** shows the characteristics of the ULDs used in the model. This table specifies the dimensions, weight, and other relevant characteristics for each ULD type.

Table 4-1. ULD Characteristics

ULD		Dimensions (inches)			Tare weight (pounds)	Cube (square feet)
Type	Code	Length	Width	Height		
A1	AAD	125	88	96	508	507
A1O	AAX	125	88	93	575	472
A2N	AAY	125	88	81	480	420
AMP	AMP	125	96	64	509	418
AXY	AXY	108	60.2	77	282	240
L11	ALP	125	60.4	64	355	253
L9N	AAZ	125	88	64	470	365
L9O	AAP	125	88	64	487	379
LD3	AKE	54	75.6	64	157	156
LD8	DQF	96	60.4	64	257	244
M1N	AMJ	125	96	96	633	607

- **Expand ULD options as updated data becomes available**: The ULD characteristics can be updated in the future as more data become available from DFW or carriers. This allows the model to remain accurate as operational standards or equipment change over time.

- **Assign ULDs to aircraft based on flight schedules**: The FFM assigns ULDs to the aircraft based on the aircraft configuration specified in the flight schedule.

4.1.3 Aircraft Configurations

Aircraft configurations—*to model cargo storage locations*—dictate how cargo is stored on an aircraft, which impacts the GSE movement and cargo handling times. The FFM models different cargo compartment configurations for various aircraft types.

- **Identify cargo compartment configurations for different aircraft**: Aircraft vary in their cargo configurations based on their type. Most freighters have multiple cargo compartments, with the main deck typically having the largest capacity. Some aircraft may also have lower decks that are subdivided into fore and aft compartments. The FFM includes all relevant configurations to model these different aircraft layouts.

- **Distinguish between main deck and lower deck (fore/aft) storage**: In the FFM, the main deck and lower decks are treated as distinct storage areas. The types of ULDs being handled depend on whether cargo is being loaded or unloaded from the main deck or a lower deck. This distinction allows the simulation to reflect real-world operations more accurately.

- **Randomize deck configurations for missing data**: The available flight schedules do not provide specific cargo deck data, so the FFM will randomly choose deck configurations based on the available aircraft type. This ensures that the simulation runs even in the absence of detailed configuration data. The available configurations for each cargo compartment are shown in **Table 4-2**.

- **Simulate cargo loading/unloading based on aircraft layout constraints:** Once the aircraft configuration is determined, the FFM simulates the cargo loading and unloading process based on the compartment layout. This includes accounting for how the cargo is distributed across the different decks and ensuring GSE is deployed accordingly.

Table 4-2. Aircraft Configurations

<table>
<tr><th colspan="2">Aircraft</th><th rowspan="2">Cargo Deck</th><th rowspan="2">Deck Configuration</th><th rowspan="2">ULD Type</th><th rowspan="2">Number of ULDs</th></tr>
<tr><th>Model</th><th>Variant</th></tr>
<tr><td rowspan="5">A300</td><td rowspan="5">600F</td><td rowspan="2">aft</td><td>A</td><td>L9O</td><td>3</td></tr>
<tr><td>B</td><td>AMP</td><td>3</td></tr>
<tr><td rowspan="2">forward</td><td>A</td><td>L9O</td><td>4</td></tr>
<tr><td>B</td><td>AMP</td><td>4</td></tr>
<tr><td>main</td><td>A</td><td>A1</td><td>22</td></tr>
<tr><td rowspan="6">B747</td><td rowspan="6">400F</td><td rowspan="2">aft</td><td>A</td><td>L9O</td><td>4</td></tr>
<tr><td>B</td><td>AMP</td><td>4</td></tr>
<tr><td rowspan="2">forward</td><td>A</td><td>L9O</td><td>5</td></tr>
<tr><td>B</td><td>AMP</td><td>5</td></tr>
<tr><td rowspan="2">main</td><td rowspan="2">A</td><td>A1</td><td>29</td></tr>
<tr><td>A1O</td><td>1</td></tr>
<tr><td rowspan="3">B747</td><td rowspan="3">8F</td><td>aft</td><td>A</td><td>M1N</td><td>5</td></tr>
<tr><td>forward</td><td>A</td><td>M1N</td><td>7</td></tr>
<tr><td>main</td><td>A</td><td>M1N</td><td>34</td></tr>
<tr><td rowspan="2">B757</td><td rowspan="2">200F</td><td rowspan="2">main</td><td rowspan="2">A</td><td>A2N</td><td>14</td></tr>
<tr><td>AXY</td><td>1</td></tr>
<tr><td rowspan="6">B767</td><td rowspan="2">200F</td><td>lower</td><td>A</td><td>LD8</td><td>10</td></tr>
<tr><td>main</td><td>A</td><td>A2N</td><td>19</td></tr>
<tr><td rowspan="4">300F</td><td>aft</td><td>A</td><td>LD8</td><td>7</td></tr>
<tr><td>forward</td><td>A</td><td>LD8</td><td>8</td></tr>
<tr><td rowspan="2">main</td><td rowspan="2">A</td><td>A1</td><td>24</td></tr>
<tr><td>L9N</td><td>2</td></tr>
<tr><td rowspan="3">B777</td><td rowspan="3">F</td><td>aft</td><td>A</td><td>LD3</td><td>14</td></tr>
<tr><td>forward</td><td>A</td><td>LD3</td><td>18</td></tr>
<tr><td>main</td><td>A</td><td>M1N</td><td>27</td></tr>
<tr><td rowspan="6">MD</td><td rowspan="6">11F</td><td>aft</td><td>A</td><td>L11</td><td>7</td></tr>
<tr><td rowspan="2">forward</td><td>A</td><td>L9O</td><td>6</td></tr>
<tr><td>B</td><td>AMP</td><td>6</td></tr>
<tr><td rowspan="3">main</td><td rowspan="2">A</td><td>A1</td><td>4</td></tr>
<tr><td>M1N</td><td>22</td></tr>
<tr><td>B</td><td>A1</td><td>26</td></tr>
</table>

4.1.4 Cargo Weight

Cargo weight—*to estimate cargo volume and transport logistics*—is a critical factor in determining the efficiency of cargo loading/unloading and the operation of GSE.

- **Extract monthly enplaned and deplaned cargo data**: The FFM uses the monthly cargo data provided by DFW, which includes the total weight of cargo enplaned and deplaned by carrier. The 2023 cargo data shown in **Figure 4-3** was used as a baseline for simulating cargo flow at DFW.

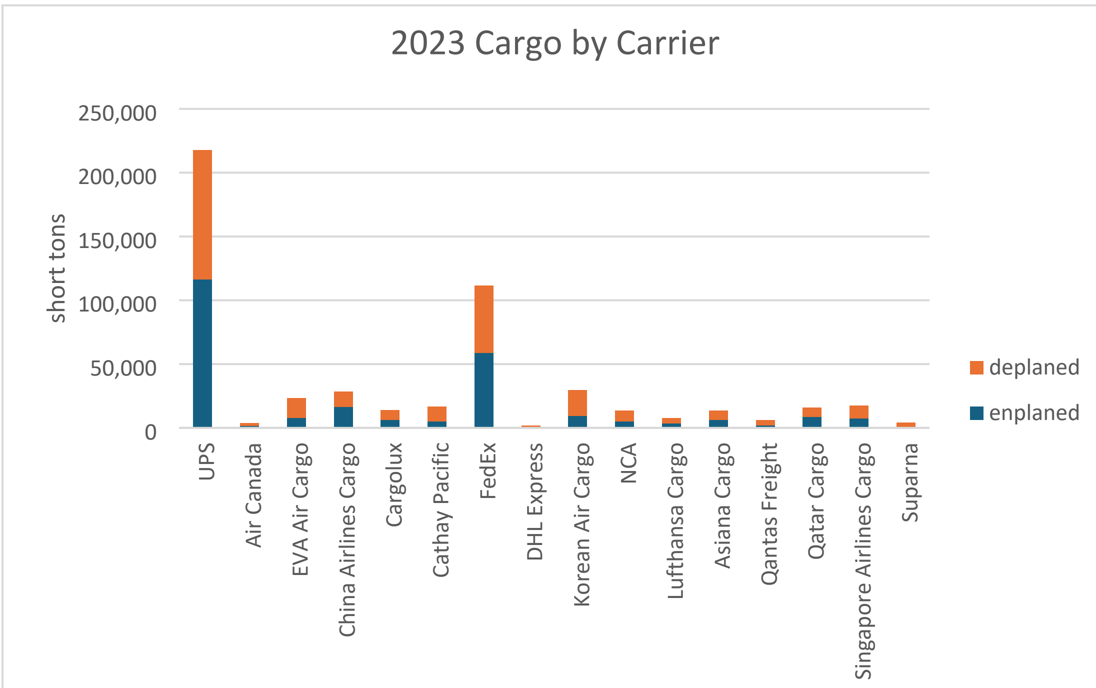

Figure 4-3. 2023 Freight by Carrier

- **Apply weight-density assumptions for cargo estimation**: The model assumes a cargo density of 10 pounds per cubic foot. This density is used to convert the volume of cargo into weight, which is crucial for simulating the appropriate GSE requirements. The assumption allows the model to estimate how much cargo can be loaded into a given ULD or aircraft.

- **Distribute freight volumes across aircraft**: Based on the flight schedule and cargo data, the model simulates how freight volumes are distributed across different aircraft. This helps to estimate how much cargo each GSE will need to handle during loading and unloading processes.

4.1.5 Data Assumptions

The following assumptions are made in FFM to simulate GSE operations more accurately, despite some data limitations.

- **Standardize aircraft refueling time**: The refueling process is assumed to take a standardized 60 minutes, which is based on industry averages and operational constraints.
- **Limit tug tractor capacity**: The tug tractor is modeled to tow a maximum of 5 dollies at a time. This limitation reflects realistic towing capacity and helps simulate GSE operations within the airport.

- **Adjust travel time for facility-aircraft transfers**: An additional 5-minute buffer is added to the calculated travel time between the freight facility and aircraft. This accounts for logistics such as paperwork, tie-downs, and coordination.
- **Set aircraft pushback distance**: The pushback distance for an aircraft is set to 200 feet, with a 10-minute duration. This reflects typical operational requirements, including air traffic control delays and paperwork processing.
- **Define GSE charging logic**: The model includes a charging protocol for electric GSE. If the GSE's battery drops below 20%, it will be recharged to 80% capacity before returning to service. This helps the simulation model accurately reflect the battery management of electric vehicles in a real-world airport setting.
- **Assign a single loader for cargo operations**: For simplicity, the model assumes a single loader is used for loading and unloading operations at the aircraft, even though multiple loaders would be more realistic in some cases. This assumption simplifies the simulation and can be adjusted when more operational data is available.
- **Exclude bulk cargo**: The model does not include bulk cargo (non-ULD cargo) in the simulations. This is due to a lack of operational data for bulk cargo handling processes.

4.2 MODEL RUN AND SIMULATION RESULTS

The FFM simulates aircraft scheduling by incorporating arrival times, cargo volumes, and GSE usage. It determines the number of ULDs enplaned and deplaned based on monthly cargo tonnage and assigns aircraft configurations to estimate the available cargo capacity. Using cargo density factors, it calculates the proportion of ULDs loaded per turnaround, ensuring alignment with realistic volume constraints. The following illustrative example provides a clearer understanding of aircraft cargo loading calculations.

Illustrative Example: Aircraft Cargo Loading Calculation
To determine cargo distribution, the model selects an aircraft configuration and calculates available capacity using a standard air cargo density factor (10 lbs per cubic foot). Since cargo aircraft typically fill up by volume before reaching weight limits, the model ensures realistic load estimates. For example, if the simulation horizon is from 16 January to 15 February, the amount of cargo loaded is (16/31) of the January cargo enplaned plus (15/28) of the February cargo enplaned. The same logic applies for calculating ULDs to be unloaded.

Example Calculation:

- Carrier enplaned **10,305 tons** in January and **9,111 tons** in February.
- For a simulation horizon of **Jan 15 – Feb 15**:

$$\text{Enplaned tonnage} = \left(\frac{16}{31} \times 10,305\right) + \left(\frac{15}{28} \times 9,111\right) = 9,867 \text{ tons}$$

- Available ULD volume: **4,611,074 cubic feet**
- Using cargo density:

$$\text{Total capacity} = 23,055 \text{ tons}$$

- Capacity utilized:

$$\frac{9,867}{23,055} = 42.8\%$$

- Each aircraft loads **42.8% of its max ULDs.**

4.3 MODEL OUTPUTS

The FFM generates outputs that inform analysts about simulated operations and compiles them into a Microsoft Excel workbook. One worksheet details hourly equipment usage and key parameters for energy calculations. Agile@ utilizes these data to predict GSE energy consumption. A sample worksheet is shown in Figure 4-4.

equipment	date	hour	activity	dollies (loaded)	dollies (empty)	distance (miles)	weight (pounds)	time (hours)
loader	1/1/2025	2	travelling to plane			0.095		0.093
tug tractor	1/1/2025	2	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	2	unloading				8585	0.285
tug tractor	1/1/2025	3	travelling to facility	5		0.095	11085	0.090
tug tractor	1/1/2025	3	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	3	unloading				8585	0.251
tug tractor	1/1/2025	3	travelling to facility	5		0.095	11085	0.090
tug tractor	1/1/2025	3	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	4	unloading				8585	0.310
loader	1/1/2025	4	travelling to plane			0.095		0.093
tug tractor	1/1/2025	4	travelling to facility	5		0.095	11085	0.090
tug tractor	1/1/2025	4	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	4	unloading				22686	0.313
tug tractor	1/1/2025	4	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	4	unloading				23543	0.253
tug tractor	1/1/2025	4	travelling to facility	5		0.095	25186	0.090
tug tractor	1/1/2025	4	travelling to facility	5		0.095	26043	0.090
tug tractor	1/1/2025	5	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	5	unloading				27890	0.341
tug tractor	1/1/2025	5	travelling to plane		5	0.095	2500	0.090
loader	1/1/2025	5	unloading				33515	0.299

Figure 4-4. FFM Output: GSE Activity

5. RESULTS AND DISCUSSION

This section analyzes GSE energy consumption through Monte Carlo simulations applied to real-world data, integrating hourly, daily, and weekly trends alongside multi-week heatmaps. Findings are interpreted for GSE operators, airport planners, policymakers, and other key stakeholders.

5.1 AGGREGATE ENERGY CONSUMPTION PATTERNS FOR GSE

5.1.1 Hourly energy consumption patterns

Figure 5-1 illustrates the estimated hourly distribution of energy usage for the four most common GSEs—loaders, tug tractors, forklifts, and pushback tractors (illustrated in Figure 1-2). The figure displays both central tendencies (median) and variability (confidence intervals derived from Monte Carlo simulations), highlighting typical hour-by-hour consumption patterns for all four GSEs put together over a day. The shaded confidence intervals, representing the 5th to 95th percentiles, emphasize the variability. Notable peaks in energy usage are observed during the morning and late afternoon, while overnight hours show relatively low consumption. Specifically, during the quiet overnight period (approximately 23:00–05:00), energy consumption trends lower—often below 20 kWh. In contrast, the morning (07:00–09:00) and late afternoon (16:00–18:00) intervals experience pronounced surges, with consumption reaching or exceeding 45–50 kWh at the upper bounds. These results confirm that only a few hours each day account for a disproportionate share of total GSE consumption, reflecting the concentrated nature of flight arrival/departure schedules and cargo handling tasks.

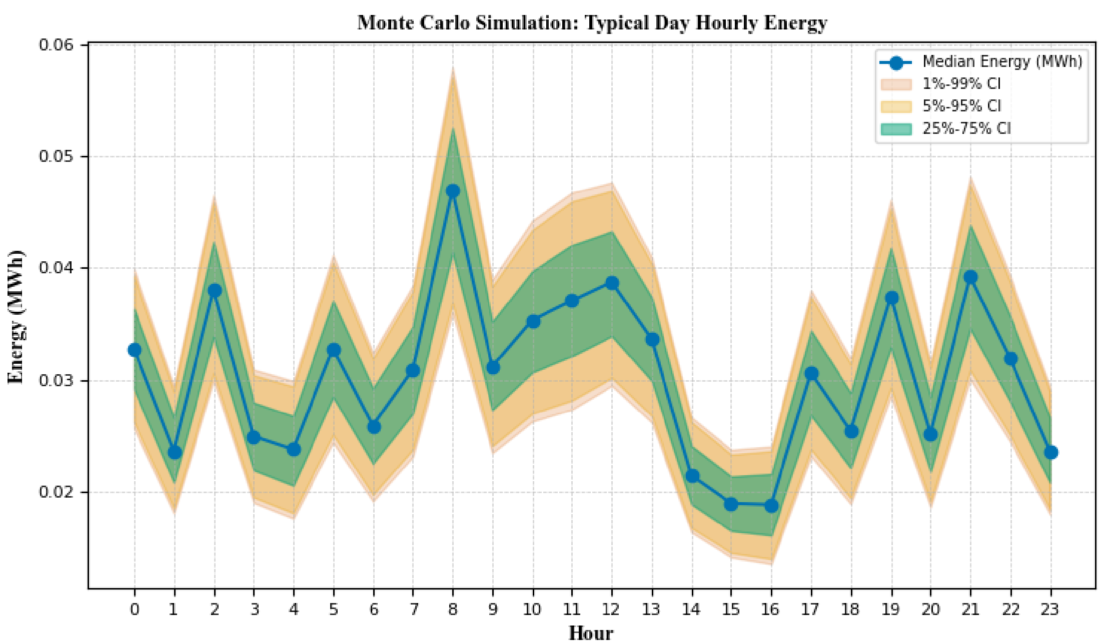

Figure 5-1. Hourly GSE Energy Consumption Over a Day

5.1.2 Daily energy consumption patterns

Figure 5-2 builds on Figure 5-1 by aggregating hourly data into daily load totals over a month, illustrating total daily energy usage for loaders, tug tractors, forklifts, and pushback tractors. The median trend line and confidence bands capture day-to-day variability and surge events. The Monte Carlo analysis estimates a median daily load of ~0.45 MWh, with a 5th–95th percentile range of ~0.3–1 MWh, occasionally exceeding 1.4–1.8 MWh. These extremes, driven by factors like simultaneous wide-body arrivals, heavy cargo loads, or schedule misalignments, highlight operational volatility. For airport operators, such insights inform resource allocation, ensuring adequate staffing, equipment rotations, and contingency planning and power solutions.

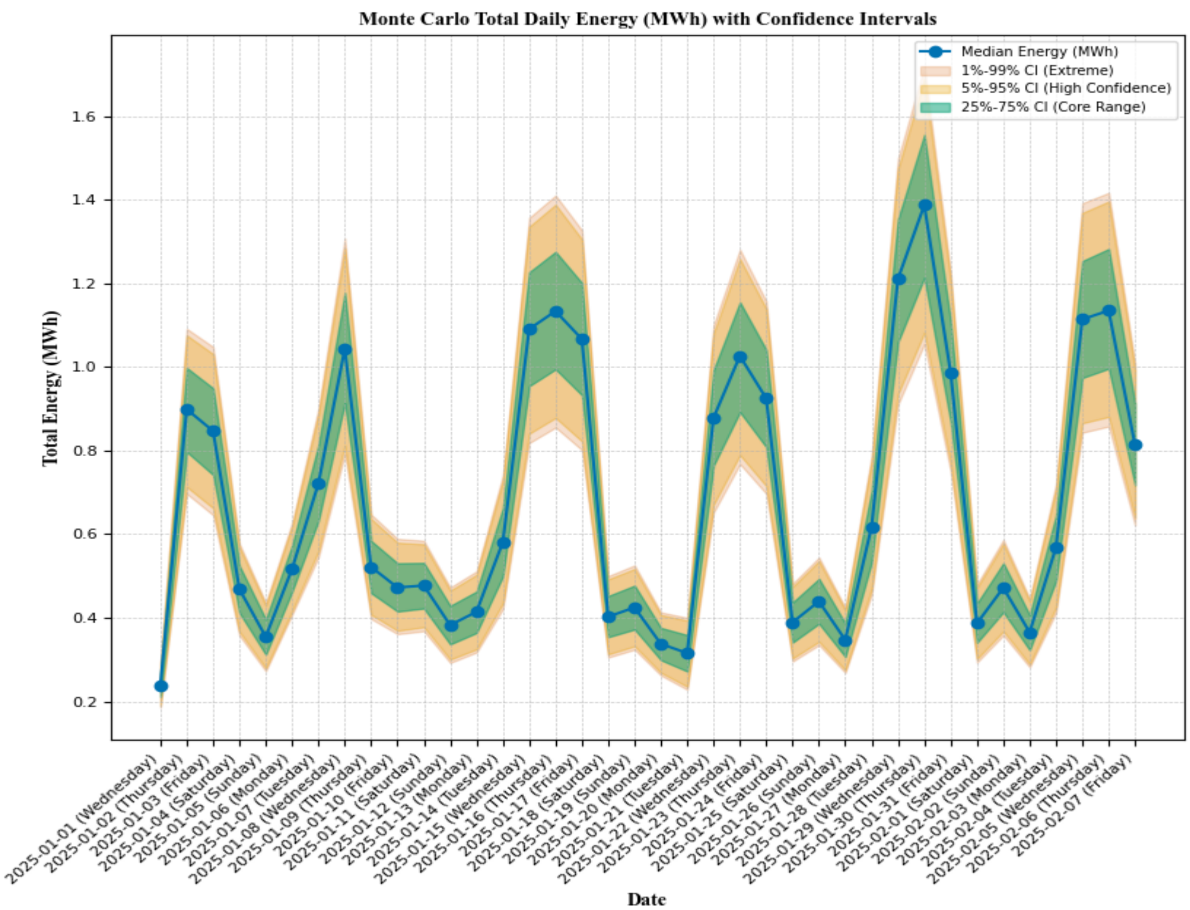

Figure 5-2. Daily GSE Energy Consumption Over a Month

5.1.3 Weekly energy consumption patterns

Figure 5-3 depicts weekly aggregate consumption, with the median cumulative totals typically ranging from ~2.5–5 MWh but exceeding 5 MWh during peak days. It shows how daily fluctuations accumulate into weekly totals, with trend line in blue representing the sum of energy consumption over each seven-day window, highlighting recurring high-demand weeks versus moderate-demand weeks. These surges emphasize the need for sufficient energy infrastructure, transformer capacity, on-site storage, or flexible grid connections—to ensure power service reliability. Weeks with two or three days near 6 MWh can strain the system and increase the risk of logistical bottlenecks.

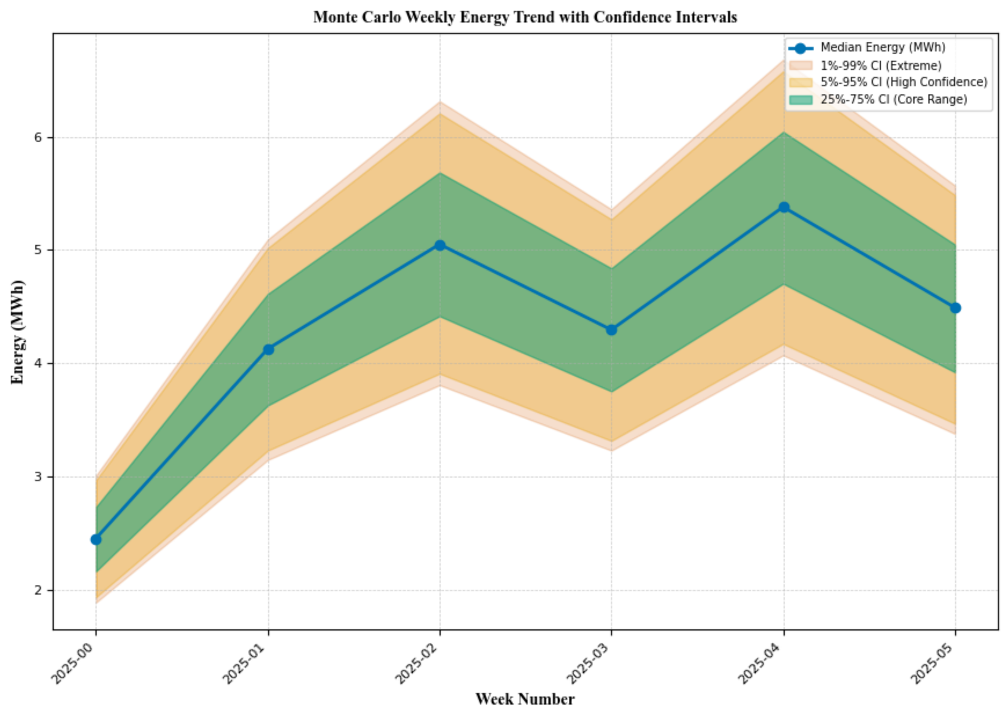

Figure 5-3. Weekly GSE Energy Consumption

5.2 ADVANCED ANALYTICS: ENERGY CONSUMPTION PATTERNS BY GSE TYPE

5.2.1 Hourly energy consumption patterns

Figure 5-4 shows hourly energy consumption for four GSE types—forklift, loader, pushback tractor, and tug tractor—over a 24-hour period, with Monte Carlo-derived confidence intervals (e.g., 1–99%, 5–95%, and 25–75%) shading variability. The tug tractor exhibits the largest spikes, often exceeding 0.02–0.03 MWh/hour, reflecting higher operational demands during cargo handling when hauling cargo or towing multiple dollies. Loaders and pushback tractors show moderate consumption (0.01–0.02 MWh/hour), while forklifts remain the most efficient (below 0.01 MWh/hour). Morning and evening peaks highlight short bursts of activity tied to flight schedules or cargo arrivals. Operators can leverage the overnight lull (below 0.01 MWh/hour) for fueling, recharging, and maintenance, ensuring readiness for peak demand. Monte Carlo simulations reveal tug tractors peak at 30–40 kWh, loaders and pushback tractors at 10–20 kWh, and forklifts stay below 10 kWh.

5.2.2 Daily energy consumption patterns

Figure 5-5 shifts to a daily perspective, plotting total GSE energy usage by type over a sequence of days. The tug tractor peaks at 0.4–0.5 MWh on busy days, marking it as the largest energy consumer. Loaders and pushback tractors range between 0.1–0.3 MWh/day, while forklifts stay below 0.1 MWh/day. Daily spikes in tug tractor consumption occur during heavy cargo flights or extended towing tasks, while lighter days see usage closer to 0.2 MWh. This variability highlights the need for anticipating high-demand days through flight schedule forecasting and cargo monitoring, and adjusting staffing, fueling, and equipment accordingly. Monte Carlo simulations show tug tractor use between 200–500 kWh on busy days, loaders and pushback tractors at 100–300 kWh, and forklifts under 100 kWh. Spikes reflect high-activity periods.

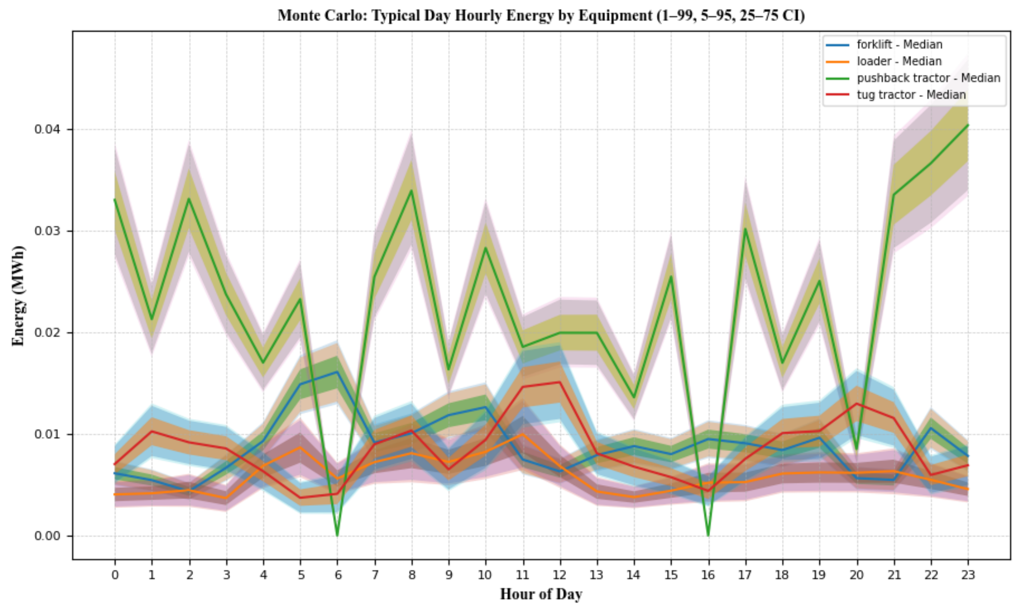

Figure 5-4. Hourly Energy Use Profile of GSEs by type

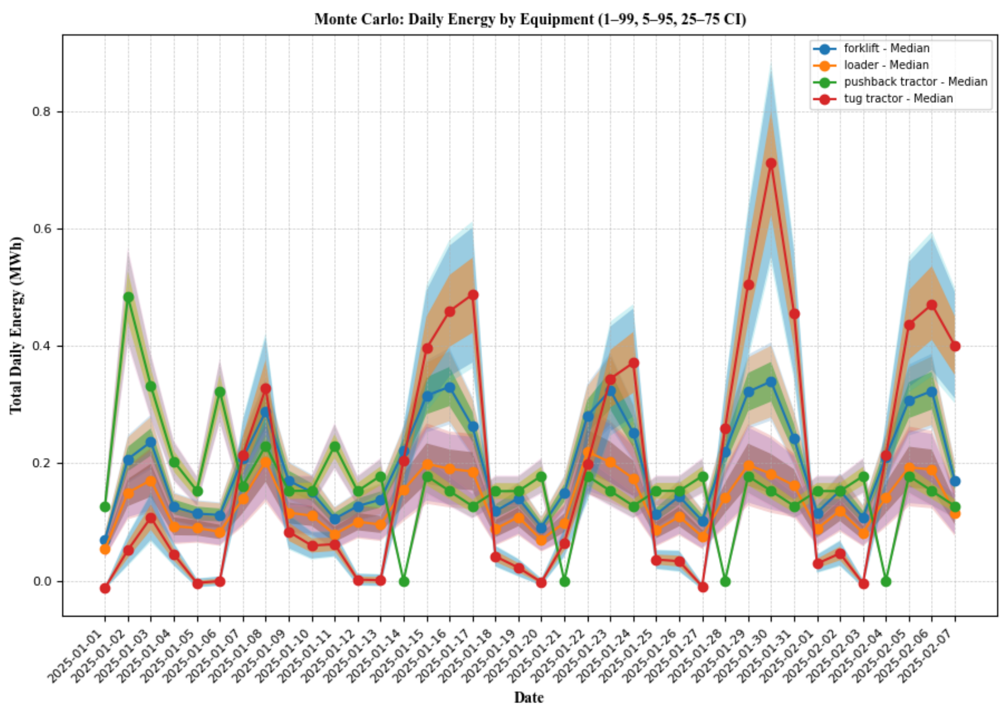

Figure 5-5. Daily Energy Use Profile of GSEs by type

5.2.3 Weekly energy consumption patterns

Figure 5-6 aggregates data into weekly totals, illustrating how daily fluctuations accumulate over seven consecutive days. The tug tractor can exceed 2.0 MWh per week, while pushback tractors and loaders peak at 1.0–1.5 MWh, and forklifts remain below 1.0 MWh. Some weeks experience significant increases in tug tractor usage, potentially surpassing 2.5 MWh during high-activity periods, indicating cargo-heavy operations or frequent aircraft movements. Airport planners can use this data to evaluate fueling or charging infrastructure capacity and schedule major maintenance during lighter-load intervals. Monte Carlo simulations reveal weekly totals ranging from 300–400 kWh for typical weeks, with peak weeks exceeding 420 kWh, largely driven by tug tractor usage.

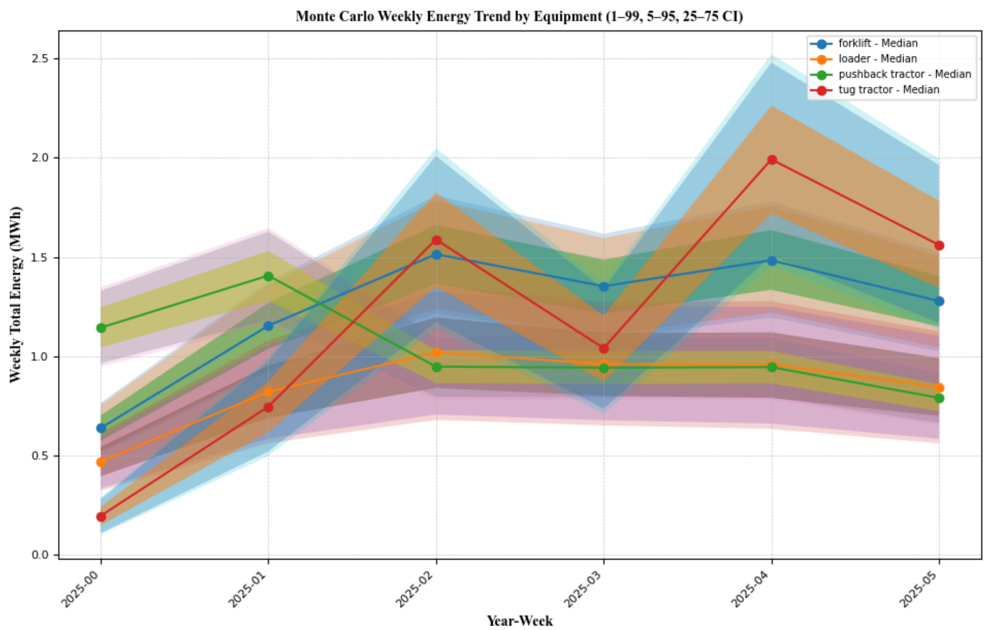

Figure 5-6. Weekly Energy Use of GSE by type

Figures 5-4, 5-5, and **5-6** confirm that the tug tractor shows the greatest variability and peaks, while the forklift remains stable. The loader and pushback tractor display moderate swings tied to flight traffic. By understanding these consumption patterns, ground operations managers can optimize task distribution, resource planning, and prevent GSE capacity or airport infrastructure overload.

5.3 HEATMAPS AND EQUIPMENT-SPECIFIC HIGHLIGHTS

Figures 5-7, 5-8, and **5-9** expand on the Monte Carlo framework by focusing on equipment-specific energy use distributions and day-of-week vs. week-by-week variations:

1. **Figure 5-7 (Typical Day Heatmap):** Displays hour-by-hour energy usage across multiple days, color-coded by intensity. Darker cells indicate higher load, pinpointing when simultaneous flight operations drive peak usage. It highlights high-load periods, typically in the mid-to-late morning and late afternoon. This heatmap emphasizes shifting load pockets, aiding operators in making short-term decisions, such as scheduling forklift downtime.

2. **Figure 5-8 (Day-of-Week vs. Week-by-Week):** Illustrates which days and weeks are most prone to surges, such as repeated Wednesday "hotspots" above 1 MWh. Airport planners can exploit this insight—e.g., scheduling GSE overhauls or battery replacements on Sundays, when usage is consistently 20–30% lower. It highlights how each day's consumption fits into its corresponding week and is useful for spotting recurring 'heavy' days (e.g., Tuesdays or Thursdays) across multiple weeks, and identifying potential scheduling opportunities for off-peak maintenance.

3. **Figure 5-9 (Equipment-Segregated MC Results):** Breaks down energy usage by equipment type under separate Monte Carlo simulations. It reveals the most variable equipment, such as tugs with dollies, and highlights predictable equipment, like pushback tractors. Operators can plan accordingly, retaining extra tugs for peak demand. It separates the energy consumption ranges (min–max or percentile bounds) for loaders, tug tractors, forklifts, and pushback tractors, revealing which equipment type exhibits the greatest variability or highest peak demands.

Together, these figures highlight how hourly, daily, weekly, and equipment-specific patterns complement each other. The analysis underscores the variability of GSE demand from average estimates, emphasizing the need for targeted scheduling, maintenance, and policy interventions to mitigate extremes.

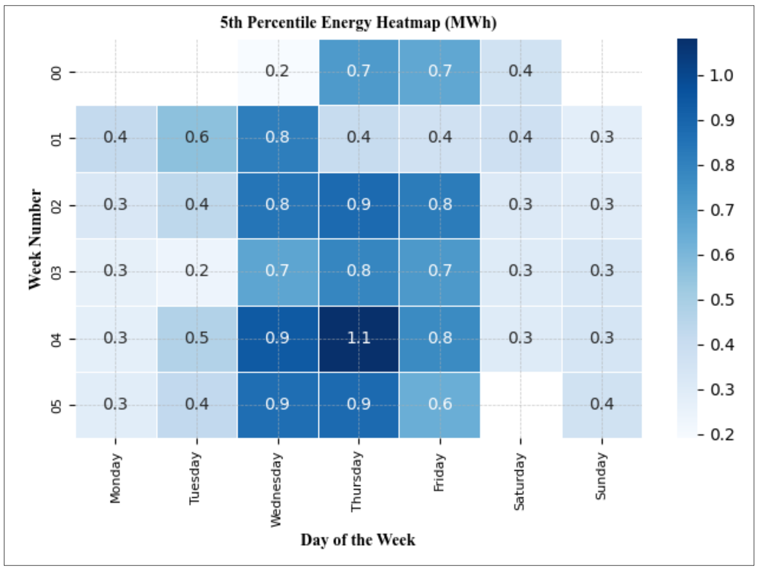

Figure 5-7. Day-of-Week vs. Hour-of-Day Heatmap

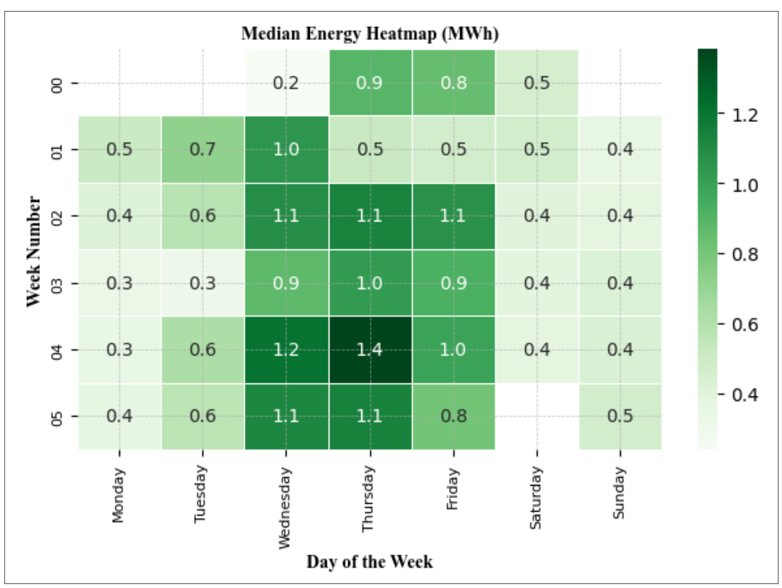

Figure 5-8. Week-by-Week vs. Hour-of-Day Heatmap

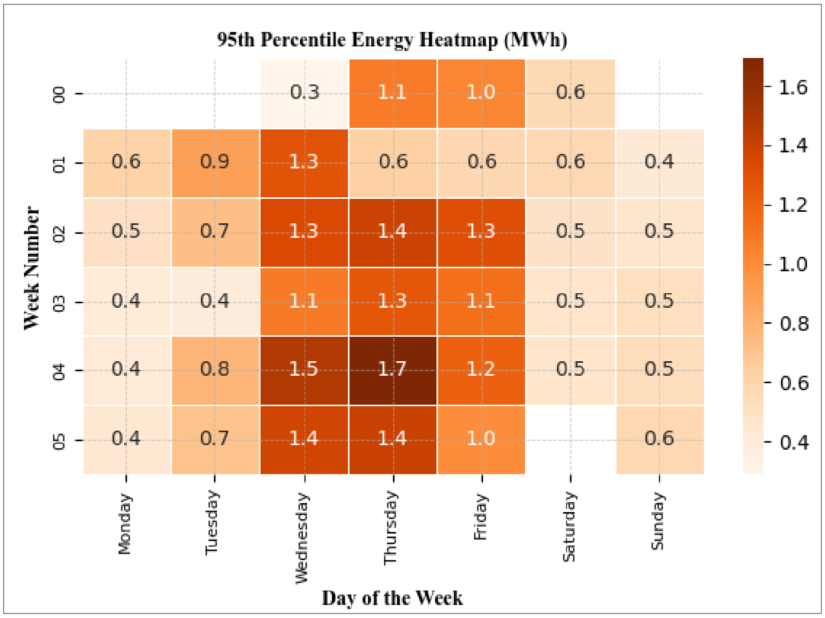

Figure 5-9. Equipment-Specific Monte Carlo Distributions

5.4 DISCUSSION

The figures presented in this chapter highlight the complexity and volatility of airport GSE operations, revealing several key insights:

1. **Peak Concentration**
   Data from **Figures 5-1 to 5-3** show consumption peaks during distinct morning and afternoon windows. This emphasizes the need for strategic recharging/refueling, flexible staffing, and buffer capacity, particularly for tugs and loaders.
2. **Strategic Scheduling**
   Figures 5-5 and 5-8 identify consistent mid-week surges and off-peak times (Sundays and overnight hours) with load dips. Operators can leverage these periods for maintenance and low-priority tasks, ensuring availability during peak hours.
3. **Policy and Infrastructure Planning**
   Weekly aggregates (**Figure 5-3**) and advanced heatmaps (**Figures 5-7 to 5-9**) support policy-making decisions, such as advocating for peak-shaving measures, dynamic flight scheduling, or infrastructure investments to enhance grid capacity and battery storage.
4. **Equipment-Level Insights**
   Disaggregated data by breaking down usage among loaders, tugs, forklifts, and pushback tractors (**Figure 5-9**) highlights equipment categories with the highest uncertainty, guiding operational decisions. For example, if the tug + trailer's 95th percentile usage surpasses the median by a significant margin, it justifies acquiring standby tug or expanding the cargo tractor fleet.

These findings provide an operational map for managing GSE, from tactical scheduling to strategic infrastructure development. They emphasize the importance of risk-aware planning to ensure resilience, cost efficiency, and service reliability. As airports transition to low-emission or electric GSE, this data-driven approach is critical for accommodating worst-case load scenarios without compromising performance.

Overall, the nine figures in this chapter present a detailed, interconnected view that aids ground operators, airport management, and policymakers in making informed decisions on workforce and equipment deployment, infrastructure scheduling, and long-term capital investments, all while minimizing disruptions and optimizing costs.

6. CONCLUSION

Electrification of GSE at airports offers cost savings, improved reliability, and operational efficiency. Their structured operations, short routes, low speeds, and centralized maintenance—enable a seamless transition. As cost pressures and regulations increase, electrifying GSE presents a strategic opportunity to reduce fuel costs and emissions while optimizing workflows.

This study simulated GSE energy consumption at Dallas-Fort Worth International Airport (DFW) to evaluate electrification's impact on energy demand. Results show that while GSE electricity consumption remains a small fraction of the airport's total use, accurate estimates are crucial for infrastructure planning. Understanding peak and average load profiles helps optimize charging strategies, reducing strain on local grids and minimizing costs.

The approach used in this study is scalable and adaptable, allowing similar energy demand assessments across airports of varying sizes and cargo profiles. Although initially demonstrated at DFW, the Agile@ platform is readily adaptable for use across diverse airport scales and logistics environments. Its modular design—where operational schedules, fleet configurations, energy intensities, and growth parameters are defined as user-input variables—enables application at regional airports, large cargo hubs, or even intermodal logistics facilities beyond the aviation sector. By adjusting inputs reflective of local operational characteristics and market conditions, stakeholders can leverage Agile@ to conduct detailed scenario analyses and infrastructure assessments at virtually any site managing electrified logistics equipment.

APPENDIX A. NEWTONIAN MECHANICS-BASED ENERGY CALCULATIONS

I. PUSHBACK ENERGY CALCULATION

Below is a step-by-step method to derive more "precise" (physics-based) estimates of electric energy consumption for an aircraft pushback. In practice, exact values still vary with local conditions (pushback distance, ramp slope, weather, tractor design/efficiency, etc.), but the framework below shows how one can move from first principles to a reasonably detailed calculation.

1. Key Inputs

To calculate pushback energy for a specific aircraft, you need:

1. **Aircraft Mass (m_ac)**
    - Typically use the maximum ramp or taxi weight if you want a worse case (heaviest) scenario.
    - Example: B747-8F max ramp weight can be about 448 t (≈ 448,000 kg).
2. **Tractor Mass (m_tug)**
    - Large electric pushback tractors can weigh from 30 t up to 60–70 t for widebody operations.
    - Example: 50,000 kg for a typical high-capacity electric tug.
3. **Pushback Distance (D)**
    - The path length from the gate to the handoff point on the taxiway.
    - Often ranges 30–300 m but can be more at certain airports.
    - Example: 150 m.
4. **Rolling Friction Coefficient (f)**
    - For slow towing on level pavement, common values can range 0.002 – 0.02.
    - Real-world conditions (turning friction, slight slope, ramp imperfections) tend to push the effective value higher than the textbook rolling resistance of a free-rolling wheel.
    - Example: 0.006–0.01 is a reasonable starting assumption for heavy aircraft towing on good pavement.
5. **Average Pushback Speed (v)**
    - Typically, in the range of 1–2 m/s (2–4 mph).
    - Used to estimate pushback duration T=D/vT = D / vT=D/v.
    - Example: 1.5 m/s → 150 m in about 100 s (~1.7 min) of rolling time.
6. **Auxiliary/Overhead Power (P_aux)**
    - The tractor's own systems (hydraulics, air conditioning for electronics, lights, etc.) consume power whenever it is powered on and connected to the aircraft.
    - Example: 20 kW is a plausible ballpark for a large electric tug's non-traction loads.
7. **Regenerative Braking Efficiency (η_regen)**
    - Some portion of the kinetic energy may be recovered when decelerating.
    - Assume 25–50% recovery, or 0% if the system is not regenerative.
    - Example: 25% recovery.
8. **Drivetrain Efficiency (η_drive)**
    - Electric motor and power electronics efficiency from battery to wheels.
    - Often 75–80% for high-quality industrial EV drivetrains.
    - Example: 75%.

2. Calculate the Traction Energy (Rolling + Acceleration)

(a) Rolling Friction Work

$E_{fric} = f \times \left[(m_{ac} + m_{tug}) \times g\right] \times \frac{D}{3{,}600{,}000}$

f is the rolling friction coefficient

$(m_{ac} + m_{tug}) \times g$ is the total normal force in N

D is the distance in meters

E_{fric} is the rolling friction work done in kWh

(b) Kinetic Energy (Acceleration)

$E_{accel} = \frac{1}{2} \times (m_{ac} + m_{tug})v^2$

v is the target pushback speed (m/s)

(c) Sum of Traction Energy

$E_{traction} = E_{fric} + (1 - \eta_{regen})E_{accel}$

η_{regen} is the fraction of energy recovered in regeneration. A factor of 0.25 is assumed here.

3. Account for Overhead / Auxiliaries

During pushback, the tug also draws "hotel" or auxiliary power. If pushbacks (including hooking up, final alignment, etc.) occupies a total time T_{push}, overhead energy is:

$E_{aux} = P_{aux} \times T_{push}$

P_{aux} is in kW and $T_{push}$is in hours.

The total mechanical and auxiliary energy before drivetrain losses:

$E_{raw} = E_{aux} + E_{traction}$

4. Drivetrain Efficiency

Let η_{drive} be the overall efficiency (motor + power electronics + gear train):

$E_{battery} = \frac{E_{raw}}{\eta_{drive}}$

5. Example Calculation

Below is a worked example for several freighter aircraft at **max ramp weight**, assuming:

- Tractor mass m_{tug}=50,000kg
- Distance D=150 m
- Rolling friction coefficient f=0.006
- Speed v=1.5 m/s → rolling time ≈ 100 s
- Regeneration η_{regen}=25%
- Overhead power P_{aux}=20 kW
- Total operation time (hook-up + push) ≈4 min=0.0667 h
- Drivetrain efficiency η_{drive}=75%

Aircraft Weights (examples):

- A300-600F: ~170 t
- B747-400F: ~396 t
- B747-8F: ~448 t
- B757-200F: ~115 t

- B767-200F: ~159 t
- B767-300F: ~187 t
- B777F: ~347 t
- MD-11F: ~286 t

Including 50 t tractor, we get total masses from 165 t to nearly 500 t. Below is a condensed table of results for each aircraft under these uniform assumptions.

Note: If your actual pushback distance is longer (say 300 m) or overhead time is greater (e.g. 6–7 min), energy numbers can be 2× higher or more.

Worked Example Table

Aircraft	Max Ramp Weight (t)	Total Mass (ac + tug) (t)	Friction + Accel (kWh)	Aux Overhead (kWh)	Raw Sum (kWh)	/ Drivetrain 75% → Battery (kWh)
A300-600F	170	220	0.57	1.33	1.90	2.11
B747-400F	396	446	1.16	1.33	2.49	2.77
B747-8F	448	498	1.30	1.33	2.63	2.92
B757-200F	115	165	0.43	1.33	1.76	1.96
B767-200F	159	209	0.54	1.33	1.88	2.08
B767-300F	187	237	0.62	1.33	1.95	2.17
B777F	347	397	1.04	1.33	2.37	2.63
MD-11F	286	336	0.88	1.33	2.21	2.45

In typical conditions (100–300 m pushback, large widebody, 3–5 minutes total), **2–6 kWh** per pushback is a reasonable range if the process is efficient. Due to extra time spent maneuvering, hooking up, waiting, or dealing with suboptimal pavement/slope— in real airport operations, the consumption can be between **5–10 kWh**.

II. LOADER ENERGY CALCULATION

The energy calculation of the loader is given below:

1. **Loads & Masses (per ULD):**
   - **Lower-deck ULD:**
     • Payload (cargo + container): ~2,600 kg (≈2,500 kg cargo plus ~100 kg container)
     • Loader "moving platform" mass (lifted with the load): ~1,200 kg
     • Total mass lifted: 2,600 + 1,200 = 3,800 kg
   - **Main-deck ULD:**
     • Payload (cargo + pallet): ~6,200 kg (≈6,000 kg cargo plus ~200 kg pallet)
     • Platform mass for a main-deck loader: ~2,000 kg
     • Total mass lifted: 6,200 + 2,000 = 8,200 kg

2. **Lift Height (h):**
   - **Lower Deck:** Assume ~2.5 m
   - **Main Deck:** Varies by aircraft. For our range we use:
     • Lower–end: 3.5 m (narrower freighter doors)
     • Upper–end: 5.5 m (e.g. for a B747 main deck)
     • (Other aircraft, such as the B777 or MD-11, fall in between.)

3. **Gravitational Acceleration:**
   g≈9.81 m/s2

4. **Ideal Lifting Energy:**
   The ideal work to lift a mass mmm through a height h is
   E_ideal=m g h/ (3.6×10^6) (in kWh)
   (The factor 3.6×10^6 converts Joules to kWh.)

5. **Drive-Train Efficiency:**
   Only 40% of the energy drawn from the battery is converted into useful lifting work. In effect, the actual electrical energy for the lift is
   E_lift=E_ideal/0.40

6. **Auxiliary Energy (Overheads):**
   – We assume that for each deck operation the loader (while "on-duty" for that deck) draws a fixed aux power.
   – For our "high-end" scenario, we assume a total overhead (aux plus short-range driving) of between 7 kWh (minimum) and 10 kWh (maximum) per deck operation.
   – This energy is "spread out" over all ULD positions on that deck.

7. **Payload Basis for Normalization:**
   – Lower deck: 2,500 kg cargo per ULD (ignoring the container's dead weight for normalization)
   – Main deck: 6,000 kg cargo per ULD

8. **Operation Time:**
   – We assume that a "deck operation" takes about 1 hour; hence the energy numbers below may be expressed in kWh/h (i.e. a power rate) and then normalized by the cargo mass.

Step 1. Calculate the Ideal Lifting Energy

Lower Deck (per ULD)
- Total mass lifted: 3,800 kg
- Lift height: 2.5 m
- Ideal energy: E_ideal_lower=3,800×9.81×2.53.6×106≈0.026 kWh
- Adjusted for 40% drive–train efficiency: E_lift_lower=0.026/0.40≈0.065 kWh per ULD

Main Deck (per ULD)
For the main deck the total mass lifted is 8,200 kg. We calculate two extremes:
- At 3.5 m: E_ideal_main=8,200×9.81×3.5/(3.6×10^6)≈0.078 kWh per ULD
- At 5.5 m: E_ideal_main=8,200×9.81×5.5/(3.6×10^6)≈0.123 kWh per ULD

Step 2. Add Overhead (Auxiliary) Energy
For each deck operation the overhead energy (aux power + short drive) is assumed to be between 7 and 10 kWh. This is "shared" by all ULDs on that deck.
Thus, the overhead energy per ULD is:
Eoverhead, per ULD=Eoverhead totalNULDsE_{\rm overhead,per\,ULD} = \frac{E_{\rm overhead\,total}}{N_{\rm ULDs}}Eoverhead,perULD=NULDsEoverheadtotal
For example, if a deck has 14 ULD positions then:
- Min: 7/14=0.5 kWh per ULD
- Max: 10/14≈0.714 kWh per ULD

Step 3. Compute Total Energy per ULD and Then per kg
For each deck type we add the (inefficient) lifting energy plus the overhead energy and then normalize by the payload (cargo) per ULD.

Example Calculations
A) A300-600F

1. **Lower Deck (14 ULDs):**
   - *Lifting energy:* 0.065 kWh per ULD
   - *Overhead per ULD:*
     • Min: 7 kWh total → 7/14 = 0.50 kWh
     • Max: 10 kWh total → 10/14 ≈ 0.714 kWh
   - *Total energy per ULD:*
     • Min: 0.065 + 0.50 = 0.565 kWh
     • Max: 0.065 + 0.714 = 0.779 kWh
   - *Normalized to payload:* (Assume 2,500 kg cargo per lower–deck ULD)
     kWh/kg=0.565/2500≈0.000226 kWh/kg (min)
     0.779/2500≈0.000312 kWh/kg (max)
2. **Main Deck (22 ULDs, door sill ≈3.5 m):**
   - *Lifting energy:* 0.1955 kWh per ULD
   - *Overhead per ULD:*
     • Min: 7/22 ≈ 0.318 kWh
     • Max: 10/22 ≈ 0.455 kWh
   - *Total energy per ULD:*
     • Min: 0.1955 + 0.318 ≈ 0.5135 kWh
     • Max: 0.1955 + 0.455 ≈ 0.6505 kWh
   - *Normalized to payload:* (Assume 6,000 kg cargo per main–deck ULD)
     0.5135/6000≈0.0000856 kWh/kg (min)
     0.6505/6000≈0.0001084 kWh/kg (max)

3. **Weighted Average for the A300–600F:**
   – Total lower–deck cargo: 14 × 2,500 = 35,000 kg
   – Total main–deck cargo: 22 × 6,000 = 132,000 kg
   – Total cargo = 35,000 + 132,000 = 167,000 kg
   – Total energy (min):

14×0.565+22×0.5135≈7.91+11.30=19.21 kWh14 \times 0.565 + 22 \times 0.5135 \approx 7.91 + 11.30 = 19.21\,\text{kWh}14×0.565+22×0.5135≈7.91+11.30=19.21kWh

   – Total energy (max):

14×0.779+22×0.6505≈10.91+14.31=25.22 kWh

   – Weighted average (kWh/kg):

• Min: 19.21/167000≈0.000115 kWh/kg
• Max: 25.22/167000≈0.000151 kWh/kg

Because we are assuming a 1–hour operation per deck, these numbers are in kWh per hour per kg.

B) Similar Calculations for Other Aircraft
Using the same method, we account for the different numbers of ULD positions and door sill heights. (A summary of results follows; see the "Detailed Calculations" section below for each aircraft.)

- **B747–400F**
  • Lower–deck (18 ULDs): kWh/kg ≈ 0.000182 to 0.000248

• Main–deck (30 ULDs, h = 5.5 m): kWh/kg ≈ 0.000090 to 0.000107
• Weighted average: ≈ 0.000108 to 0.000135 kWh/k

- **B747–8F**
  • Lower–deck (12 ULDs): kWh/kg ≈ 0.000259 to 0.000359
  • Main–deck (34 ULDs, h = 5.5 m): kWh/kg ≈ 0.000086 to 0.000100
  • Weighted average: ≈ 0.000108 to 0.000133 kWh/kg
- **B757–200F (main deck only, 15 ULDs, h = 3.5 m):**
  kWh/kg ≈ 0.000110 to 0.000144
- **B767–200F**
  • Lower–deck (10 ULDs): kWh/kg ≈ 0.000306 to 0.000426
  • Main–deck (19 ULDs, h = 3.5 m): kWh/kg ≈ 0.000094 to 0.000120
  • Weighted average: ≈ 0.000132 to 0.000175 kWh/kg
- **B767–300F**
  • Lower–deck (15 ULDs): kWh/kg ≈ 0.000213 to 0.000293
  • Main–deck (26 ULDs, h = 3.5 m): kWh/kg ≈ 0.000077 to 0.000097
  • Weighted average: ≈ 0.000104 to 0.000135 kWh/kg
- **B777F**
  • Lower–deck (32 ULDs): kWh/kg ≈ 0.000114 to 0.000151
  • Main–deck (27 ULDs, h ≈ 3.65 m): kWh/kg ≈ 0.000077 to 0.000096
  • Weighted average: ≈ 0.000089 to 0.000114 kWh/kg
- **MD–11F (main deck only, 7 ULDs, h = 4.1 m):**
  kWh/kg ≈ 0.000205 to 0.000276

Step 4. Overall Weighted Average Across All Aircraft
Using the individual aircraft totals (where we sum the energy for each deck and divide by the total payload handled per plane), one finds (using our illustrative numbers):

- Total Cargo Across All Aircraft: ~1,332,500 kg
- Total Energy (min case): ~147.36 kWh
- Total Energy (max case): ~189.39 kWh

Thus, the overall weighted average energy consumption is:
Min: 147.36/1,332,500≈0.0001105 kWh/h/kg
Max: 189.39/1,332,500≈0.0001421 kWh/h/kg
That is about 0.11 to 0.14 Wh per kg per hour of cargo handled.

Summary of Key Results

- **Lower Deck (per ULD):**
  – Lifting energy (after 40% efficiency): ~0.065 kWh
  – Overhead (distributed): ~0.50–0.71 kWh per ULD
  → Total ≈ 0.565–0.779 kWh per ULD → ≈ 0.000226–0.000312 kWh per kg
- **Main Deck (per ULD):**
  – Lifting energy: ranges from ~0.1955 kWh (h = 3.5 m) up to ~0.3073 kWh (h = 5.5 m)
  – Overhead (distributed): typically 0.23–0.45 kWh per ULD (depending on ULD count)
  → Total ≈ 0.4647–0.6505 kWh per ULD → ≈ 0.000077–0.000108 kWh per kg
- **Weighted Average per Aircraft (combining decks):**
  Ranges from about 0.000089 kWh/h/kg (≈0.089 Wh/kg/h) up to about 0.000175 kWh/h/kg (≈0.175 Wh/kg/h) on an individual aircraft basis.
- **Overall Fleet–Weighted Average:**
  Approximately 0.0001105 to 0.0001421 kWh/h/kg (i.e. about 0.11–0.14 Wh per kg per hour).

Caveats

• These estimates assume a 1–hour loading cycle per deck and that the aux overhead (high–end scenario) is between 7 and 10 kWh per deck operation.

• The "payload" is taken as the useful cargo (2,500 kg for lower deck and 6,000 kg for main deck), while the additional masses (container/pallet and loader platform) add to the energy penalty.

• The drive–train efficiency of 40% significantly increases the electrical energy drawn compared with the ideal gravitational work.

• Real operations may have longer dwell times or additional losses; these numbers serve as a first–order engineering estimate.

This example demonstrates how, when all factors are included, the energy consumption can be expressed in the compact unit kWh/h/kg—with our illustrative values yielding a range roughly from 0.11 to 0.14 Wh per kilogram of cargo handled per hour.

While our first-principles estimates might indicate, for example, around 0.11–0.14 Wh per kg per hour under ideal conditions, a combination of the above factors could theoretically raise that value by 2–4 times.

III. TUGS ENERGY CALCULATION

1. Introduction

Here is a detailed methodology for calculating the energy consumption of tugs and dollies used in ground support operations. The calculations include energy consumption per unit distance per kilogram of cargo (kWh/km/kg) to assess efficiency.

2. Parameters Considered

Tug (Tractor) Parameters:

- Power Rating (P_t): Rated power of the tug (kW)
- Operating Time per Trip (t_t): Time spent operating per trip (hours)
- Trips per Day (n_t): Number of trips a tug makes per day
- Efficiency Factor (η_t): Mechanical and electrical efficiency factors
- Distance per Trip (d_d): Distance covered per trip (km)
- Cargo Weight per Trip (W_d): Total cargo weight transported per trip (kg)

Dolly Parameters:

- Rolling Resistance Coefficient (C_r): Resistance factor based on surface type
- Efficiency Factor (η_d): Efficiency of dolly movement

3. Energy Consumption Formulas

3.1 Tug Energy Calculation

Energy consumption per trip for tugs is given by: $E_t = P_t \times t_t \times \eta_t$

To normalize per km and per kg: $E_{t,norm} = E_t / (d_d \times W_d)$

where:

E_t = Energy consumed per trip (kWh)

d_d = Distance per trip (km)

W_d = Cargo weight per trip (kg)

$E_{t,norm}$ = Normalized energy consumption (kWh/km/kg)

3.2 Dolly Energy Calculation

The force required to pull the dollies is calculated as: $F_d = W_d \times C_r$

The work done per trip: $W_d = F_d \times d_d \times 1000$

Energy required per trip: $E_d = W_d / (\eta_d \times 3600 \times 1000)$

Normalized energy consumption for dollies: $E_{d,norm} = E_d / (d_d \times W_d)$

4. Example Calculation
For example:

- Tug Power: kW
- Operation per Trip: 0.5 hrs
- Trips per Day: 30
- Tug Efficiency: 0.9
- Cargo per Dolly: 2000 kg
- Rolling Resistance: 0.01
- Distance per Trip: 2 km
- Dolly Efficiency: 0.9

Using the formulas above:

- Tug Energy Consumption: 0.003 kWh/km/kg
- Dolly Energy Consumption: 3.27 × 10^-6 kWh/km/kg

IV. FORKLIFT ENERGY CONSUMPTION

The energy consumption of an electric forklift in kWh/kg can be calculated using the following formula:
Energy Consumption=Total Energy Consumed (kWh)/Total Weight Lifted (kg))
Where:

- Total Energy Consumed (kWh) is the electricity used by the forklift, which depends on battery capacity and efficiency.
- Total Weight Lifted (kg) is the cumulative load handled by the forklift over a given period.

Typical Energy Consumption Values
Electric forklifts typically consume between 1.5 kWh to 3.5 kWh per hour of operation, depending on factors such as:

- Load weight
- Lift height
- Operating conditions (idle time, travel distance)
- Battery efficiency

Example Calculation -
Assuming:

- An electric forklift operates for 5 hours and consumes 2.5 kWh/hour.
- Total weight lifted in this period is 10,000 kg.

Total Energy Used=5×2.5=12.5 kWh Energy Consumption per kg=12.5/10,000=0.00125 kWh/kg
Thus, the energy consumption is 0.00125 kWh/kg (or 1.25 Wh/kg). Taking into account the practical operation considerations and inefficiency and onboard power consumption, a fact 2 was used. Hence the energy consumption is 0.0025 kWh/kg.