Life Cycle Cost Modeling of High-Speed Commercial Aircraft

Final Review – AnyLogic Model Development

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NASA SBIR/STTR Contract #80NSSC22C0008

Agenda

8:00 – 9:00	Executive Summary	John Olds
9:00 – 10:00	**AnyLogic Model Development**	**Ami Patel**
10:00 – 10:15	*Break*	
10:15 – 11:30	Trade Study Details	Hayden Magill
11:30 – 12:00	Data Exploration and Discussion	Mark Schaffer

AnyLogic Modeling & Simulation | Objective

- **Develop a modeling and simulation (M&S) tool to provide greater insight and analysis into fleet operations and economic behavior**

- **Initial development of the M&S tool should roughly match the current capabilities of the existing ROSETTA Model**

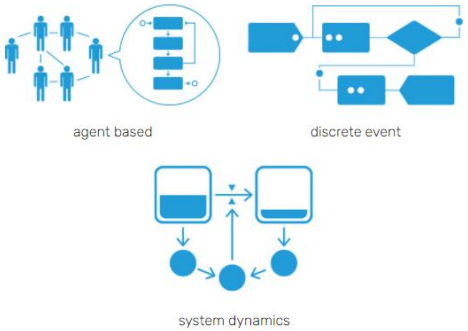
- **Validate model behavior by comparing against results generated from the ROSETTA Model during this effort**

ROSETTA Model

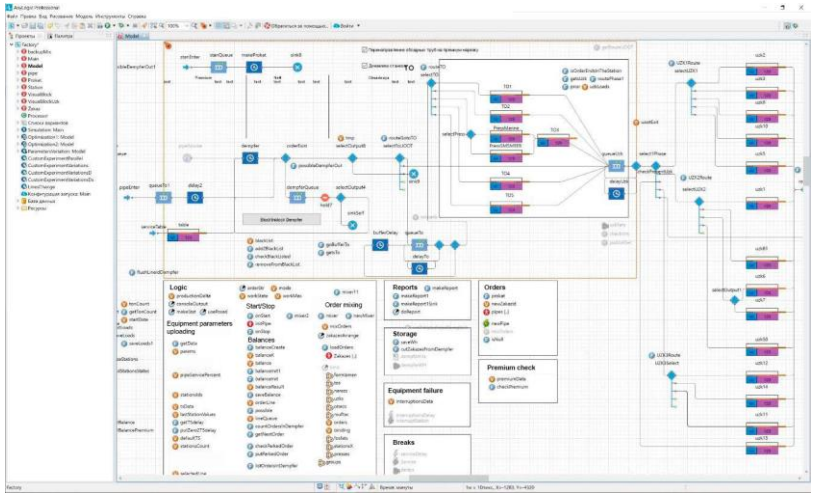
AnyLogic Modeling & Simulation | Overview

- **SpaceWorks elected to leverage the modeling and simulation capabilities of AnyLogic, which is a multi-method simulation modeling tool**

- **AnyLogic utilizes discrete event simulation (DES) modeling, agent-based modeling, and system dynamics modeling**
  - For a given project, any combination of these modeling types can be used



- **End product will provide greater resolution and insight into the economic behavior of the high-speed flight industry**
  - Risk-free environment to test “what-if” scenarios through 2D/3D visualization



AnyLogic Modeling & Simulation | Development Process

- **The AnyLogic Model will focus on the economic side of the ROSETTA Model only**
  - The aircraft sizing and performance models will still utilize Excel
    - These models can be rapidly executed, and are expected to generate a database of aircraft designs and parameters to feed into the AnyLogic Model for economic analysis

- **To recreate the capabilities of the existing ROSETTA Model in AnyLogic, formulas and calculations had to be transferred and integrated within AnyLogic**
  - Given the improved resolution and differences in how the model is set up, results will not be one-to-one in some cases
  - Improvements in modeling economic behavior were implemented when applicable
    - For example, maintenance and retirement are now based on an individual aircraft's flight hours rather than fixed intervals observed for a given year

- **Validation cases were run to calibrate the model with the understanding that results would not be exact matches**

AnyLogic Modeling & Simulation | Roadmap

AnyLogic Model development is complete

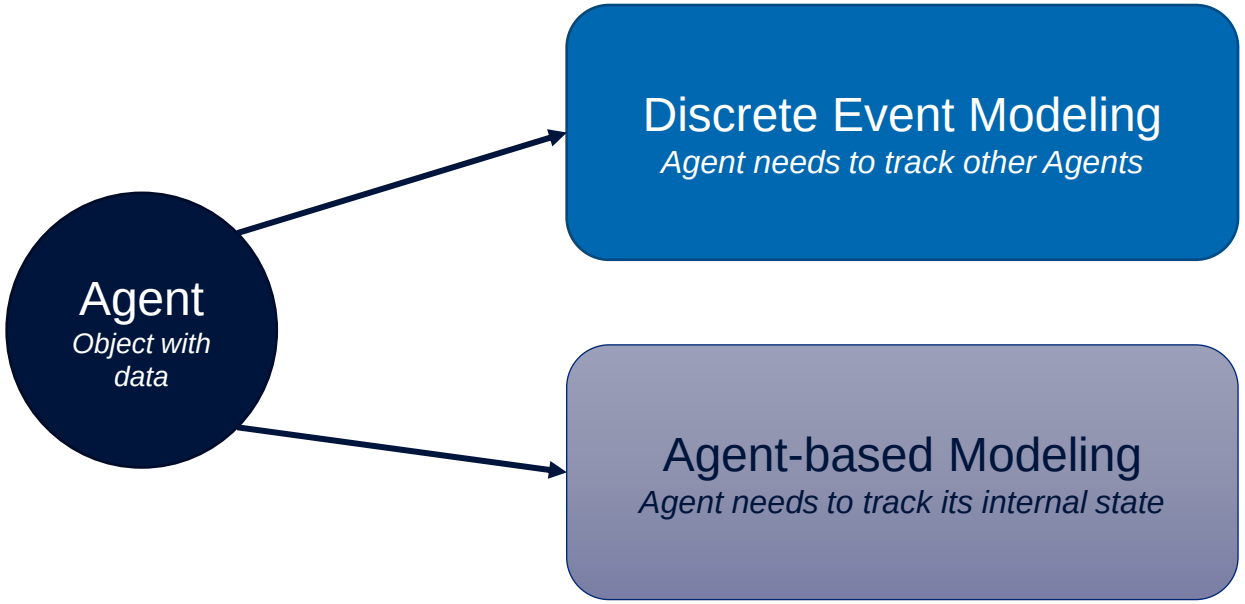
Inputs	Initialization	Demand & Flights	Maintenance & Purchase	Outputs
Route Inputs	Initialize each Route	Model demand for each Route	Add/Remove Airplanes per maintenance	Revenue
Aircraft Inputs	Initialize each Airplane	Generate Flight per demand	Add/Remove Airplanes per demand growth	Cost
Airport Inputs	Initialize each Airport	Determine Fleet utilization		IRR, NPV
				Emissions

Model Development Phases

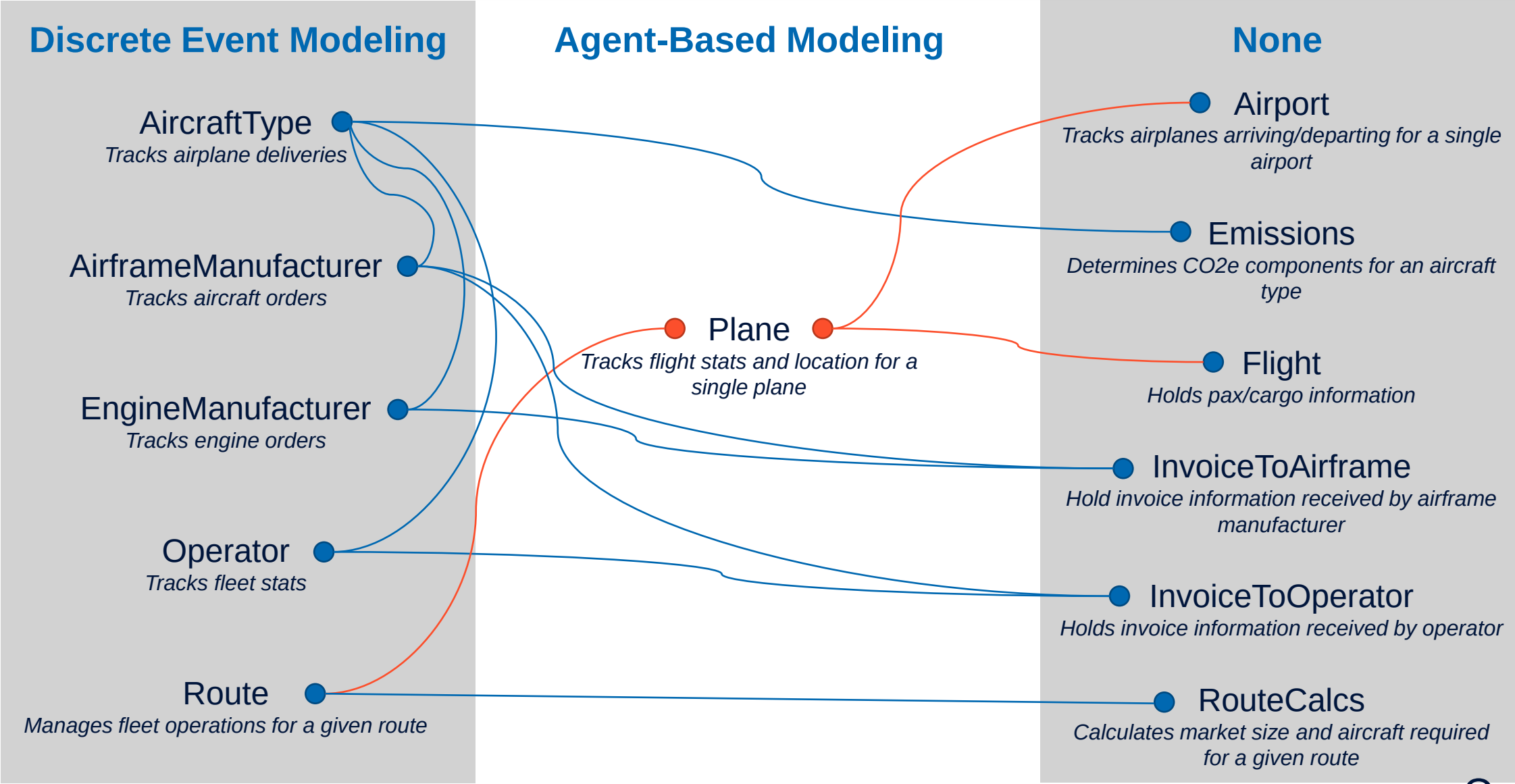
Complete | Needs Refinement | In Progress | Not Started

AnyLogic Modeling & Simulation | Terminology

- The term Agent represents any object with data in the AnyLogic simulation
- The high-speed flight study uses a mix of Agents leveraging discrete event (DES) and agent-based modeling techniques
- Modeling technique determined by if an agent needs to track: 1) other agents or 2) its own internal state
- Aircraft Type differentiates between short-range and long-range aircraft



AnyLogic Modeling & Simulation | Key Agents



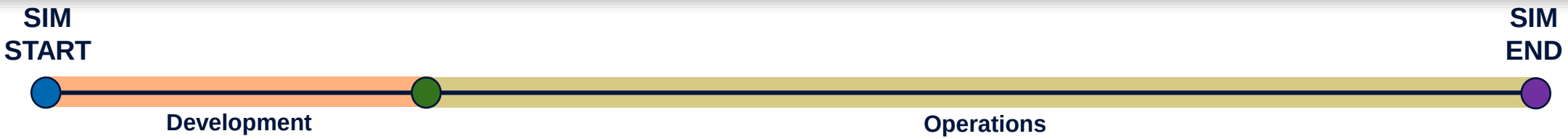
AnyLogic Modeling & Simulation | Model Inputs

- **Simulation inputs are specified via an external Excel file for accessibility**

- **Users have the flexibility to specify multiple aircraft types for assessment**

Category	Key Information
Aircraft	Mach, Design Range, Passenger Capacity, Ticket Price Fuel Type, Fuel Consumption Rate Airframe/Engine DDT&E and TFU
Cost	Captain, First Officer, Flight Attendant Salaries Hangar Rental, Training, Depreciation, Insurance
Airport	Longitude, Latitude, Landing Tax
Routes	Distance, Initial Market Size, Taxes, Growth Rate (%/Year)
Fuel Prices	Prices for Jet-A, SAF, SAF 50/50, LNG, LH2
Emissions	Conversion factors for CO2e component calculations

AnyLogic Modeling & Simulation | Model Operations



Initialize Model

- For each **Route**, determine applicable **AircraftType**
- Calculate *Flights/Day* and *Aircraft/Route* for viable routes

Initialize Operator

- Initialize **Operator** with initial fleet size
- For each **AircraftType** supported, initialize **AirframeManufacturer** and **EngineManufacturer**

Aircraft Development

- DDT&E applied for manufacturers
- **Operator** pays **AirframeManufacturer** down payment
- **AirframeManufacturer** pays **EngineManufacturer** down payment

Aircraft Production

- Production rates vary throughout model
- Military aircraft are delivered first
- Routes become active as **Planes** are delivered
- Each **Plane** has a 6-month pre-service delay

Fleet Operations

- **Planes** retired based on flight hours
- New **Planes** purchased per market growth or **Plane** retirement

Business Metrics

- At simulation end, business metrics (NPV, IRR, Max Exposure) are calculated for **Operator** and **Manufacturers**

AnyLogic Model Validation

- Notable Model Changes
- Assumptions
- Results

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AnyLogic Modeling & Simulation | Notable Model Changes

- **The following table indicates major changes between the ROSETTA Model and AnyLogic Model:**

Item	Change	ROSETTA MODEL	ANYLOGIC MODEL
1	Airplane Retirement	Retire after 15 years	Retire after 45,000 Flight Hours with Mach scaling
2	Max Fleet Utilization	Specific correlation per route	Single correlation for all routes
3	Active Routes	Fixed set of active routes determined at model initialization based on initial market size	Initially inactive routes can become active over time based on market growth
4	Maintenance Schedule	Based on expected maintenance intervals and duration annually	Based on flight hours (Concorde) with Mach scaling
5	Airplane Tracking	Uses weighted average and distance to generalize total fleet metrics	Tracked at individual level and aggregated for annual statistics

- **AnyLogic Model has greater resolution into fleet operations**

- **The following notes other core assumptions made in the AnyLogic Model**
  - Aircraft types are assumed to be non-competing, therefore each route only services one aircraft type
  - A route consists of two airports only
  - There is only a single operator, with the expectation that additional operators will be enabled in future development efforts
  - Each aircraft type has an associated engine and airframe manufacturer

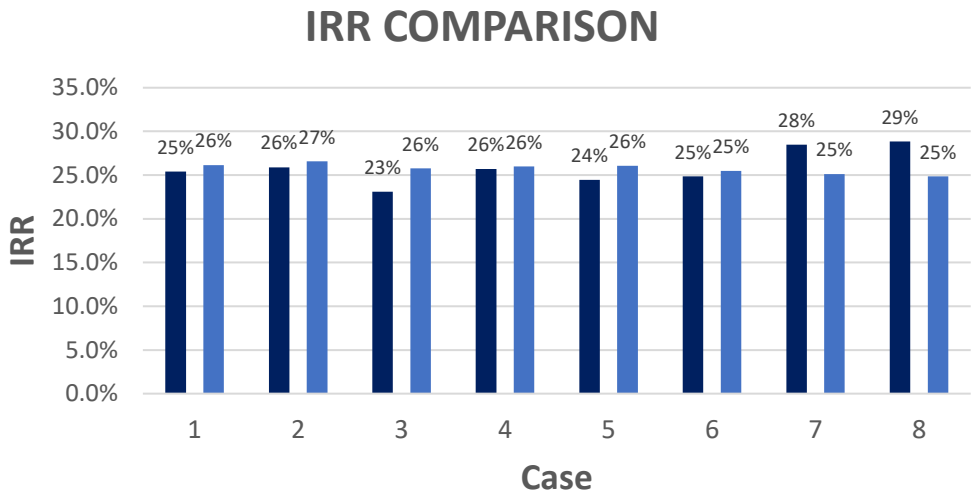
AnyLogic Modeling & Simulation | Validation Overview

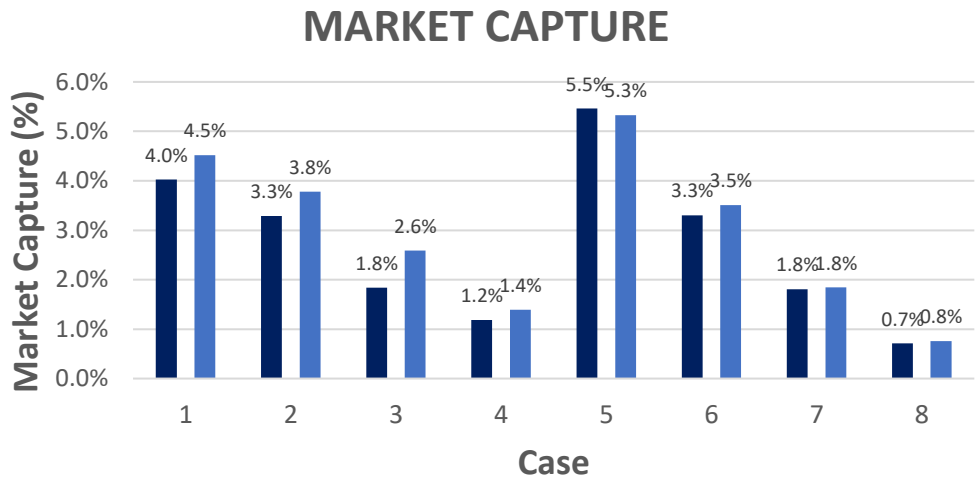
- **Execute sweep of validation cases for short-range aircraft**
- **Objective was to have AnyLogic results roughly match ROSETTA Model results**
- **The following slide shows the metrics of interest used to validate results**
  - Results were mostly consistent with each other
  - Small discrepancies exist as a result of some modeling behavior changes
- **Overall, SpaceWorks is satisfied with the AnyLogic Model results to move forward with it**
  - However, the model will continue to be tested against the ROSETTA Model to ensure consistency and to refine behaviors as necessary

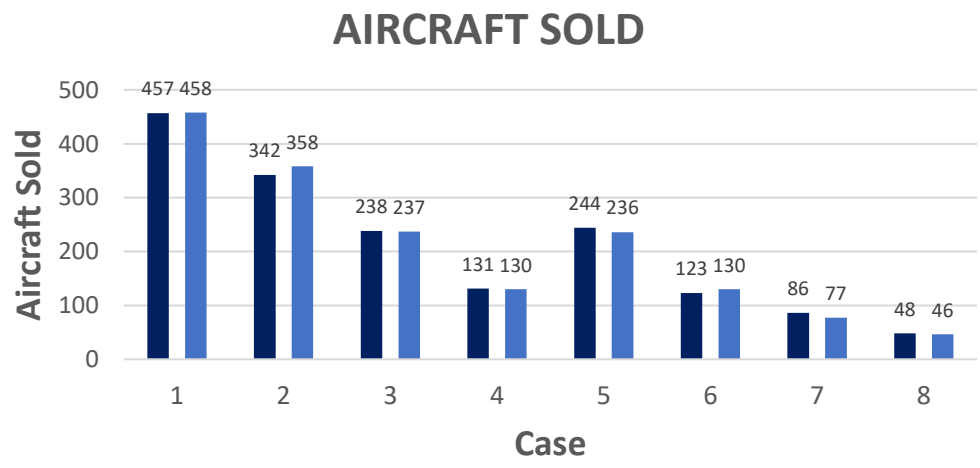
Case	Mach	Range	Pax	Ticket Price
1	2	4000	20	$4,179
2	3	4000	20	$5,543
3	4	4000	20	$7,622
4	5	4000	20	$13,228
5	2	4000	50	$3,406
6	3	4000	50	$5,568
7	4	4000	50	$9,366
8	5	4000	50	$15,100

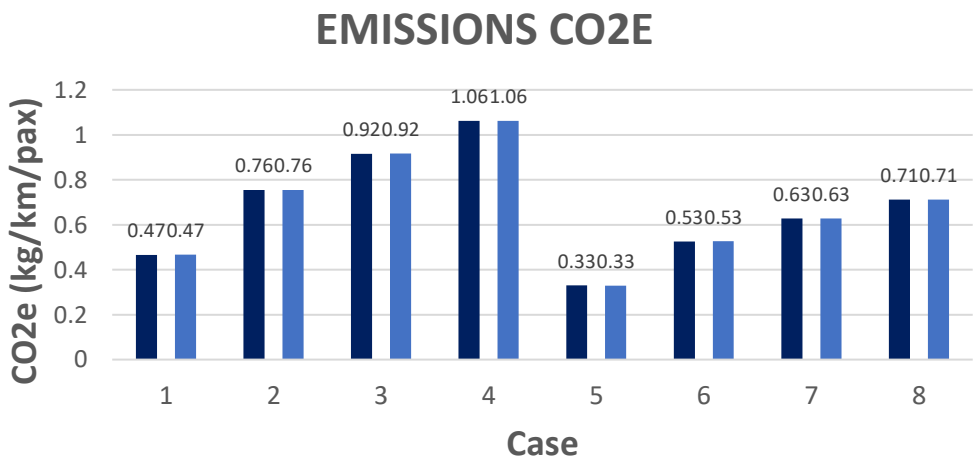
AnyLogic Modeling & Simulation | Validation Overview

AnyLogic results are consistent with ROSETTA Model









AnyLogic Sim ROSETTA

AnyLogic Modeling & Simulation | Key Takeaways

- **With the Excel-based ROSETTA Model having essentially reached its limit in terms of modeling capability, SpaceWorks recommends moving to the AnyLogic Model for future analysis work**

- **The validation cases proved the AnyLogic Model can generate similar results to the ROSETTA Model which ensures results will remain mostly consistent as SpaceWorks shifts analysis work to the AnyLogic Model**

- **The AnyLogic Model has also proved it can provide greater resolution and insight into the operations and behavior of the business case for high-speed aircraft with metric tracking at the aircraft level**
  - By extension, improved modeling behavior can be and has been implemented throughout the model

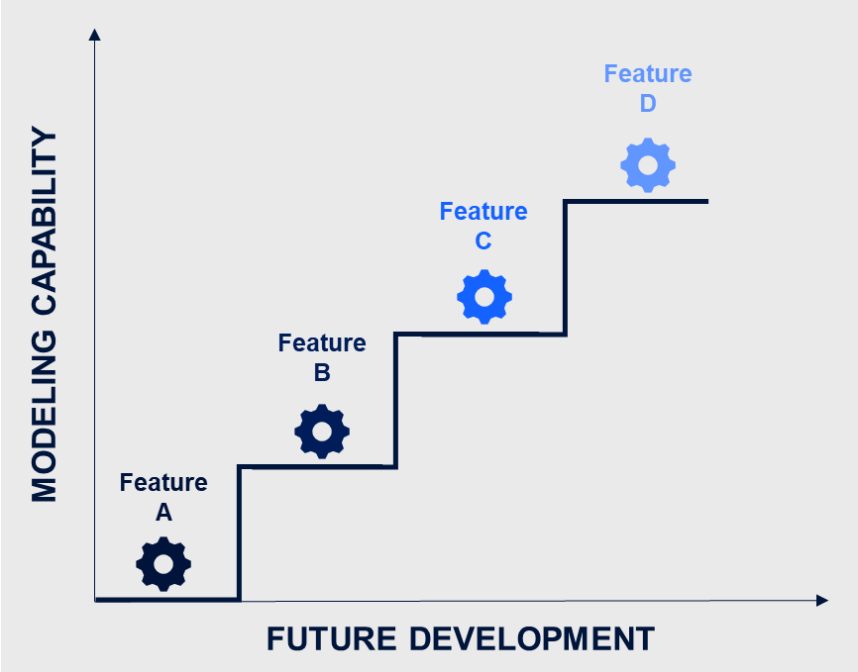
- **Overall, SpaceWorks is excited by the possibilities and potential of using a modeling and simulation tool like AnyLogic and expects analysis for this project as well as others to be greatly improved going forward**

AnyLogic Model Demo

- Live Demo

AnyLogic Modeling & Simulation | Recommended Features

- **Rework model structure to allow for multiple operators**
  - Enables competitive market analysis
- **Improve resolution into manufacturing process with time and variability impacts**
- **Expand route modeling to allow for more than two airports**
  - Enables tech stops
- **Account for time zone changes to improve flight scheduling**
  - Addresses same-day flight scenarios
- **Incorporate airport infrastructure**
  - Fuel deliveries, price variance per region, weight/size restrictions



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AnyLogic Modeling & Simulation | NASA Study Dashboards

Primary Animation Dashboard

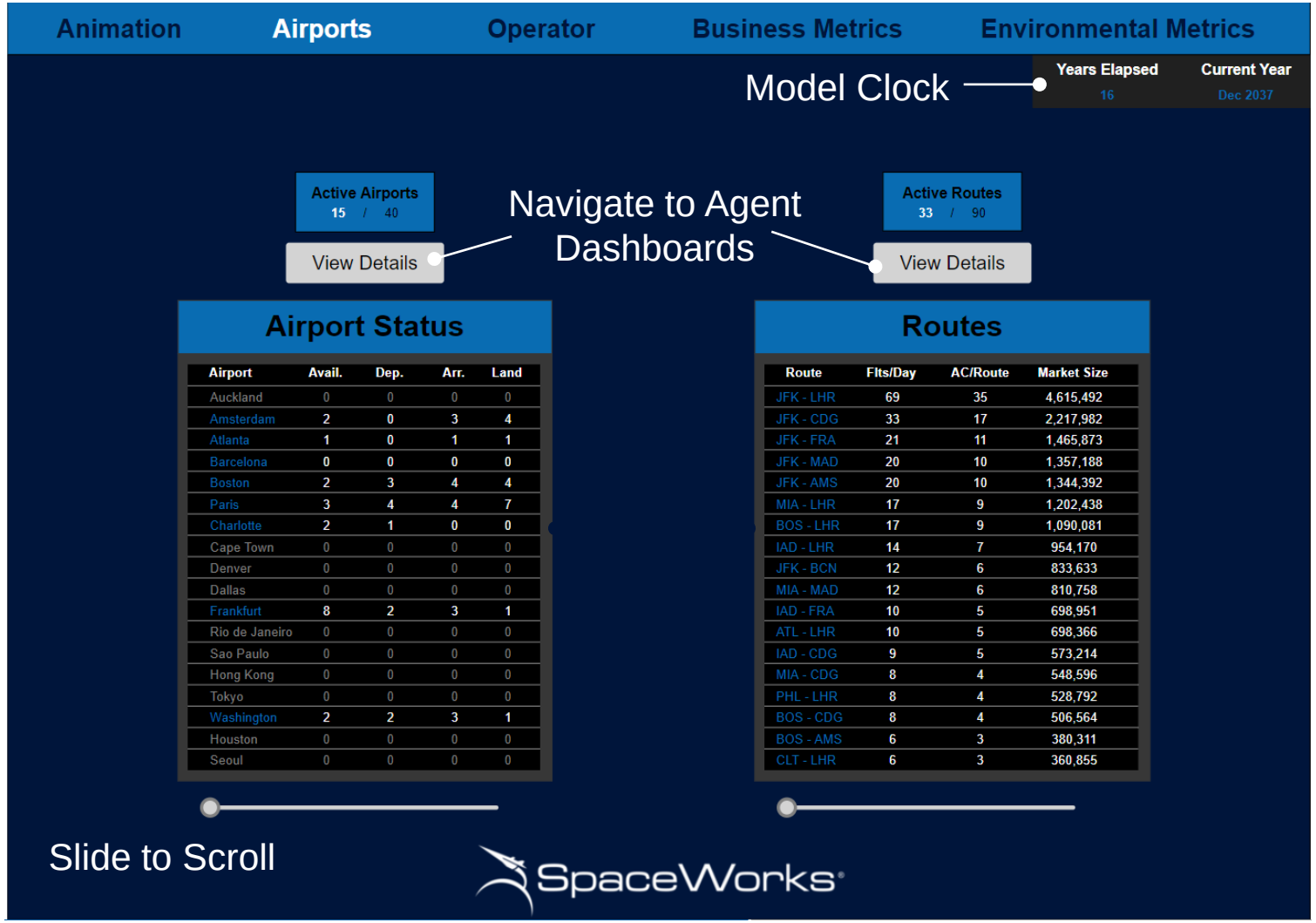
Navigation Pane

Active Routes/Airports

Model Clock

Users able to select airport or airplane to view stats

Airport and Route Dashboard



Airport Status

Airport	Avail.	Dep.	Arr.	Land
Auckland	0	0	0	0
Amsterdam	2	0	3	4
Atlanta	1	0	1	1
Barcelona	0	0	0	0
Boston	2	3	4	4
Paris	3	4	4	7
Charlotte	2	1	0	0
Cape Town	0	0	0	0
Denver	0	0	0	0
Dallas	0	0	0	0
Frankfurt	8	2	3	1
Rio de Janeiro	0	0	0	0
Sao Paulo	0	0	0	0
Hong Kong	0	0	0	0
Tokyo	0	0	0	0
Washington	2	2	3	1
Houston	0	0	0	0
Seoul	0	0	0	0

Routes

Route	Flts/Day	AC/Route	Market Size
JFK - LHR	69	35	4,615,492
JFK - CDG	33	17	2,217,982
JFK - FRA	21	11	1,465,873
JFK - MAD	20	10	1,357,188
JFK - AMS	20	10	1,344,392
MIA - LHR	17	9	1,202,438
BOS - LHR	17	9	1,090,081
IAD - LHR	14	7	954,170
JFK - BCN	12	6	833,633
MIA - MAD	12	6	810,758
IAD - FRA	10	5	698,951
ATL - LHR	10	5	698,366
IAD - CDG	9	5	573,214
MIA - CDG	8	4	548,596
PHL - LHR	8	4	528,792
BOS - CDG	8	4	506,564
BOS - AMS	6	3	380,311
CLT - LHR	6	3	360,855

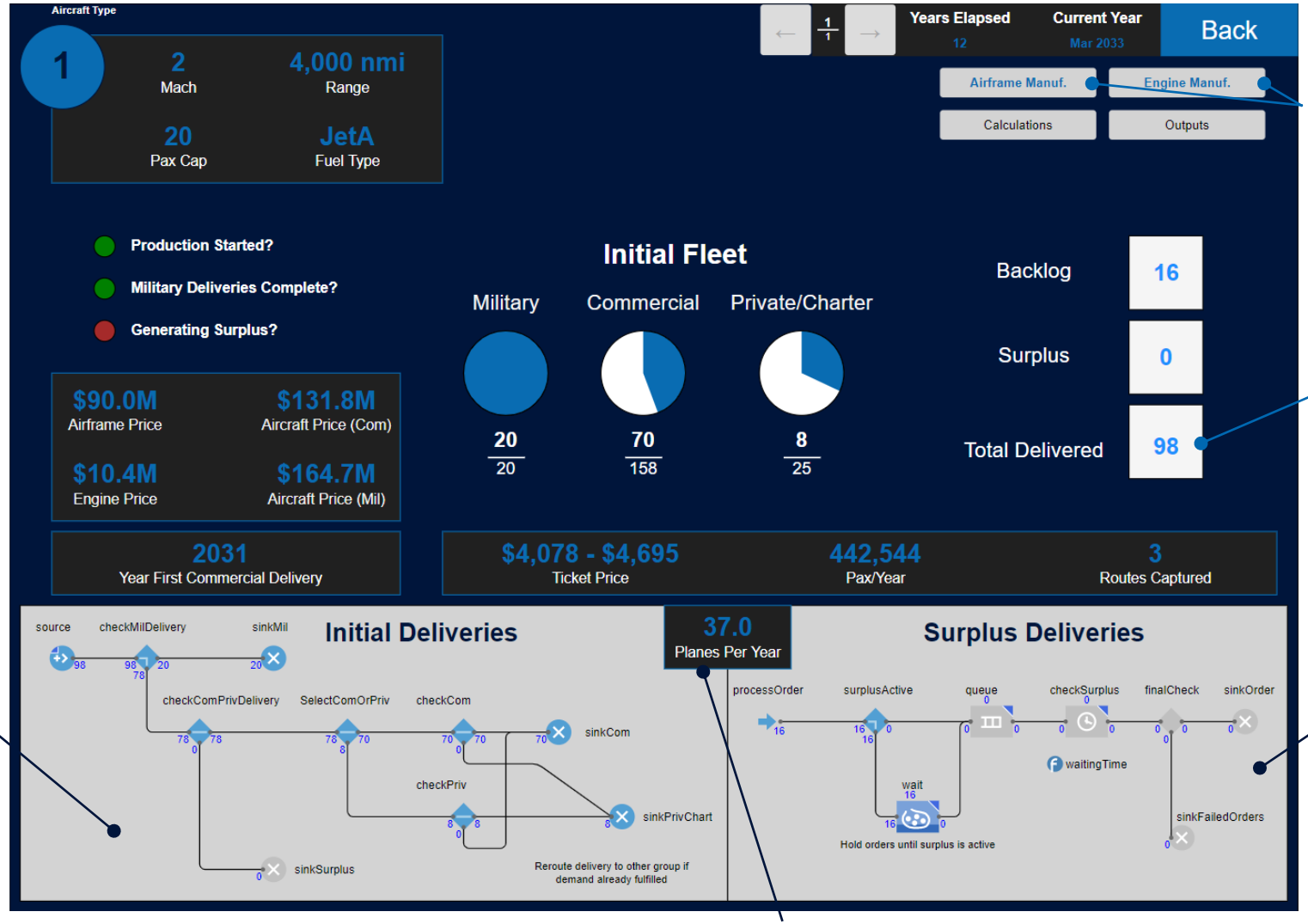
Provides high-level information for airports and routes

Operator Dashboard

Year	Ann. Cost	Cum. Cost	Ann. Rev.	Cum. Rev.
0	$0.00M	$0.00M	$0.00M	$0.00M
1	$0.00M	$0.00M	$0.00M	$0.00M
2	$0.00M	$0.00M	$0.00M	$0.00M
3	$0.00M	$0.00M	$0.00M	$0.00M
4	$0.00M	$0.00M	$0.00M	$0.00M
5	$1041.18M	$1041.18M	$0.00M	$0.00M
6	$780.89M	$1822.07M	$0.00M	$0.00M
7	$780.89M	$2602.96M	$0.00M	$0.00M
8	$780.89M	$3383.85M	$0.00M	$0.00M
9	$780.89M	$4164.74M	$0.00M	$0.00M
10	$2587.60M	$6752.33M	$225.88M	$225.88M
11	$4010.75M	$10763.08M	$3036.52M	$3262.40M
12	$5458.04M	$16221.12M	$6408.45M	$9670.85M
13	$6769.06M	$22990.19M	$9369.72M	$19040.57M
14	$8099.94M	$31090.13M	$11787.28M	$30827.86M
15	$10586.13M	$41676.26M	$13791.45M	$44619.31M
16	$10164.58M	$51840.84M	$14654.57M	$59273.88M
17	$9273.24M	$61114.07M	$14318.75M	$73592.63M

Plane ID	Route	Status	Aircraft Type
1	JFK - LHR	RETIRED	1
2	JFK - LHR	RETIRED	1
3	JFK - LHR	RETIRED	1
4	JFK - LHR	RETIRED	1
5	JFK - LHR	RETIRED	1
6	JFK - LHR	RETIRED	1
7	JFK - LHR	RETIRED	1
8	JFK - LHR	RETIRED	1
9	JFK - LHR	RETIRED	1
10	JFK - LHR	RETIRED	1
11	JFK - LHR	RETIRED	1
12	JFK - LHR	RETIRED	1
13	JFK - LHR	RETIRED	1
14	JFK - LHR	IN SERVICE	1
15	JFK - LHR	IN SERVICE	1
16	JFK - LHR	IN SERVICE	1
17	JFK - LHR	IN SERVICE	1
18	JFK - LHR	IN SERVICE	1

AircraftType Dashboard



Navigate to Agent Dashboards

Includes initial deliveries and surplus deliveries

Manages initial deliveries

Manages surplus deliveries

Current production rate

Manufacturer Dashboard

Airframe Manufacturer

Operator | Years Elapsed 26 | Current Year Sep 2047 | Back

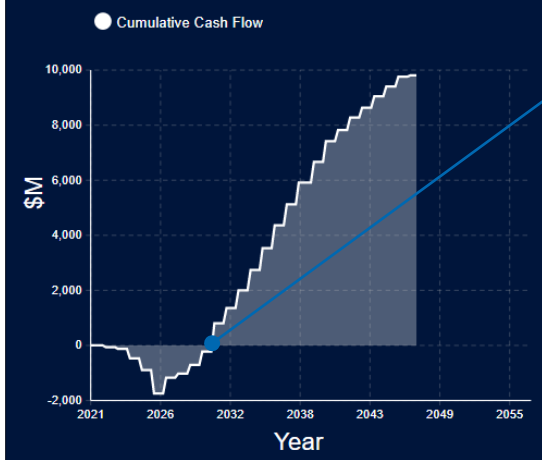
Calculations

Perseus

1	9
Aircraft Type	Years of Development

Sales

20	213	92	325
Military	Commercial	Private/Charter	Total



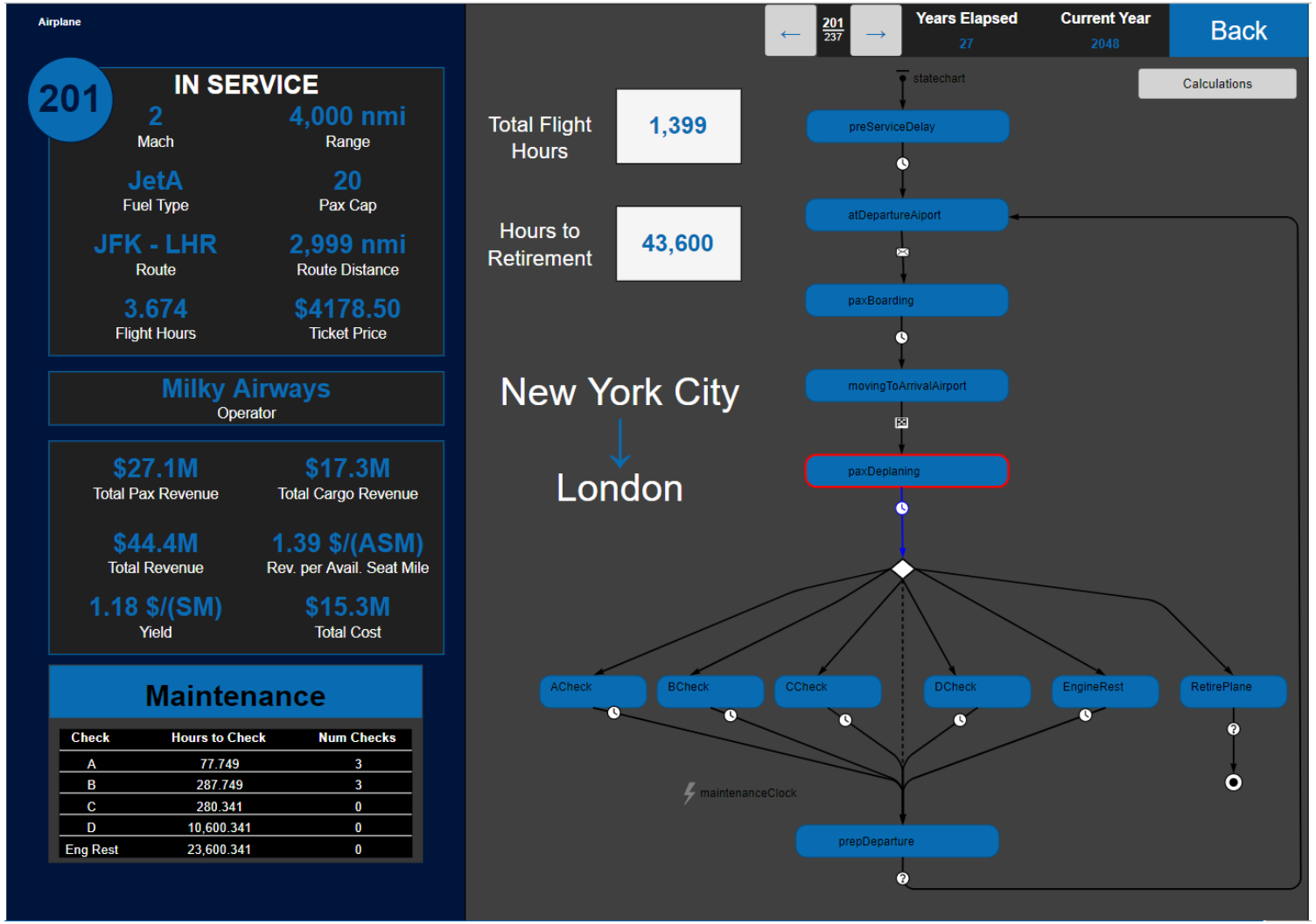
Break Even Year
2030

End of Year Accounting

Year	SG&A	DDT&E	Op	Prod	Total Cost	Revenue	Ann CF	Cum. CF	Num Sold
0	$12.5M	$50.0M	$62.5M	$0.0M	$62.5M	$0.0M	$-62.5M	$-62.5M	0
1	$12.5M	$50.0M	$62.5M	$0.0M	$62.5M	$0.0M	$-62.5M	$-125.0M	0
2	$68.7M	$274.7M	$343.4M	$0.0M	$343.4M	$0.0M	$-343.4M	$-468.4M	0
3	$85.8M	$343.4M	$429.2M	$0.0M	$429.2M	$0.0M	$-429.2M	$-897.6M	0
4	$103.0M	$412.1M	$845.2M	$0.0M	$845.2M	$0.0M	$-845.2M	$-1742.8M	0
5	$120.2M	$480.7M	$799.0M	$0.0M	$799.0M	$1370.7M	$571.7M	$-1171.1M	0
6	$137.4M	$549.4M	$884.8M	$0.0M	$884.8M	$1028.0M	$143.2M	$-1028.0M	0
7	$103.0M	$412.1M	$713.2M	$0.0M	$713.2M	$1028.0M	$314.8M	$-713.1M	0
8	$68.7M	$274.7M	$541.5M	$0.0M	$541.5M	$1028.0M	$486.5M	$-226.6M	0
9	$354.9M	$0.0M	$553.0M	$1419.7M	$1972.7M	$3004.9M	$1032.3M	$805.7M	15
10	$697.0M	$0.0M	$697.0M	$2787.8M	$3484.8M	$4032.9M	$548.2M	$1353.9M	37
11	$650.0M	$0.0M	$650.0M	$2600.0M	$3250.1M	$3901.1M	$651.1M	$2005.0M	37
12	$633.4M	$0.0M	$633.4M	$2533.4M	$3166.8M	$3901.1M	$734.4M	$2739.3M	37
13	$622.4M	$0.0M	$622.4M	$2489.7M	$3112.1M	$3901.1M	$789.1M	$3528.4M	37
14	$614.3M	$0.0M	$614.3M	$2457.4M	$3071.7M	$3901.1M	$829.4M	$4357.8M	37
15	$280.1M	$0.0M	$280.1M	$1120.2M	$1400.3M	$2161.4M	$761.2M	$5119.0M	17
16	$262.5M	$0.0M	$262.5M	$1049.9M	$1312.4M	$2108.7M	$796.4M	$5915.4M	16
17	$245.2M	$0.0M	$245.2M	$980.7M	$1225.8M	$1976.9M	$751.1M	$6666.5M	15

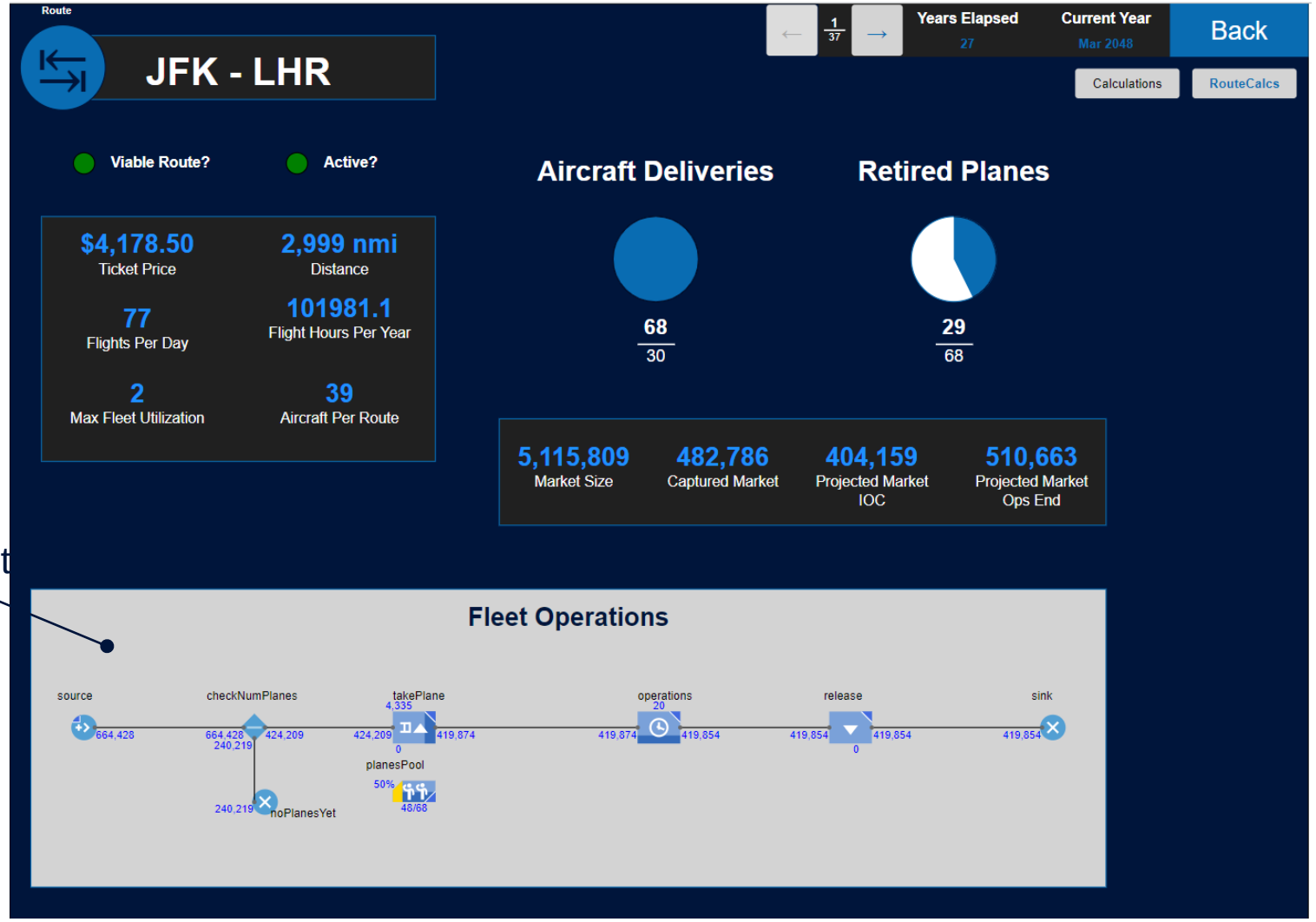
SpaceWorks

Airplane Dashboard



Agent-Based Modeling

Route Dashboard

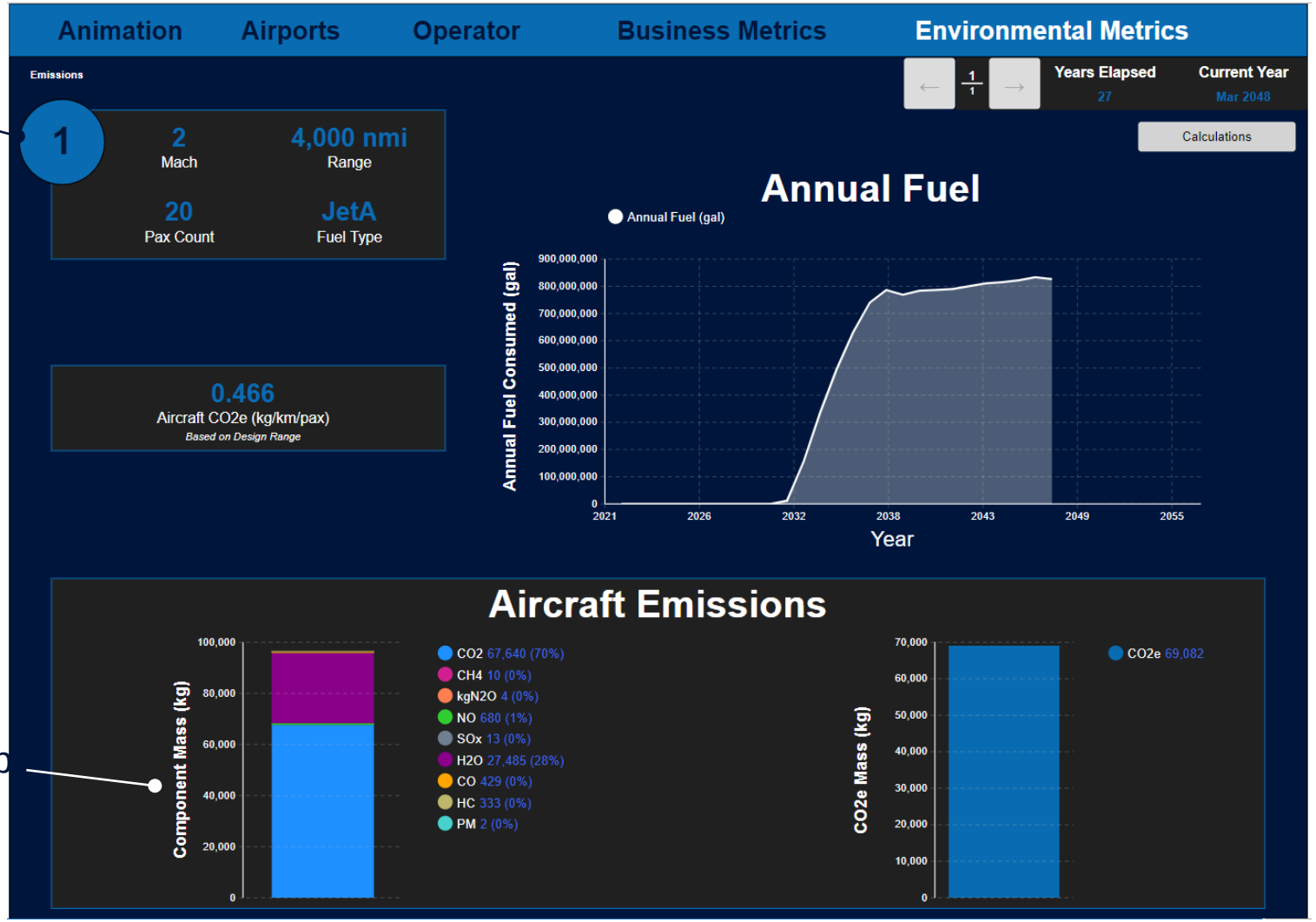


Manages daily fleet operations

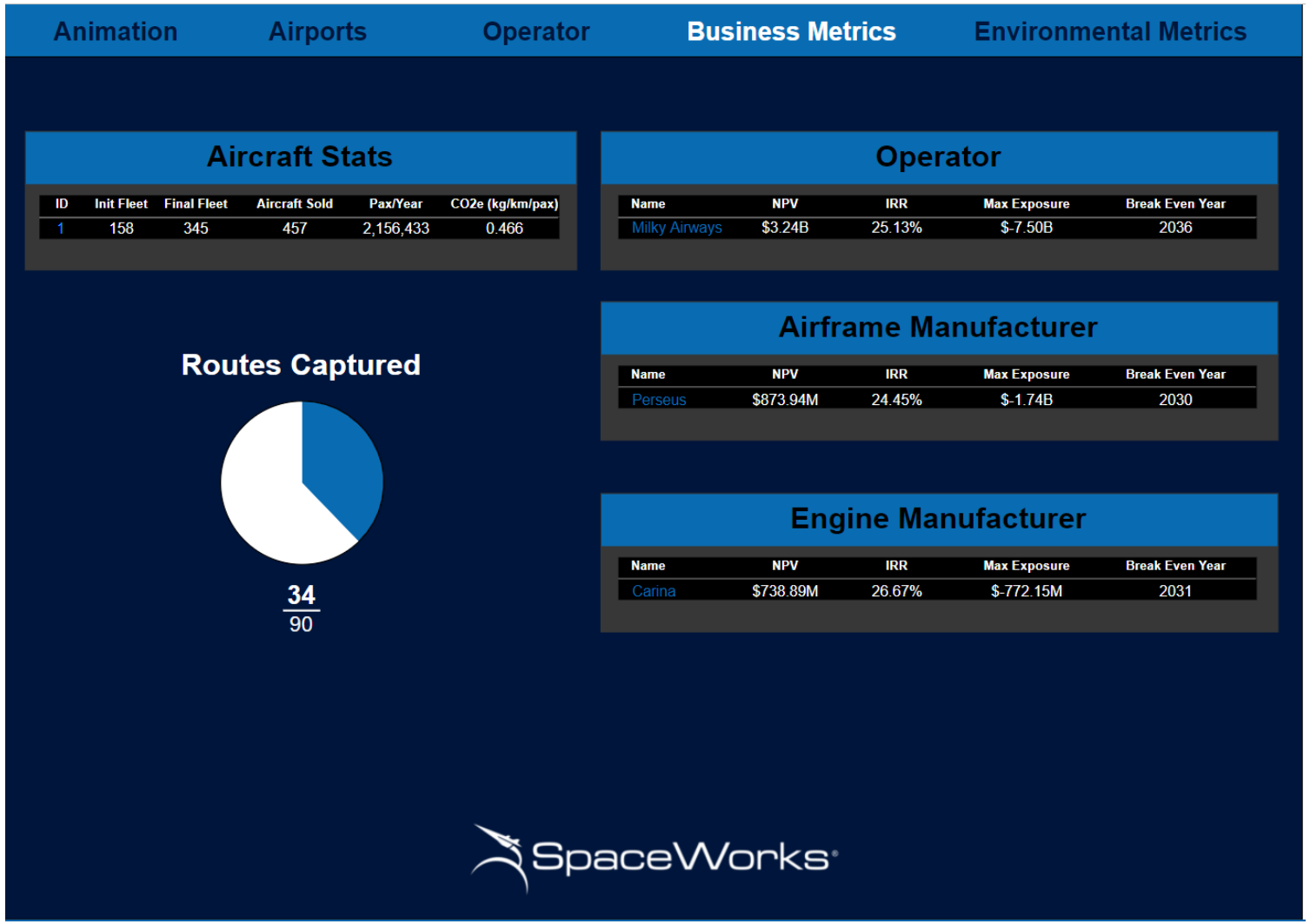
Emissions Dashboard

AircraftType

Emissions Stack-up



Business Metrics Dashboard



Displays business metrics for Operator and Manufacturers