Simulating Global Hypersonic Point-To-Point Transportation Networks

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Various organizations, both public and private, are currently developing the next generation of high-speed flight vehicles. Many of these vehicles are being designed for very specific missions depending on the business models within which they are being funded. The FastForward study, led by analysts at SpaceWorks Engineering, Inc (SEI), is investigating the feasibility of a global point-to-point transportation network that could be served by various hypersonic vehicle concepts. The notional networks connect various sets of cities worldwide with hypersonic links, allowing for high-speed delivery of, in this case, high-priority commercial packages. With input from various individuals and organizations in the space community as well as the commercial shipping industry, SEI has several interdependent models used to gain a deeper understanding of the requirements and implications of such a network. One of these models is used to compare vehicle capabilities to the capabilities of existing package delivery services, and measure how much improvement is possible along these long-distance international routes. A second uses Rockwell Automation's discrete event simulation software Arena to simulate a network as a whole, determining for a given vehicle what fleet size and turnaround time are needed to support worldwide operations. Additional models take outputs from these two and allow analysis of a standalone business case for hypersonic point-to-point package delivery. Whether for use in analyzing independent shipping or passenger networks, or for investigating alternative allocations of future vehicle concepts, these tools can lead to important insights into both the capabilities and challenges of a global transportation network.

Nomenclature

CABAM	=	Cost and Business Analysis Module
DES	=	Discrete Event Simulation
FF	=	FastForward
GHoST	=	Global Hypersonic Shipping Time
GMT	=	Greenwich Mean Time
SEI	=	SpaceWorks Engineering, Inc.

I. Introduction

FOR several years, engineers at SpaceWorks Engineering, Inc. (SEI) have been among those debating the merits of global hypersonic point to point networks. In August 2008, this interest led to the assembly of the FastForward (FF) study group, a pre-competitive collection of representatives from various stakeholder organizations that meets regularly to discuss the future possibilities of such a network. While the group has recently broadened its focus to take in passenger service, the first study efforts were targeted towards high-priority small package shipping.[1] In order to determine whether the whole transportation network was a feasible idea, estimates had to be made of market potential. This required building models to help quantify how hypersonic service compared with available subsonic services, as well as aiding in the vehicle design process by defining what levels of performance were required to represent significant advantages over that service. While these models have been

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mentioned in previous work written by the FF group, they have been further developed over the last year to make them both more flexible and more informative, and the purpose of this paper is to explain them in greater detail.

In the original FastForward study, there was a concept vehicle designed which had a range of 12,000 km and an average speed of 4000 km/h using a periodic trajectory. In addition, the network was defined in terms of three possible 'tiers' of cities in between which all possible routes would be flown. Tier 1, the base case, consisted of Los Angeles, New York, London, Cologne, Shanghai, Hong Kong, and Tokyo. The second tier added Mumbai, Dubai, and Sydney, and tier 3 added Buenos Aires, Sao Paulo, and Johannesburg. In all of these cases, routes are not flown between cities serving the same global region. For example, given the nature of existing regulations, a hypersonic New York – Los Angeles flight would be impossible. The other groupings without links to each other are London and Cologne; Shanghai, Hong Kong, and Tokyo; Mumbai and Dubai; and Buenos Aires and Sao Paulo. All other routes are potentially flows, subject to the constraints of the vehicle studied. The FastForward vehicle and these city groups, having already been selected, were used as the base case for the models described here.

II. GHoST Calculator

The Global Hypersonic Shipping Time (GHoST) Calculator is a spreadsheet model developed to enable easy analysis of the time advantages achievable by a high-speed vehicle compared to existing commercial package service on a given shipping network. GHoST is maintained at SEI, and is currently utilized in support of the FastForward study group's efforts to understand the market potential of this type of global hypersonic service. The layout of GHoST is dominated by a complete list of all theoretically possible routes between any two cities, with each route's data occupying fifty cells in a single row. The routes are grouped by the tiers of service and, in effect, each of the three tiers is being analyzed in parallel within the same model. Above the list of routes is a set of outputs summarizing the advantage of the given vehicle over existing service.

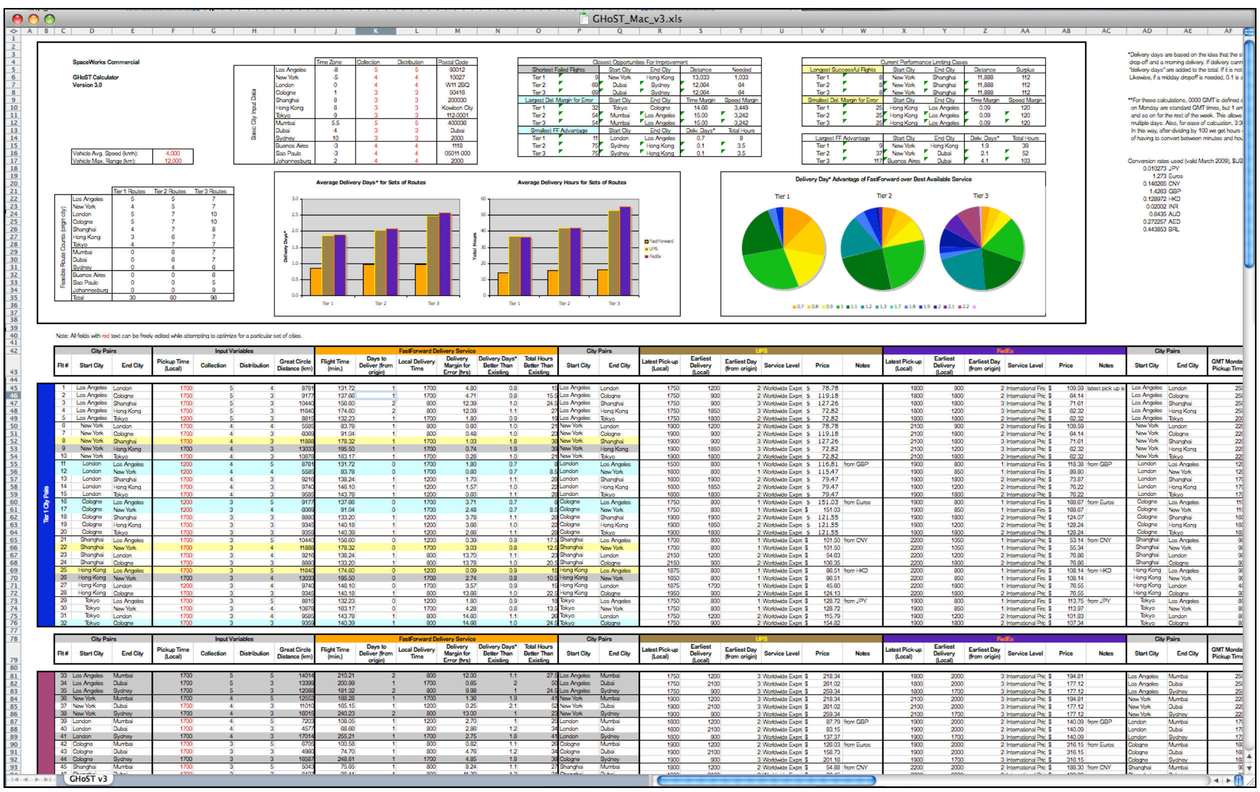

Figure 1. Screenshot of GHoST Calculator

The first step taken towards filling out the spreadsheet, and the first step that would be taken with any new set of cities, is to fill in the columns representing fixed data about each route. This includes the great circle distance (in km) between the two cities, as well as the existing UPS and FedEx fastest available services. The data collected on commercial service include the latest pickup time allowed, the time and day of the earliest delivery option, the name of this service level, and the price. As a rule, all inquiries were made using the company's websites, and assumed a Monday drop off/pickup, to prevent any weekend schedule abnormalities from affecting the delivery time.

Once the existing service options have been entered, there is a need to translate pickup and delivery times into a standardized metric against which a hypersonic service can be compared. The immediately obvious option is total delivery hours. This can be conceptualized by thinking of a customer starting a stopwatch immediately before dropping it off, and the recipient reading the time off of the stopwatch as soon as it is delivered to them. To calculate this time the pickup and delivery times had to be converted into a modified form of Greenwich Mean Time (GMT). To allow for easy arithmetic across multiple days, midnight on Sunday in the GMT time zone was considered to be time 0000, midnight Monday was time 2400, midnight Tuesday was 4800, etc. Additionally, increments shorter than an hour were modified such that 8:30 am Monday became 0850, rather than the standard 0830. Similarly, 3:45 pm Monday (in the GMT zone) is represented as 1575, 9:15 am Tuesday is 3125, and so forth. By stating the pickup and delivery times in this form, subtracting pickup from delivery and dividing by 100 gives a decimal representation of the number of hours spent in transit. For each route, the delivery hours offered by UPS and FedEx are both calculated, with the better service being stored for comparison to the high-speed concept.

Although the idea of delivery hours is simple, objective, and easy to understand, and while it is displayed as one form of comparison, it does not always make sense in this industry. For example, if an existing service can deliver a package by 8 am on Wednesday, it doesn't generally make a real difference if a new service can deliver the package by 2 am. Despite being "6 hours faster," this won't have the package in the hands of the recipients any earlier. To explain this concept, the idea of a 'delivery day' was developed. Delivery days are based on the idea that the standard delivery paradigm consists of an afternoon drop off and a morning delivery. An 'overnight' service matching this pattern is labeled as 1.0 delivery days. If delivery cannot be guaranteed until midday, 0.1 delivery days are added. If it is not guaranteed until the close of business, 0.2 days are added. Likewise, if a midday drop off is needed for morning delivery, that adds 0.1 delivery days. As with standard hours, the delivery days offered by UPS and FedEx are calculated and compared, with the better service being used as the benchmark for hypersonic service.

At this point all the constants and comparison points are established, and the user can input the variables that describe their specific concept. These inputs include vehicle range in km, average speed in km/h, and local network processing times. All routes longer than the given range will be visually greyed out, and excluded from analysis. The speed cannot be the average cruising speed, but rather an estimate of the actual average speed for the entire flightpath since it is used to calculate total flight time for each route. The local processing times are much more subjective, and are meant to represent the amount of time from package pickup to airplane take off, and from landing until the package is delivered. A collection time and a distribution time are entered for each city. Depending on the other assumptions of a particular study, these might be longer to allow a single city to reliably serve a larger area (and thus have a higher demand per flight) or shorter to improve the time-based performance. In the FF study, they were all between 3 and 5 hours. The final set of variables is the list of latest allowed package drop off times for each route. The default is 1700 (5:00 pm) for all routes, but it is possible that moving this up to 1400 or 1200 could result in a delivery day savings.

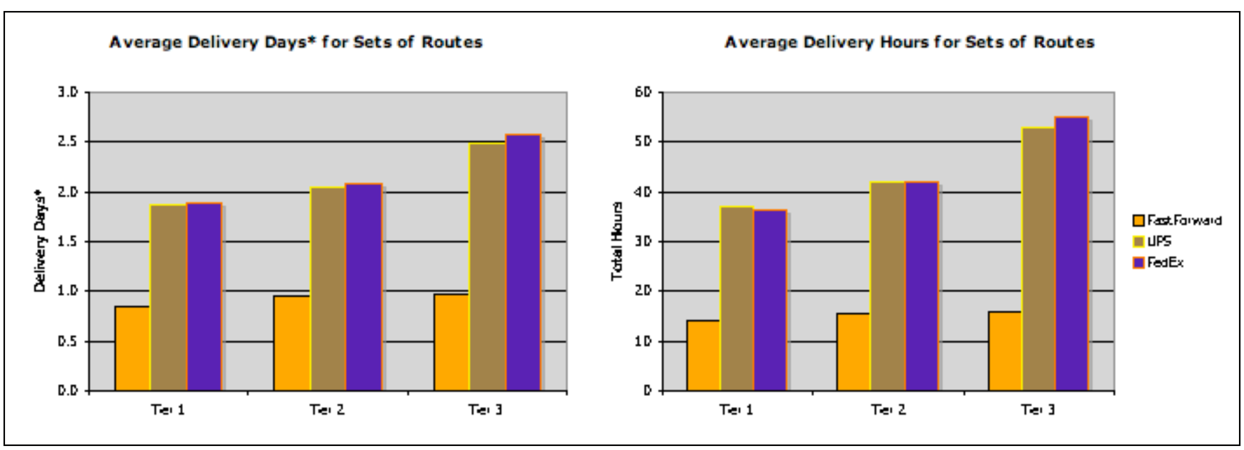

Figure 2. Average service times for FedEx, UPS, and FastForward within FF network of cities

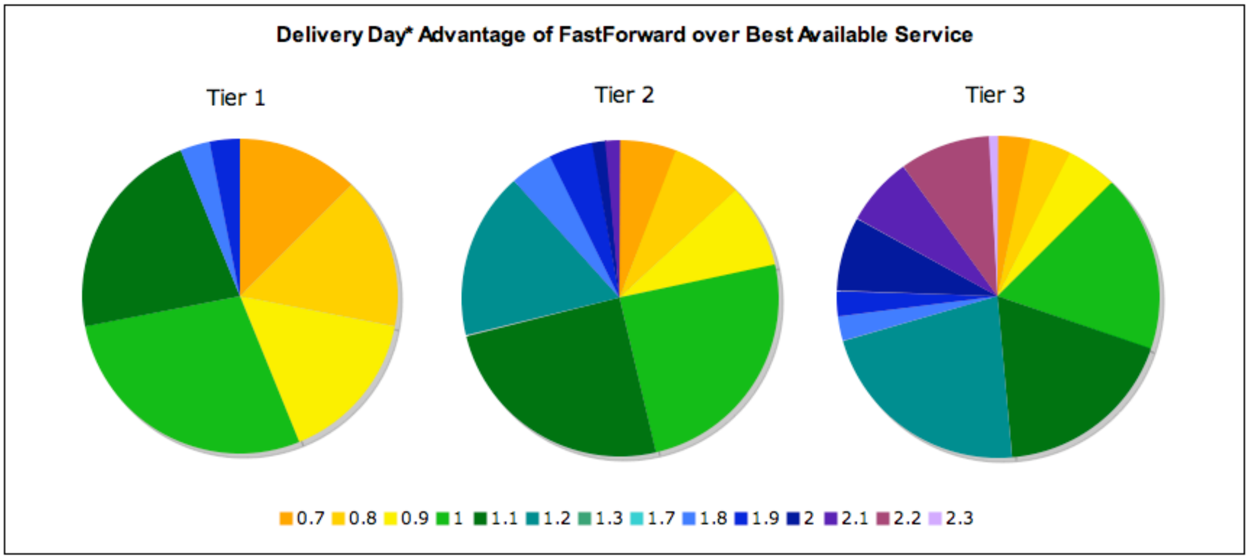

Figure 3. Distribution of delivery day advantage of FastForward over best existing service

Once all these variables are defined for the high-speed service, spreadsheet formulas calculate several metrics for each route, and several overall comparisons between services. First, any routes infeasible due to distance are greyed out and subsequently ignored. Next, to find a route's best possible delivery time, the pickup time is converted to the modified GMT format, local network collection time is added to get takeoff time, flight time is calculated from distance and speed to get landing time, local distribution time is added, and the result is converted from GMT back into the local time. The two GMT times are compared to calculate delivery hours, the two local times are compared to calculate delivery days. (Both pickup and delivery times are generalized as 'by 8:00 am,' 'by noon,' or 'by 5:00 pm' for delivery day calculation.) Each route's new best possible service is compared to the faster of UPS and FedEx service, and the advantage is reported in both hours and delivery days.

GHoST aggregates this improvement data from all feasible routes, creating a pair of bar charts showing average delivery days and delivery hours across each tier of cities, and a set of pie charts showing the frequencies of various improvement levels achieved for each tier. For examples of these, see Figs. 2 and 3. Recall that in these charts, representing FF data, that tier 2 includes the routes from tier 1, and tier 3 includes all the routes. While detailed discussion of FF study results goes beyond the scope of this paper, it is seen in Fig. 2 that FastForward's hypersonic service concept is better than existing options by an average of about 20 hours or a full delivery day in tier 1, and that this only improves as more routes are added. The color coding in Fig. 3 makes it easy to observe that, for the full set of routes, a fairly small fraction (those in yellow-orange tones) of routes are improved by less than a full delivery day; more than half of the routes (green tones) are improved between 1 and 1.3 delivery days, and over a quarter (blue and purple tones) are improved more than that. Every individual routes data is easily accessible, but these visualizations make it easy to quickly assess what kinds of improvements are being made.

Beyond these summary metrics, the GHoST calculator provides some additional information that can be used directly by the user to make incremental adjustments to their input variables that are guaranteed to result in net gains in system performance. This additional information relies on the concept of margins. When each delivery time is calculated, it is rounded to the next delivery day increment. This makes a 2 am delivery equivalent to an 8 am, but it also makes an 8:15 delivery equivalent to one at noon. The 2 am delivery can afford to be up to 6 hours slower and still achieve the same service level; it has a margin of 6 hours. Alternatively, to improve the level of service, 7 hours would have to be saved. The 8:15 am delivery can be improved by shaving off a mere 15 minutes from delivery time, and it has a margin of 3:45. Margins are calculated for every feasible route, but GHoST collects the smallest and largest margins and presents them at the top of the spreadsheet, in tables reproduced as Fig. 4.

Closest Opportunities For Improvement					
Shortest Failed Flights		Start City	End City	Distance	Needed
Tier 1	9	New York	Hong Kong	13,033	1,033
Tier 2	69	Dubai	Sydney	12,064	64
Tier 3	69	Dubai	Sydney	12,064	64
Largest Del. Margin for Error		Start City	End City	Time Margin	Speed Margin
Tier 1	32	Tokyo	Cologne	14.66	3,449
Tier 2	54	Mumbai	Los Angeles	15.00	3,242
Tier 3	54	Mumbai	Los Angeles	15.00	3,242
Smallest FF Advantage		Start City	End City	Deliv. Days*	Total Hours
Tier 1	11	London	Los Angeles	0.7	8
Tier 2	75	Sydney	Hong Kong	0.1	3.5
Tier 3	75	Sydney	Hong Kong	0.1	3.5

Current Performance Limiting Cases					
Longest Successful Flights		Start City	End City	Distance	Surplus
Tier 1	8	New York	Shanghai	11,888	112
Tier 2	8	New York	Shanghai	11,888	112
Tier 3	8	New York	Shanghai	11,888	112
Smallest Del. Margin for Error		Start City	End City	Time Margin	Speed Margin
Tier 1	25	Hong Kong	Los Angeles	0.09	120
Tier 2	25	Hong Kong	Los Angeles	0.09	120
Tier 3	25	Hong Kong	Los Angeles	0.09	120

Largest FF Advantage		Start City	End City	Deliv. Days*	Total Hours
Tier 1	9	New York	Hong Kong	1.9	39
Tier 2	37	New York	Dubai	2.1	52
Tier 3	117	Buenos Aires	Dubai	4.1	103

Figure 4. Table of critical routes

The three left-hand tables are labeled as the 'Closest Opportunities for Improvement,' since the routes listed there can be improved with by some combination of input variables. The top set of flights are currently infeasible but could be reached by increasing the vehicle range. The second set are those with the largest margins, expressed in terms of time as well as speed. These are likely to be routes featuring 0800 deliveries that could potentially be shifted to 1700 the previous day through higher speeds, shorter local network times, or an earlier pickup deadline. The third set are the routes for which the advantage over existing service is the smallest. It may not be obvious how to improve these, but if the goal (as in FF) is to demonstrate a certain minimum advantage over existing options, these are the routes that need attention. The infeasible flights are already shaded in grey, but the other improvement opportunity routes are shaded light blue to make them easily identifiable in the long list further down the spreadsheet. The blue shading can clearly be seen in Fig. 1.

The tables on the right are labeled 'Current Performance Limiting Cases.' If there is an opportunity to save costs by reducing vehicle performance, or perhaps a chance to make longer local network time assumptions to incorporate more demand, these routes represent the boundaries that cannot be crossed without sacrificing some portion of your time advantage. The first set indicates the longest route flown, implying a reduction to that length will maintain the same list intact. The second is the smallest time margin (or speed margin) for each city group. These routes are shaded yellow in the full list. Below these two is a table of the route in each tier with the largest advantage in delivery days. These are not shaded since they do not seem as likely to be directly relevant, but they still may be of interest when conceptualizing the full range of system performance.

The GHoST Calculator gives an in-depth picture of the routes achievable for a high-speed transportation network, and how the performance of those routes compares to existing commercial priority shipping options. A user is presented with useful summary graphs, and also has their attention drawn to key individual routes they can inspect to make intelligent decisions about their input parameters. The use of the delivery day as a metric is well-suited to the business model of the priority package shipment industry. In short, SEI's GHoST Calculator is an ideal model to incorporate into any study of next-generation high-speed cargo transportation networks.

III. Discrete Event Simulation Model

Once a flight schedule has been established for a desired service network, manually or using GHoST, this schedule can be used to determine the number of vehicles needed to support the network. The challenging part of this is that it cannot be calculated directly by counting the number of flights per day and assuming a vehicle can make a certain number of flights. The complexities of the service network, particularly the fact it is spread across a complete range of time zones, require a model that can keep track of the movements of every individual plane, and track its availability to carry another shipment. Discrete Event Simulation (DES) is a methodology designed to handle exactly these sorts of problems.

DES, also known as the event scheduling approach, was developed in the industrial and systems engineering community. The general concept is that no matter how complex a system, it can be broken down into a series of discrete points at which changes occur to some property of the system. Events may last a non-zero amount of time, but those events can be defined by their start and end point. The simulation begins at a set point in time and proceeds forward until it reaches the first scheduled event. The system changes according to the details of the event, which often includes adding additional events to the schedule, then the simulation moves on to the next event. This approach can also incorporate resource usage, including multiple entities competing for limited resources, as well as random generation of numbers, but neither of these were called for in this model. DES models have been used to model systems as diverse as passenger flow in airports, automotive manufacturing facilities, and major cargo shipping ports.

SpaceWorks' DES software of choice is Arena, a product of Rockwell Automation that SEI has used for its Descartes models[2] that is among the industry leaders. Arena includes a graphical interface that allows a user to build a network of modules, or 'blocks,' that resemble a flowchart, and then animate the paths entities take between these blocks. The Basic Edition of Arena gives access to eight kinds of modules: create, dispose, assign, process, decide, record, batch, and separate. Additionally, users can define variable arrays that can be referenced from the various blocks during the model run.

An Arena DES model was built to simulate a week's worth of high-speed package delivery flights over the global network defined by the FastForward study group. The model, shown in Fig. 5, included all 13 cities found in tier 3 of the FF network, and for that study modifications were later made to accommodate the more limited tier 2 and tier 1 analyses. The lines connecting city pairs seen in this screenshot represent the flight paths taken by a pair of hypersonic vehicles each day. The font colors of the city names only serve to represent which tier they belong to, with tier 1 in blue, 2 in purple, and 3 in red. It should be clear that a new model would have to be built for a new network, even one of the same size since the set of routes cannot be represented by a complete graph between the cities. Any change in vehicle range that adds or subtracts a route also requires adjustments to be made. However, for purposes of this paper, the intercity network is static, and we focus instead on the key components of the model, those being the input variables and the structure of the 'submodels' that represent operations at each city in the network.

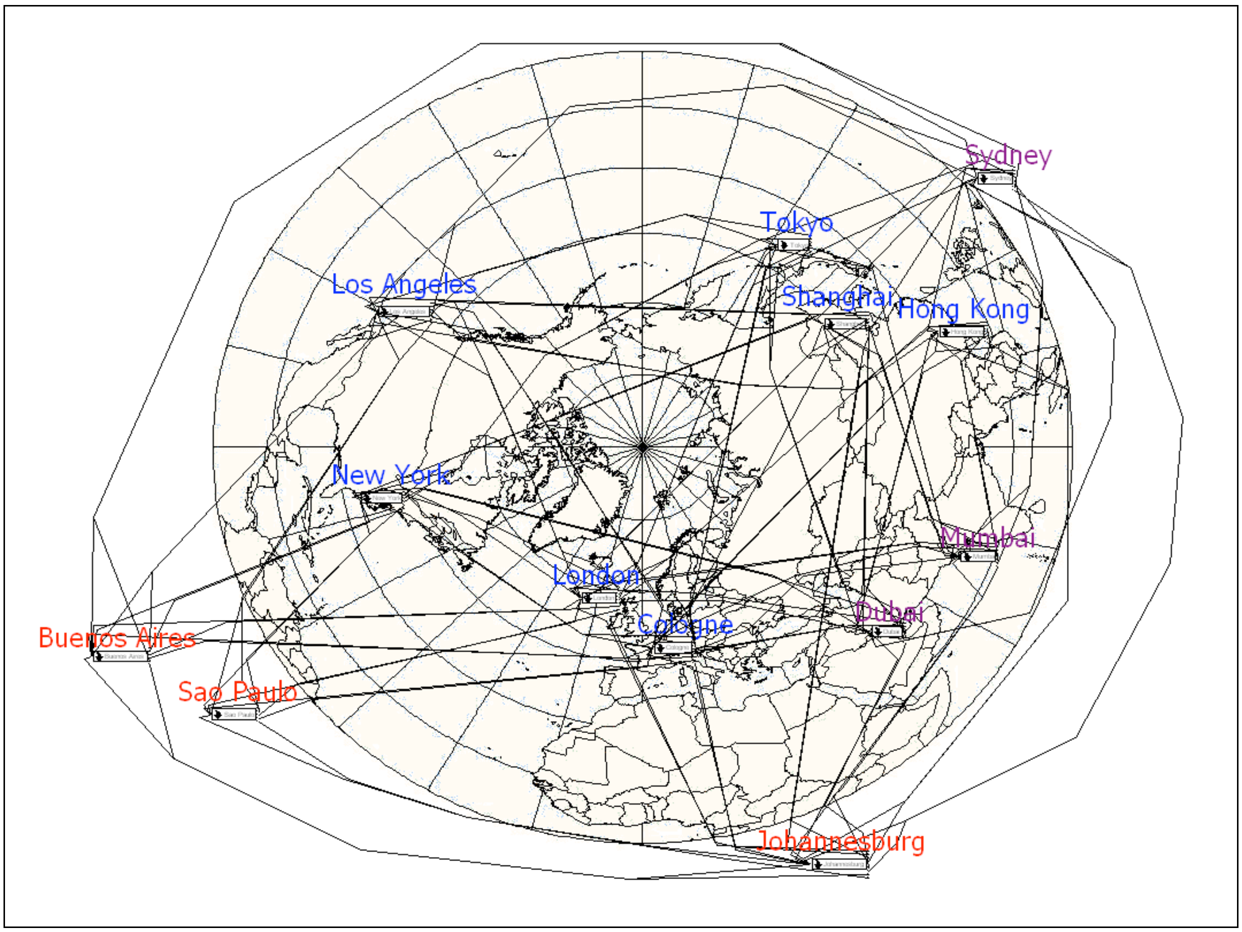

Figure 5. View of Arena DES model for network of 13 FastForward cities

There are five sets of variables required as inputs. The first is a single point, the estimated turnaround time of the vehicle between flights. The second is an array with the number of vehicles that start the week in each city. These two will be the ones changed in between runs to find the minimum cost solution. The other three are all two-dimensional arrays with a value corresponding to each flight route. One set will contain the flight time for each route, which should be readily available from GHoST. Another will contain the times of the first possible launch, converted into decimal hours using the modified GMT notation explained in section II. The final variable array will contain the landing deadline for the first delivery, that is the latest time a plane can land on a particular route and still have the package delivered by the time quoted in the schedule from GHoST, which will also be in modified GMT format. Both of these sets of times should have accounted for local collection and distribution times.

The small white rectangles under each city name are submodels, which act like folders, each containing a set of blocks that define the logical flow through that city. In this model, all the submodels are built following the same structure. Tokyo's submodel is shown in Fig. 6 as an example. When the model is initiated, the vehicle creation block in each city (seen top, near the left) creates a number of entities matching the quantity defined as starting in that city. When using this model for FastForward, the initial guess value was usually one vehicle per route originating in the city. As each of these vehicle entities is created, it moves to a decision block (diamond shaped) which decides which route that vehicle is needed on. This routing is cyclical, with the first vehicle going towards the city with the earliest initial delivery deadline. Once the simulation reaches the first departure time for a route, the appropriate create block generates a 'flight' entity, which can also be thought of as representing the shipments to be delivered that day on that route. The vehicle entity is combined with the flight entity at a batch block, and the new combined entity travels to its destination, using a process block to force the appropriate time delay to take place.

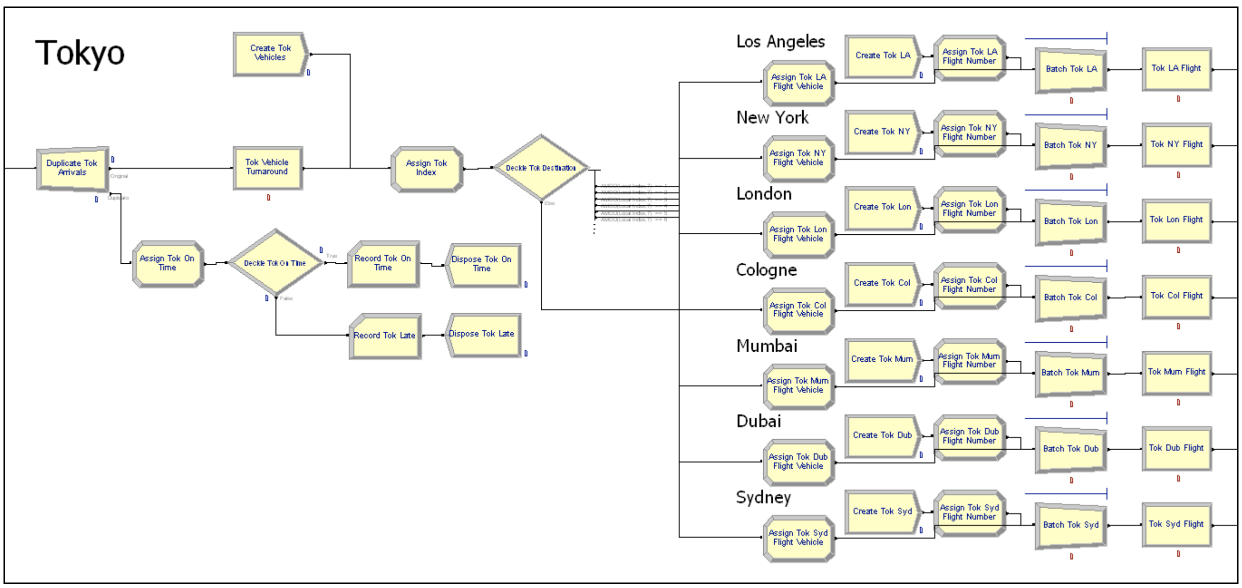

Figure 6. Tokyo submodel, a representative city within the DES model

Upon arrival in a new city/submodel, the entity arrives at the left edge of the field of view. The first block duplicates the entity, effectively separating the packages back off of the vehicle. The vehicle entity goes forward to the turnaround process, where it waits the necessary amount of time for repairs, refueling, and any other ground operations that take place. After finishing turnaround, it goes to the decision block where it is routed for its next flight. In reality, while the plane gets prepped for its next flight, the packages are being distributed in the local network. In this model, we know that the landing time was set to accommodate that local distribution, so we only have to check if the flight landed on time to know if the packages will arrive at their destinations as promised. An 'assign' block stamps the entity with its arrival time then it moves to a decision block where the arrival time is checked against the schedule. Based on the outcome, the flight is recorded as either 'on time' or 'late,' adding to a running tally maintained by one of the two record blocks, then the entity is disposed.

When the model is run, it starts at time 0000, which is midnight Sunday night, and proceeds for one week. More precisely, if proceeds until 5 flights have been completed along each route, simulating launches every night from Monday through Friday. Every time a flight launches, the takeoff time for the next flight on the route is incremented by 24 hours, and each time it lands, the 'on time' threshold for that route is also increased by a full day. After the model run is completed, Arena generates a series of reports. The 'category overview' report contains the only information with which we are concerned, in the section about record blocks. If the input variables, specifically turnaround time and the starting vehicle quantities, were chosen correctly, all of the city counters of late arrivals will be at 0. If there are late flights anywhere, then there are not enough vehicles to support the flight schedule. If there are no late flights, it is possible there is surplus capacity that can be eliminated. In practice, a series of iterations will be required to find the minimum total number of vehicles needed to cover all routes for a particular turnaround time.

In the way of an example, consider the case of starting one vehicle per route at the route's origin. Assuming the GHoST information was input correctly, all of the first day's flights are guaranteed to be on time. However, with a turnaround time in the range of 18-20 hours, it is possible that the incoming flights to Tokyo (the easternmost city and therefore the one with earliest departures) may land late enough in the day that they are not able to carry shipments from Tokyo Tuesday night. Alternatively, if many of Tokyo's outgoing routes have several hours of slack, the Tuesday night flights may use up some of this slack and then they may fall behind schedule on Wednesday night once that delay has circulated through the network. The result here is that it would be a good idea to add more vehicles to the network. If, on the other hand, turnaround time was in the range of 6-8 hours, it is likely that 100% of flights will be on time. Each vehicle can fly its daily route, get checked over, and be ready to fly with plenty of time to spare. In this case it makes sense to begin eliminating vehicles from the fleet. For example, flights to Los Angeles from Sydney and the three Far East cities could be landing when it is still just Monday morning in LA, meaning they would be ready to fly return trips by that night when the first round of departures leaves LA around midnight local time. Fig. 7 shows outputs from situations similar to both of these examples, using the 7-city tier 1 network.

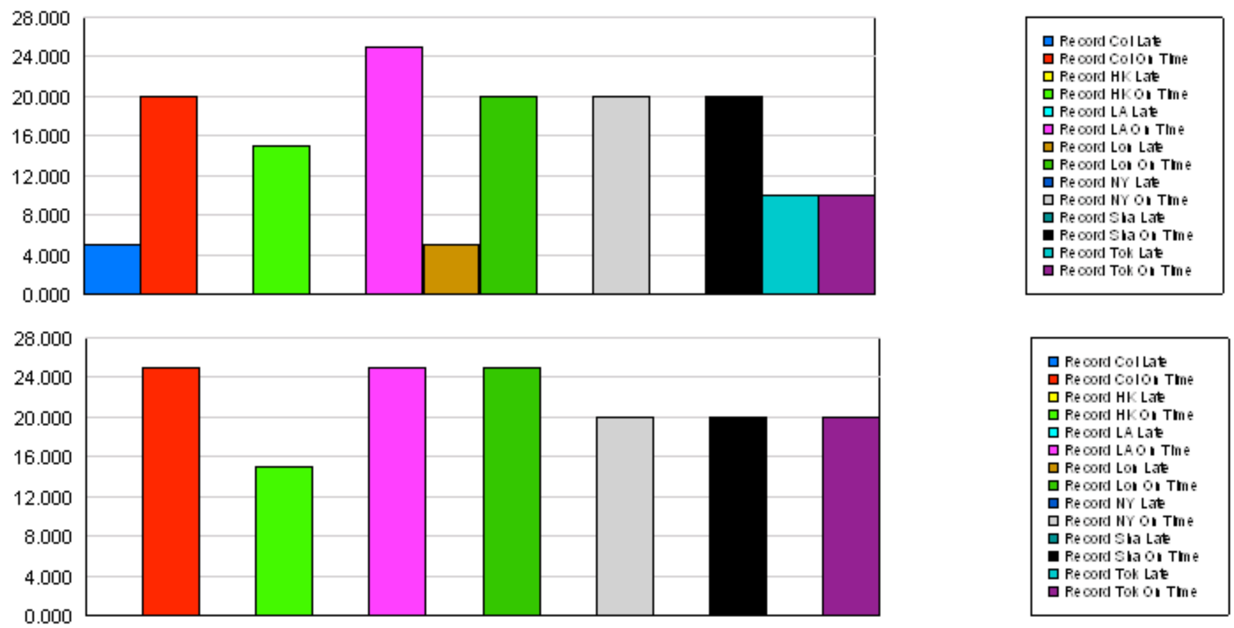

Figure 7. Simulation outputs for a 7-city network with too few airframes (top) and a network that might have surplus capacity (bottom)

While the GHoST calculator has been enhanced significantly in the last year (it is currently in version 3), the DES model is still under development and will continually be improved in the future. Unfortunately, as previously explained, a new model is required for every new set of cities and/or routes. This situation is unlikely to change. While a single route addition or deletion may only take an experienced user a few minutes to implement, the implied requirement to save a new model file for every version is inconvenient. Nevertheless, there are several enhancements possible. If desired, flight times and/or turnaround times could become randomly generated numbers from any number of distributions. Resources could be added to the turnaround process blocks, limiting the number of vehicles being worked on in parallel in each city. A likely improvement involves restructuring the data recording mechanism to provide better clues about which flights arrive late to a particular city.

IV. FastForward , CABAM, and Other Applications

Both the GHoST calculator and the DES model were developed for the specific purpose of supporting the FastForward study group's efforts to build a business case for a global hypersonic shipping network. Outputs from GHoST were used to justify various revenue-related assumptions driven by knowledge of the speed advantages of the FF service. The simulation was crucial in determining the number of vehicles that would have to be acquired, a significant driver of total program cost. As the FastForward group continues studying various scenarios, including passenger service, these models will continue to be relied upon for data. In fact, one group member has already adapted them to study whether a supersonic network would have similar advantages to the hypersonic baseline case.

Both models can also be used in conjunction with CABAM, the Cost and Business Analysis Module, a life cycle cost analysis tool maintained by SEI, originally developed in 2002 at Georgia Institute of Technology.[3] CABAM takes inputs from various disciplinary models and combines them with market assumptions and other financial factors to produce estimates of Net Present Value and other standard business metrics. CABAM is flexible enough to handle a wide range of launch vehicle programs, with varying levels of private vs. government funding, the possibility of learning curves, and it takes into account discount rates and debt-to-equity ratios, among other economic factors. The models presented here can help drive CABAM inputs, thereby improving the accuracy of the model as a whole.

Beyond future FastForward work and CABAM analyses, each of these tools has intrinsic value for the insights provided by their formulation. As they are themselves the results of many hours of discussions about the best way to confront the modeling challenges presented by these global networks, they represent the cumulative efforts of various technical experts in both aerospace and industrial and systems engineering. The 'delivery day' metric generated while building GHoST encapsulates the current priority shipping paradigm better than any other known to the authors. Experimentation with the simulation has reinforced the importance of reducing turnaround maintenance, not just to save directly in operating costs, but also to avoid purchasing larger quantities of vehicles than ought to be needed. This work cumulatively represents a significant step forward in the modeling and understanding of high-speed global transportation networks, and it is the hope of the authors that it will aide someone working towards the next steps that will eventually make these networks a reality.

Acknowledgments

The authors wish to thank our colleagues at SEI who contributed to this work. In particular, Jennifer Laperre helped conceive of and implement the original version of the GHoST calculator, and Caleb Hodes assisted in the refinement of both models.

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