



A Large Scale Enterprise Level Systems of Systems Simulation Tool

Gio K. Kao, PhD & Steven M. Handy

gkkao@sandia.gov smhandy@sandia.gov

**Sandia National Laboratories
Albuquerque, NM 87135**

**INFORMS 2009
San Diego, California
October 11-14, 2009**

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

© Copyright 2009, Sandia Corporation, All rights reserved.

Outline

- **Motivation**
- **The Simulation Tools**
- **Features**
- **Summary**

Motivation

The beginning:

- **Simulation capability motivated by the US Army's need to analyze a brigade-level System of Systems (SoS)**
 - **SoS analysis is necessary to capture interrelationships in a complex large-scale logistics and sustainment environment**
 - **Analysis support provide to**
 - **US Army Program Manager Future Combat Systems Brigade Combat Team (PM FCS (BCT))**
 - **US Army Program Executive Office of Ground Combat Systems (PEO GCS)**
 - **Analyzes focused on quantify impacts to changes in reliability, maintenance, and supply requirement and CONOPS**
- **SoSAT (System of Systems Analysis Toolset)**
 - **System of Systems State Model tool**
 - **Stochastic simulation tool**
 - **Advanced data visualization tools**
 - **Optimization tools**

SoSAT provides modeling capabilities for sustainment and logistic analysis of a large system of systems

SoSAT Overview

- **SoSAT provides analysis capability:**

- SoSAT is a SoS tool that can simulate detailed organizational operation over a defined mission or set of missions
- Simulates any or all of a system of systems organizational structure
- Typical Problem Dimensions
 - Force structure consisting of over 1500 platforms organized at company level
 - Average of more than 200 elements per platform
 - Multiple day mission
 - Includes fuel, water, ammo utilization, storage and distribution
 - Includes spares and supplies optimization analyses

- **Features**

- Element reliability failures, consumable depletion
- Maintenance modeled with repair time distributions and any spares or services required for the repair
- Supply reorder for consumables and spare inventories
- Combat damage modeling
- Network modeling
- Prognostics and health management
- External conditions and external references

System of Systems Analysis Toolset (SoSAT) Enterprise

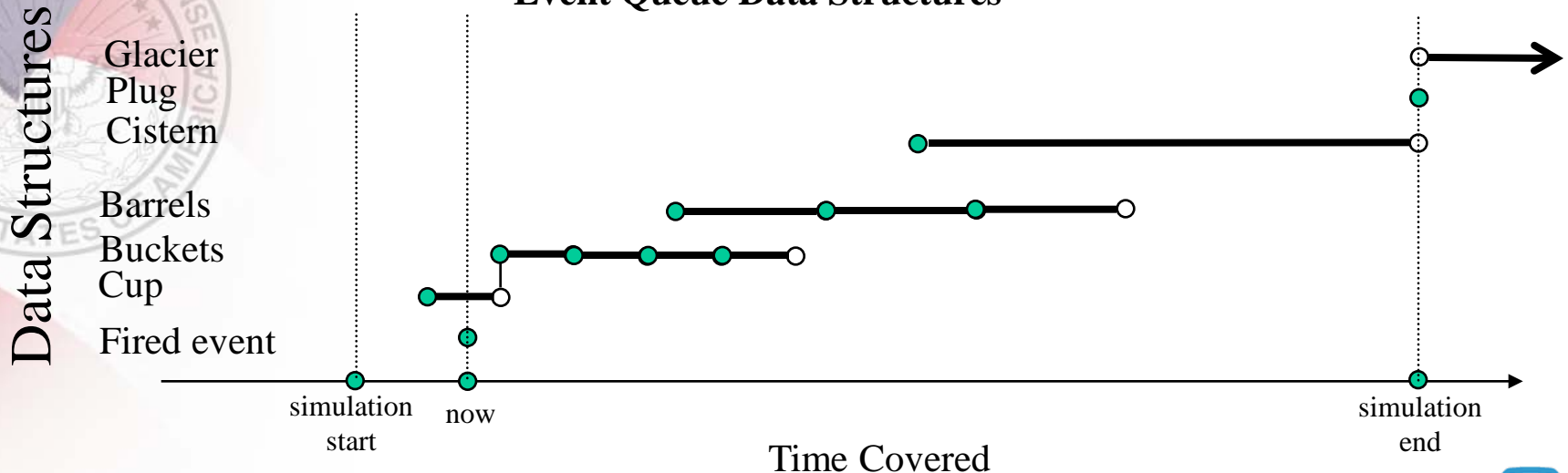
The evolution:

- Capability motivated by the US Army's need to assess long-term life-cycle operations and support (O&S) metrics and cost beyond the brigade level
- Enterprise expansion (SoSAT Enterprise)
 - Built on top of SoSAT simulation
 - Expanded analysis scope to multiple brigades (entire fleet) and support infrastructure
 - Supply and repair-chain logistics simulation tool
 - Inventory management
 - O&S cost constraints
 - Resources and personnel workflow
- Enhanced simulation performance
 - New architecture coupling SoSAT
 - Multi-layered discrete event queue
 - Performance tuning

Enhanced Simulation Performance: The Event Queue

- **Combination of a Calendar Queue and Lazy Queue**
 - Adaptive: Adjusting number of buckets and width
 - Multi-layers to help with multi-modal distribution of events
 - Hand-tuned for performance
- **Dumping**
 - Only a single sorted list of *near* events
 - *Far* events are “dumped” to different data structures as time advances
- **Rebinning**
 - Adjust the number of buckets and barrels
 - Design to help handle skewed distributions (surges of events)
 - Barrels cover most events
 - Buckets sized to limit the number of sorted elements

Event Queue Data Structures

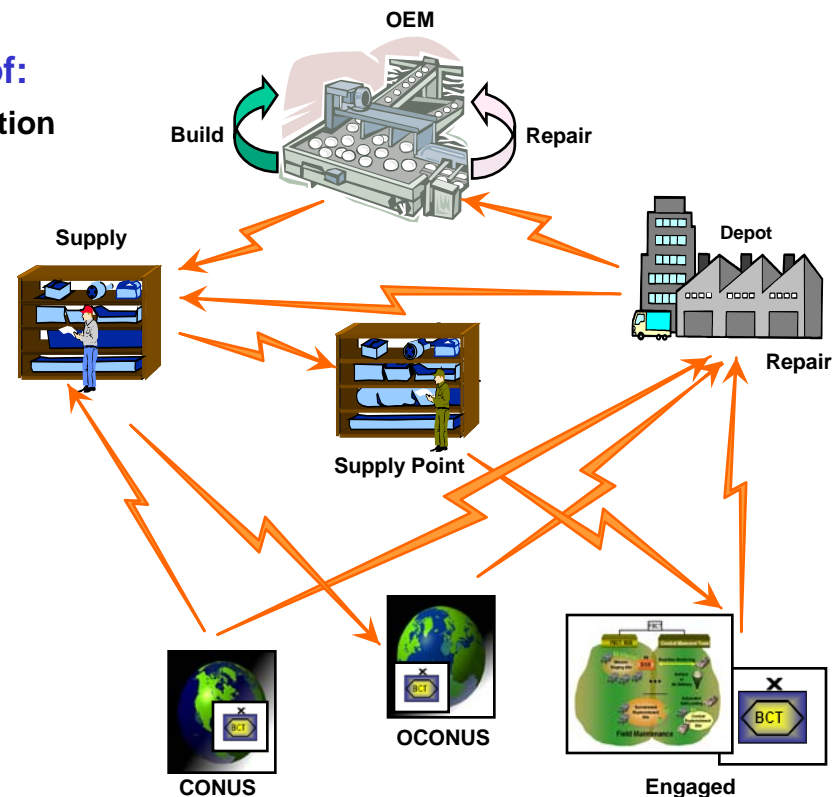


SoSAT Enterprise Expansion

- SoSAT Enterprise provides analysts the capability to:
 - Support business decisions at a global logistics scale
 - Determine cost drivers for life-cycle analysis
 - Perform trade studies with various performance metrics
 - Assess impacts of architecture changes on performance metrics

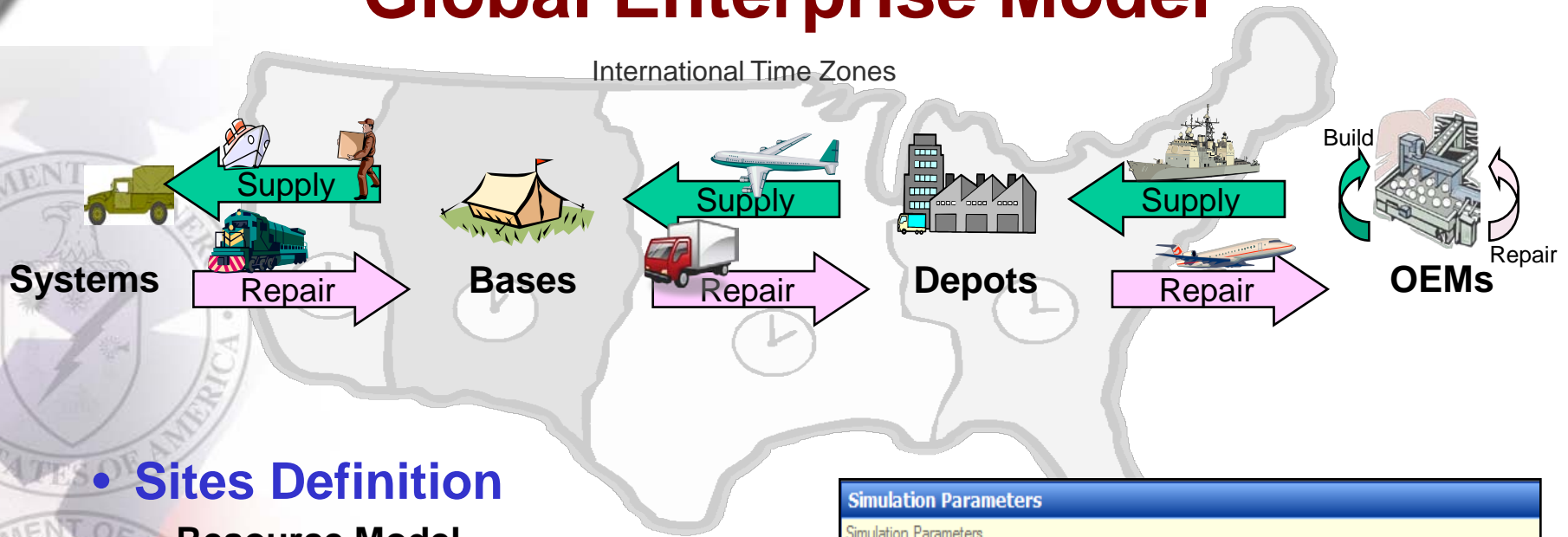
- Basic modeling features include the simulation of:
 - Global logistics infrastructure including transportation
 - Support structure
 - Supply and repair chain management
 - Resource usage at multiple echelons
 - OEM capabilities with build models
 - Detailed task modeling

- SoSAT Enterprise Problem Scale
 - Multiple Brigades
 - Thousands of systems
 - Hundreds of sites worldwide
 - Hundreds of types of support equipment
 - Multiple personnel skill types
 - Simulate multiple years of operation



Arbitrary multi-echelon support structure

Global Enterprise Model



- **Sites Definition**

- Resource Model
- Workflow Model
- OEM Build Capability

- **Repair Chain Management**

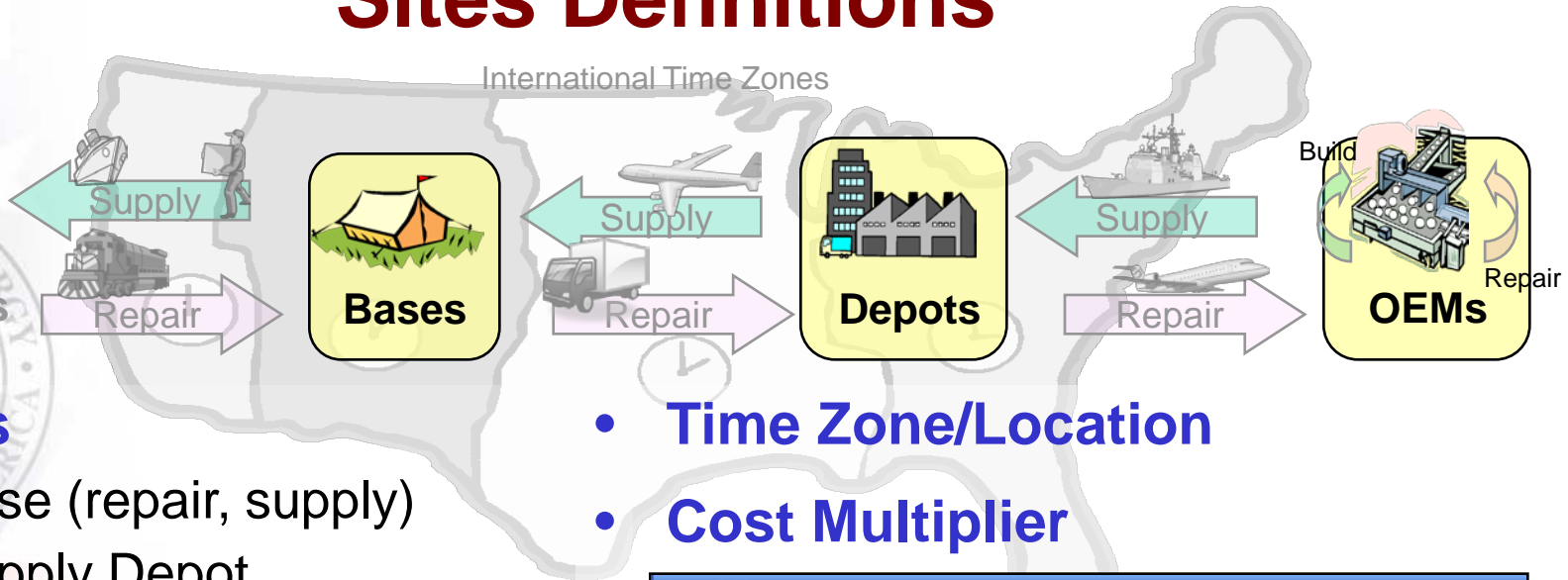
- **Supply Chain Management**

- **Transportation Model**

- **Enterprise Cost**

| Simulation Parameters | |
|---|----------|
| Simulation Parameters | |
| 1 2 * Settings | Value |
| SoSAT Settings | |
| Number of Simulation Trials | 1 |
| Random Seed | 11111 |
| Simulation Duration (hr) | 1000 |
| Simulation Time Step (hr) | 0.2 |
| Details Interval | 1 |
| Enterprise Settings | |
| Start Date | 1/1/2050 |
| Enterprise-Shipper Split | 1 |
| Summary Periods | Monthly |
| 1 2 * Options | |
| SoSAT Settings | |
| <input type="checkbox"/> Enable Network | |
| <input type="checkbox"/> Save Parts Inventory Details | |
| <input type="checkbox"/> Save Consumables Inventory Details | |
| Enterprise Settings | |
| <input checked="" type="checkbox"/> Enable Enterprise Model | |
| <input checked="" type="checkbox"/> Save Summary Output | |
| <input type="checkbox"/> Save Event Output | |

Sites Definitions

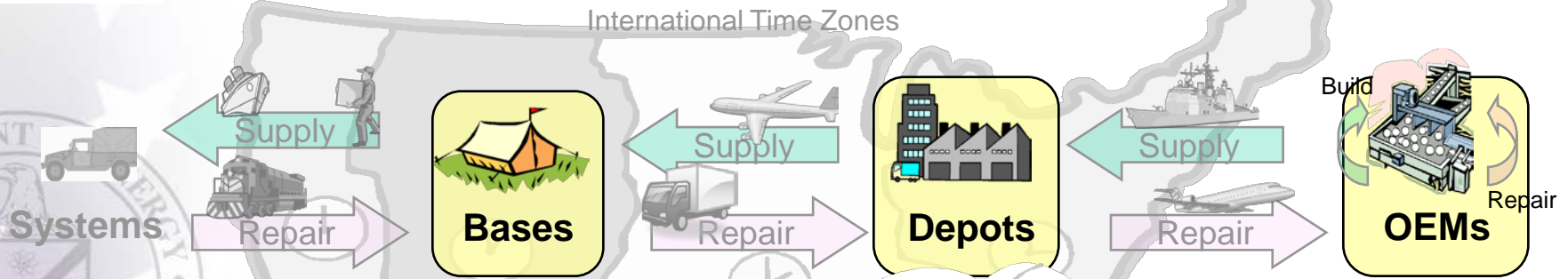


- **Types**
 - Base (repair, supply)
 - Supply Depot
 - Repair Depot
 - OEM (repair, supply, build)
- **Activation/Deactivation**
 - Initiation/Termination of sites
- **Shipping/Delivery Time**
- **Operational Hours**

- **Time Zone/Location**
- **Cost Multiplier**

| Site Definitions | | | | | | | | |
|----------------------------|-----------------------------|------------------|---------------------|-----------------------|-------------------------------------|----------------------------|--------------------------|-------------------------------------|
| Define sites. | | | | | | | | |
| Name | Type | Activation Time | Deactivation Time | Supply Chain | Repair Chain | Schedule | Pay Multiplier | |
| EU Base | Base | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | Supply base-to- | Repair base-to- | Daily-24/7 | 1 | |
| OEM Electronic | OEM | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | | | Daily-24/7 | 1 | |
| OEM Mechanical | OEM | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | | | Daily-24/7 | 1 | |
| Repair Depot Electronic | Repair | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | | Repair Electroni | Daily-24/7 | 1 | |
| Repair Depot Mechanical | Repair | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | | Repair Mechanic | Daily-24/7 | 1 | |
| Supply Depot Electronic | Supply | 1/1/2050 12:00:0 | 1/1/2100 12:00:0 | Supply Electroni | | Daily-24/7 | 1 | |
| Hourly Volume Storage Cost | Time Zone | Transport Zone | Daily Delivery Time | Daily Pickup/Delivery | Use Transport Window | Pickup/Delivery Start Time | Pickup/Delivery End Time | Commercial |
| 10 | GMT+01:00 (A) Europe | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input checked="" type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input checked="" type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input type="checkbox"/> |
| 10 | GMT+01:00 (A) Europe | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input checked="" type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input checked="" type="checkbox"/> |
| 10 | GMT+00:00 (Z) United States | | | | <input checked="" type="checkbox"/> | 6:00:00 AM | 7:59:59 PM | <input type="checkbox"/> |

Sites: Resource Model



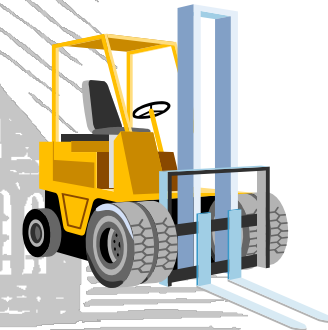
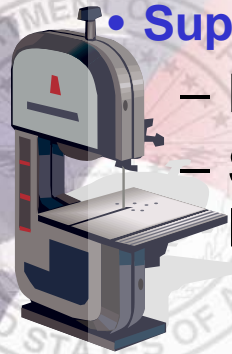
- Use of resources to perform work
 - Build, supply, repair, maintenance
 - Schedule/shift dependent

- Support Equipment (Hourly)
 - Lifecycle with replacement
 - Scheduled/Unscheduled* Maintenance

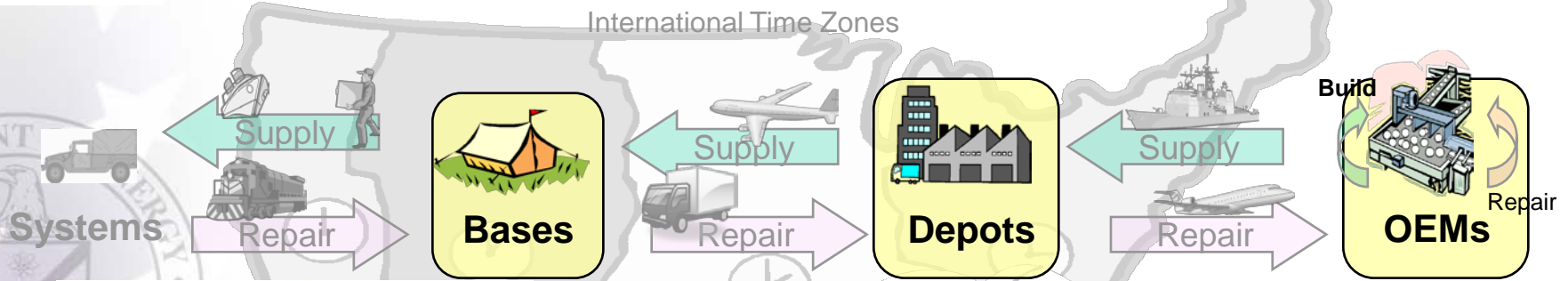
- Operational Age*, Times Used, Calendar Hour

- Personnel
 - Employee (Salaried)
 - Contractor (Hourly)

| Site Definitions | | Site Resources | |
|-------------------------|---------------|-----------------------------|--|
| Define sites. | | Define resources at a site. | |
| Name | Resource | Number | |
| EU Base | Cleanroom | 2 | |
| OEM Electronic | Diagnostic Eq | 2 | |
| OEM Mechanical | Engineer | 3 | |
| Repair Depot Electronic | Lift | 2 | |
| Repair Depot Mechanical | Mech Bay | 2 | |
| Supply Depot Electronic | QA | 3 | |
| Supply Depot Mechanical | Robot A | 3 | |
| US Base | Robot B | 3 | |



Sites: Workflow Model



- Workflows (sequences of tasks)
 - build (parts/consumables), supply, repair, maintenance

- Task Details

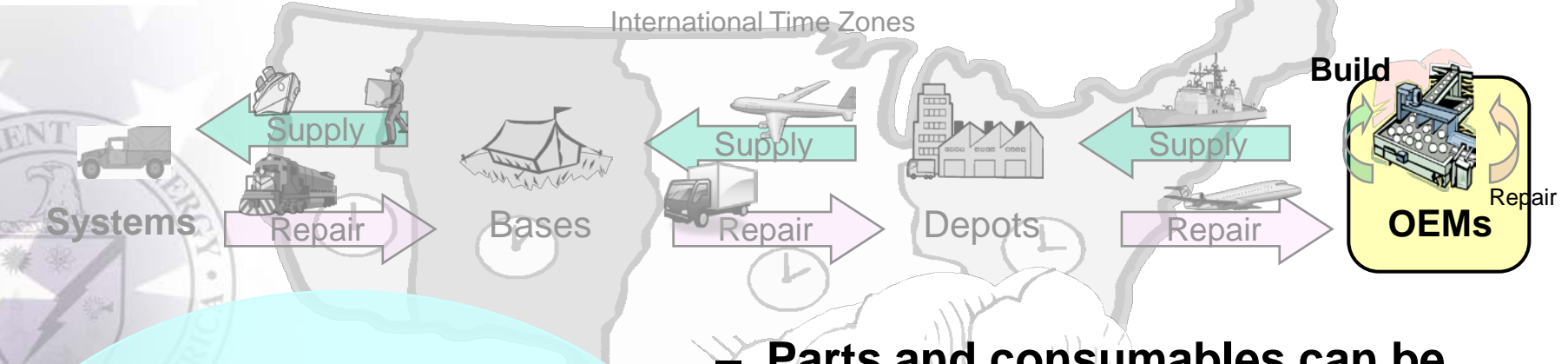
- Time distribution
- Resource(s) needs
- Penalty
- Cost



| Tasks | | | | | |
|--|------------------|--------------------|-----------------|---------------|--|
| Define tasks that are uses for supply/repair/build activities. | | | | | |
| Name | Task Time (Mean) | Task Time (St Dev) | Restart Penalty | Cost per Hour | |
| Build Elec Assembly | 16 | 1 | 1 | 100 | |
| Build Mech Assembly | 24 | 1 | 1 | 100 | |
| General Inspection | 1 | 0.1 | 0.5 | 50 | |
| General Setup | 1 | 0.01 | 0.05 | 50 | |
| General Testing | 2 | 0.5 | 0.5 | 100 | |
| Repair Elec Assembly | 8 | 1 | 1 | 100 | |

| Tasks | Task Resources | Workflow Tasks | | |
|--------------------------------|---------------------------------------|--|----------|------------------|
| Define tasks that are uses for | Define resources required for a task. | Define the tasks that are required for the | | |
| Name | Resource | Number | Sequence | Task |
| Build Elec Assembly | Cleanroom | 1 | 1 | General Inspecti |
| Build Mech Assembly | Diagnostic Eq | 1 | 2 | General Setup |
| General Inspection | Engineer | 1 | 3 | Repair Elec Ass |
| General Setup | Specialist B | 2 | 4 | General Testing |

Sites: OEM Build Model

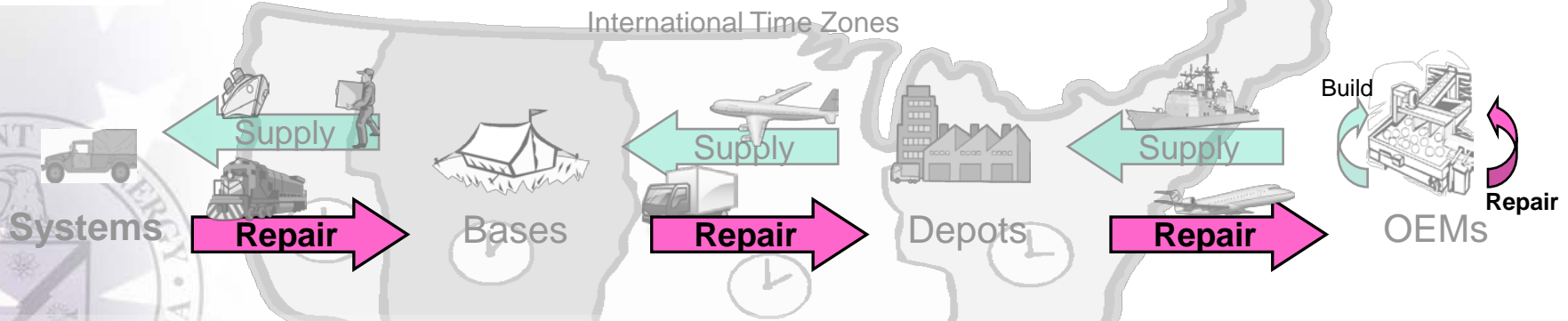


| Site Definitions | | OEM Builds | | |
|------------------|----------------|---|------------------|--|
| Define sites. | | Define workflows for an OEM to build a part | | |
| Name | Spare ▲ | Batch Size | Build Workflow | |
| OEM Electronic | Computer ▼ | 1 | Build Electronic | |
| OEM Mechanical | Radio componen | 1 | Build Electronic | |
| | Radio Wire | 1 | Build Electronic | |

| OEM Builds | | |
|---|----------------|----------------|
| Define workflows for an OEM to build a part | | |
| Consumable ▲ | Batch Quantity | Build Workflow |
| Water ▼ | 1 | Supply Water |

- Parts and consumables can be built/generated at OEM(s)
- Depleted inventory → generates build order for parts/consumables
- Batch quantity
- Detailed build workflows
- Excess parts/consumables are stored at OEM for future supply requisitions

Repair Chain Management



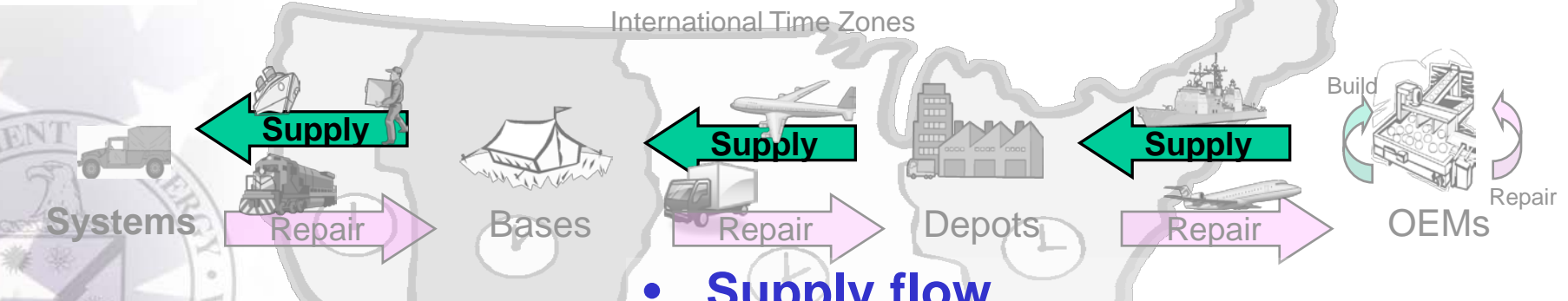
- **System Failure Requiring Spares**
 - **Flow of failed parts defined by the repair chain**
 - **Repair levels (probability)**
 - **Disposal (system level), Test Serviceable, Site Levels**
 - **Repair workflow(s)**
- **Repaired Parts**
 - **Re-enter system via supply chain (based on originating platform)**
- **Multi-echelon repair chains**

| Repair Levels | |
|-----------------------|----------------|
| Define repair levels. | |
| Description | Repair Level ▲ |
| Dispose Part | -1 |
| Base Repair | 1 |
| Depot Repair | 2 |
| OEM Repair | 3 |

| Parts Definition | Repair Classifications | |
|--------------------------------------|-------------------------------------|-------------|
| Define all the spare parts that will | Define repair levels for each part. | |
| Name | Repair Level ▲ | Probability |
| Alternator | Base Repair ▼ | 0.3 |
| Battery | Depot Repair | 0.3 |
| Computer | Dispose Part | 0.1 |
| Gear | OEM Repair | 0.3 |

Supply Chain Management

International Time Zones



| Site Definitions | | Supply Workflows | |
|-------------------------|-------------|---|--|
| Define sites. | | Define workflows for a site to supply a p | |
| Name | Type | Supply Workflow | |
| EU Base | Requisition | Supply | |
| OEM Electronic | | | |
| OEM Mechanical | | | |
| Supply Depot Electronic | | | |
| Supply Depot Mechanical | | | |
| US Base | | | |
| | | Requisition Processing | |
| | | Issue Spare Item | |
| | | Restock Item | |
| | | Order Replacement Item | |
| | | Return Item | |

- **Supply flow**

- Spare parts and consumables
- Demand generated from Systems

- **Inventory control**

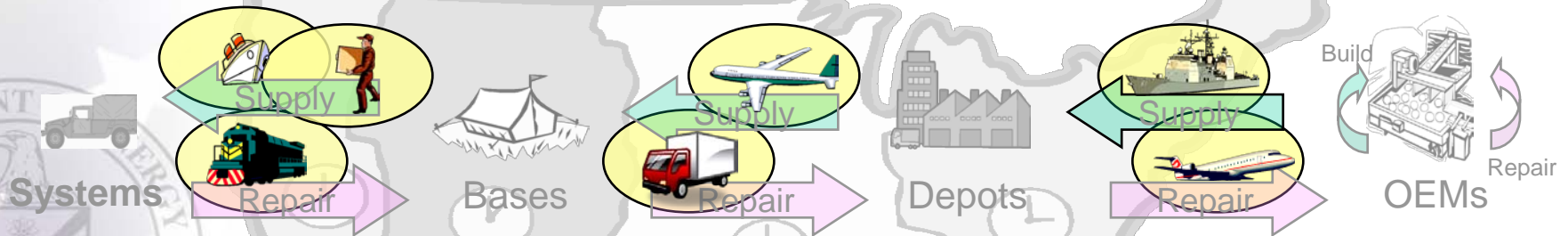
- Standard (s,S) re-order strategy
- Stock levels, overstock rule
- Supply type workflow
 - Requisition processing, Issue Spares, Restock, Order placement, Return Item

- **Flexible, multi-echelon supply chains**



Transportation Model

International Time Zones



| Transport Options | | | | |
|--|-------------------------------------|------------|---------------|------------------|
| Define the different transportation providers and the types of cargo they can transport. | | | | |
| Provider Name | Commercial Provider | Cargo Type | Source Zone | Destination Zone |
| UPS | <input checked="" type="checkbox"/> | Normal | Europe | Europe |
| UPS | <input checked="" type="checkbox"/> | Normal | Europe | United States |
| UPS | <input checked="" type="checkbox"/> | Normal | United States | Europe |
| UPS | <input checked="" type="checkbox"/> | Normal | United States | United States |
| FedEx | <input checked="" type="checkbox"/> | Normal | Europe | Europe |
| FedEx | <input checked="" type="checkbox"/> | Normal | Europe | United States |
| FedEx | <input checked="" type="checkbox"/> | Normal | United States | Europe |
| FedEx | <input checked="" type="checkbox"/> | Normal | United States | United States |
| Military Courier | <input type="checkbox"/> | Normal | Europe | Europe |
| Military Courier | <input type="checkbox"/> | Normal | Europe | United States |

- **Transportation of parts & consumables**
- **Transport activities for items occur:**
 - **From system to site**
 - **Between sites**
 - **From site to system**
- **Transportation parameters**
 - **Delivery windows**
 - **Cargo type/volume/priorities**
 - **Shipping time (distribution)**
 - **Time zone/location zone**
- **Transportation Rules**
 1. **Cheapest cost within defined standard**
 2. **Shortest transport time**

| Weight Lower Bound | Weight Upper Bound | Shipping Time Distribution | Shipping Time Minimum | Shipping Time Best Estimate | Shipping Time Maximum | Shipping Cost |
|--------------------|--------------------|----------------------------|-----------------------|-----------------------------|-----------------------|---------------|
| 0 | 1000 | Triangular | 12 | 24 | 48 | 200 |
| 0 | 1000 | Triangular | 24 | 48 | 60 | 300 |
| 0 | 1000 | Triangular | 24 | 48 | 60 | 300 |
| 0 | 1000 | Triangular | 12 | 24 | 48 | 200 |
| 0 | 1000 | Triangular | 8 | 24 | 36 | 250 |
| 0 | 1000 | Triangular | 24 | 36 | 48 | 500 |
| 0 | 1000 | Triangular | 24 | 36 | 48 | 500 |
| 0 | 1000 | Triangular | 8 | 24 | 36 | 250 |
| 0 | 1000 | Triangular | 12 | 24 | 48 | 200 |
| 0 | 1000 | Triangular | 24 | 48 | 60 | 300 |
| 0 | 1000 | Triangular | 24 | 48 | 60 | 300 |
| 0 | 1000 | Triangular | 24 | 48 | 60 | 300 |
| 0 | 1000 | Triangular | 12 | 24 | 48 | 200 |

Dynamic Simulation Changes

- **Model attributes can be changed over time**
 - **Inventory Rules**
 - **Modification of re-order strategy**
 - **Capability to model surges in demand, changes in operating strategy, etc.**
 - **Activation/Deactivation of Sites**
 - **Sites can be interrupted/disabling transportation**
 - **Capability to model attacks, transpiration cut-offs, worker strikes, closing of a plant, etc.**
 - **Resource Changes**
 - **Modification to the type and number of support equipments and personnel at a site.**
 - **Capability to model worker strikes, deployment of resources, site specific scenarios, resource constraints, etc.**
 - **Inventory Changes**
 - **Inventory levels of specific parts can be add or removed between sites**
 - **Capability to model shortages, surges, deployment, etc.**

Enterprise Cost

- **Support Equipment Cost**

- Initial SE Invest
- SE Usage Cost
- SE Maintenance
- Replace SE Invest

- **Parts Related Cost**

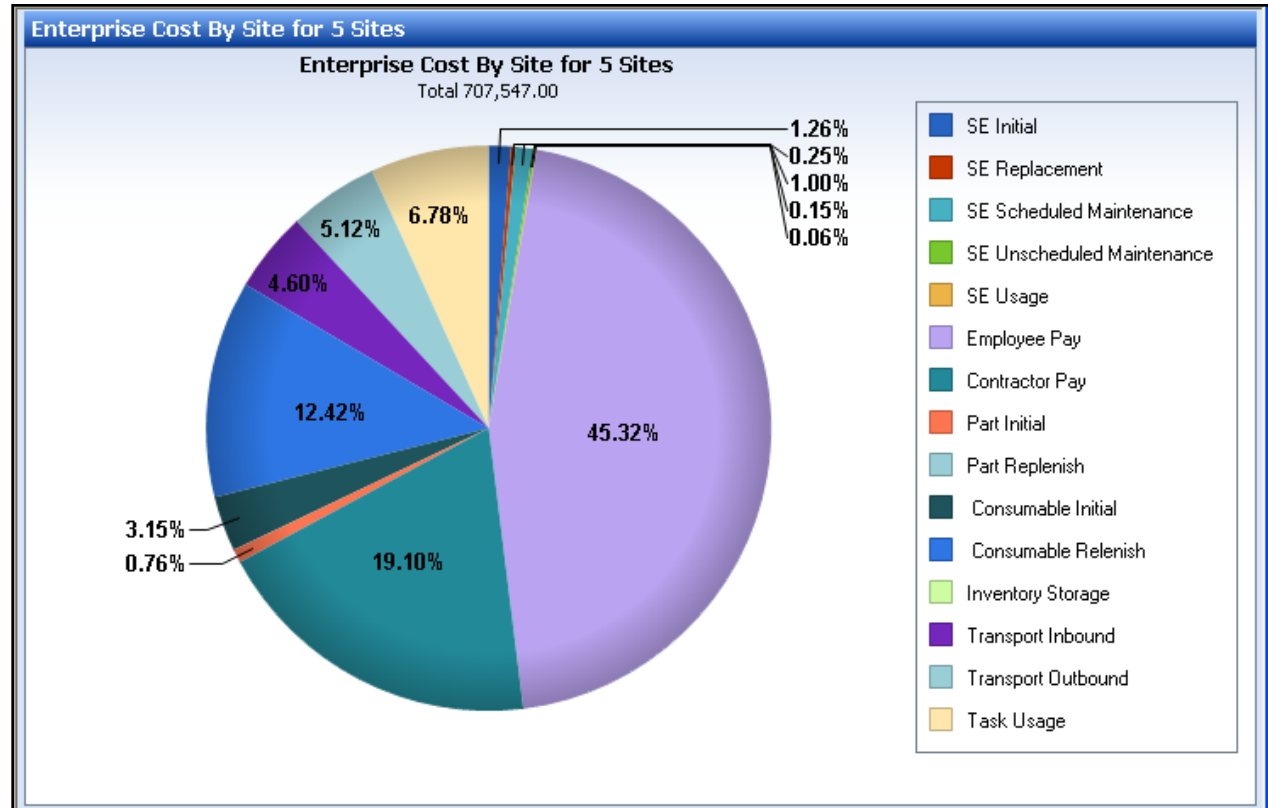
- Initial Part Invest
- Initial Consumable Invest
- Replenish Part & Consumable

- **Labor Cost**

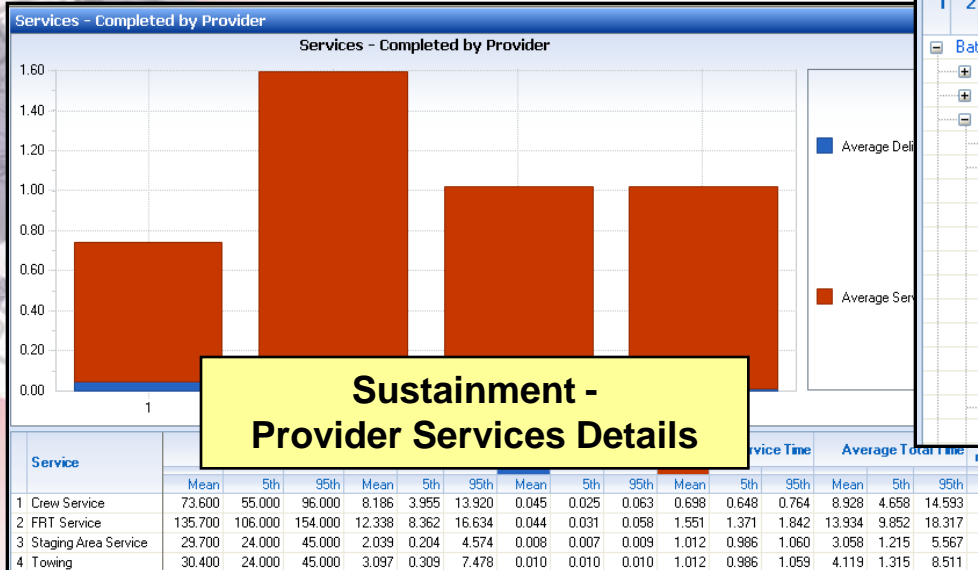
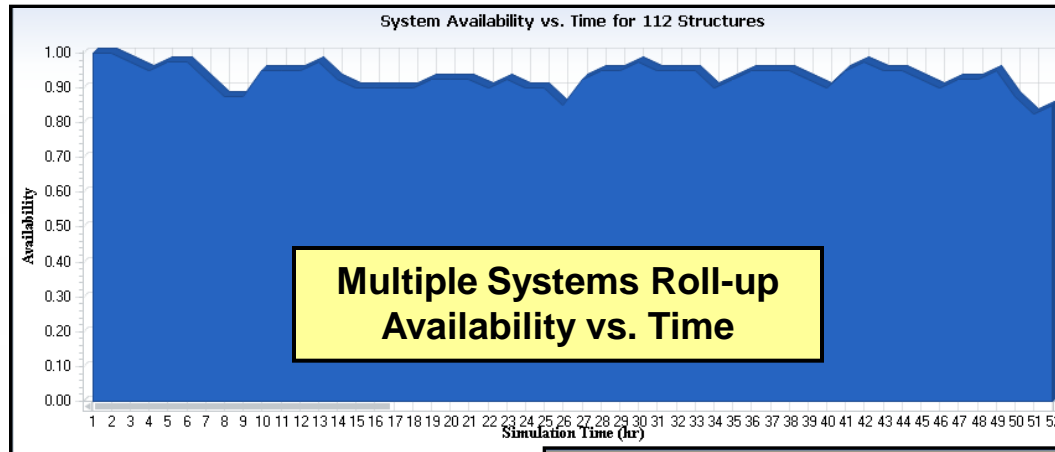
- Task Cost
- Employee Pay
- Contractor Pay

- **Transportation & Storage Cost**

- Inventory Storage
- In-Bound Transport
- Out-Bound Transport



Results



Functional Availability Rollup by Structure

| System | Mobility | | | Lethality | | | C2 | | | Operability | | |
|---------------------|----------|-------|-------|-----------|-------|-------|-------|-------|-------|-------------|-------|-------|
| | Mean | 5th | 95th | Mean | 5th | 95th | Mean | 5th | 95th | Mean | 5th | 95th |
| Battalion | 0.783 | 0.752 | 0.836 | 0.586 | 0.546 | 0.637 | 0.964 | 0.932 | 0.973 | 0.813 | 0.781 | 0.863 |
| C2 | 0.874 | 0.743 | 1.000 | 0.874 | 0.743 | 1.000 | 1.000 | 1.000 | 1.000 | 0.874 | 0.743 | 1.000 |
| Depot | | | | | | | | | | 1.000 | 1.000 | 1.000 |
| Company A | 0.763 | 0.692 | 0.814 | 0.576 | 0.526 | 0.639 | 0.965 | 0.914 | 0.978 | 0.808 | 0.758 | 0.873 |
| C2 | 0.866 | 0.773 | 0.944 | 0.866 | 0.773 | 0.944 | 1.000 | 1.000 | 1.000 | 0.866 | 0.773 | 0.944 |
| Supply Vehicles | 0.838 | 0.504 | 0.935 | 0.773 | 0.504 | 0.902 | 0.917 | 0.566 | 0.997 | 0.922 | 0.779 | 0.958 |
| Fuel Truck-001 | 0.707 | 0.303 | 0.917 | 0.689 | 0.303 | 0.861 | 0.835 | 0.310 | 1.000 | 0.694 | 0.303 | 0.861 |
| Fuel Truck-002 | 0.856 | 0.564 | 0.948 | 0.787 | 0.473 | 0.923 | 0.951 | 0.733 | 1.000 | 0.839 | 0.564 | 0.937 |
| Parts Truck-001 | 0.863 | 0.208 | 0.967 | 0.739 | 0.208 | 0.967 | 0.918 | 0.240 | 1.000 | 0.863 | 0.208 | 0.967 |
| Parts Truck-002 | 0.927 | 0.714 | 0.985 | 0.877 | 0.678 | 0.878 | 0.884 | 0.888 | 1.000 | 0.881 | 0.741 | 0.970 |
| Service Vehicle-001 | | | | | | | | | | | | 1.000 |
| Service Vehicle-002 | | | | | | | | | | | | 1.000 |
| Service Vehicle-003 | | | | | | | | | | 1.000 | 1.000 | 1.000 |
| Service Vehicle-004 | | | | | | | | | | 1.000 | 1.000 | 1.000 |
| Service Vehicle-005 | | | | | | | | | | 1.000 | 1.000 | 1.000 |
| Platoon 1 | 0.714 | 0.658 | 0.781 | 0.569 | 0.513 | 0.644 | 0.968 | 0.960 | 0.985 | 0.742 | 0.677 | 0.827 |
| C2 | 0.723 | 0.420 | 0.850 | 0.723 | 0.420 | 0.850 | 0.996 | 0.963 | 1.000 | 0.720 | 0.420 | 0.850 |

Individual Systems Details

Summary

- **High fidelity simulation**
 - Repair and supply chain simulation
 - Resource contentions
 - Multi-echelon distribution structure
 - Dynamic simulation changes
 - Detail workflow modeling
- **Efficiency**
 - Custom novel architecture
 - Hybrid of an adaptive calendar queue and lazy queue
- **Future Development**
 - Modeling overhaul/recap/reset of systems
 - Higher fidelity for repair and supply chain (SRU level)
 - Integrated optimization capabilities

Acknowledgments

- **Management Team:**
 - Bruce M. Thompson, Alan S. Nanco, Dennis J. Anderson
- **Development and Testing Team:**
 - Darryl J. Melander, Hai D. Le, Scott A. Mitchell, PhD
 - Jean-Paul Watson, PhD, David Strip, PhD
 - Jesse P. Hatcher, Jason Groves (Intera)
- **Analysis Team**
 - Steven M. Handy, Kimberly M. Welch, Matthew J. Hoffman
- **US Army PM FCS(BCT)**