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SIMULATION OF TRANSPORTATION MOVEMENTS OVER CONSTRAINED INFRASTRUCTURE NETWORKS

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ABSTRACT

The Enhanced Logistics Intra-Theater Support Tool (ELIST) is a simulation-based decision support system that evaluates a military deployment plan at the theater level for transportation and logistical feasibility. ELIST includes a discrete-event, time-stepped simulation kernel written in C, an object-oriented database written in Prolog, and a set of knowledge-bases that describe various operations, such as throughput capacity of ports, based on the attributes of the relevant objects. In the course of its development, ELIST has been used to support various planning activities.

1 INTRODUCTION

For decades, military deployment modeling has consistently focused on planning the sea and air legs of the strategic movement of U.S. forces from the continental United States (CONUS) to theater reception points, primarily sea and air ports in the European theater (Schank *et al.* 1991). With the recent pullback of U.S. forces to CONUS, greater emphasis is now placed on planning the reception and movement of forces within the theaters of interest, the number of which has expanded to include almost every region of the world. Few comprehensive theater simulation models exist. SUMMITS (ODPA&E 1993), a legacy model, is one of the few that has gained notoriety.

1.1 Questions Answered by the Model

The Enhanced Logistics Intra-Theater Support Tool (ELIST) is a simulation-based decision support system that evaluates a deployment plan at the theater level for transportation and logistical feasibility. ELIST is designed to answer four types of questions:

- When will the force arrive at the final in-theater destinations (force closure)?
- What and where are bottlenecks to forward movement (are assets or the infrastructure constraining factors)?
- Why are specific units not closed by the required time (where are units currently located)?
- What are the implications if movement capabilities are limited (for example, port closure, road unavailability)?

1.2 ELIST Overview

Figure 1 shows the main components of ELIST: an infrastructure database (input), a specification of a movement scenario that includes a movement requirement and an allocation of theater assets to support the movement (input), a scenario event list, which specifies"what-if" scenarios (input), data for displaying a coordinate-registered map for the area of interest (input), and a set of reports in various formats (output). The capability of the theater infrastructure to support movement is based on a detailed representation of the node and link structure of the transportation network. ELIST simulates the movement of items over and through the components of this infrastructure network, constrained by the nodes and links of the network and the available transportation assets. The main outputs of the system are the arrival times of items at final destinations. This information is aggregated and summarized in various textual and graphical reports.

The simulation can be operated in an interactive mode, in which the user make decisions or verifies results at each step, or in an automatic mode, in which all of the information required for the simulation, such as network and scenario file names, is passed as command line arguments at system initiation. The automatic mode is important for the simulation to be initiated and controlled by another model or system in a distributed environment.

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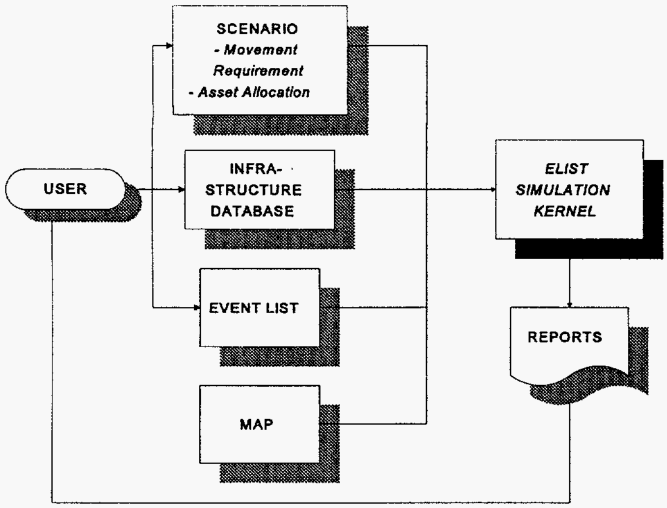

Figure 1 ELIST Overview

2 SIMULATION PROBLEM

The movement problem modeled by ELIST begins with a movement *plan* that specifies items arriving at origins and entering the theater transportation system, attributes of the items such as type of commodity, and the item arrival times. An *arrival profile* is this set of information on item arrivals along with the final theater destinations for the items and the required arrival times. An *asset allocation* specifies the assets that are available over time to affect movement of the items from origins to destinations. Taken together, an arrival profile and an asset allocation constitute a *scenario*. A *network* includes the links, nodes, and features of the infrastructure, and their associated attributes, through which all of the movements occur. A *route* is the set of links and nodes that an item traverses through the network beginning with an origin node and ending with a destination node. Movements along a route may consist of multiple transportation *modes* (highway, rail, air, water, etc.) and intermodal transfer points.

The simulation applies the available assets to model the movement of the items through the infrastructure network, over time, from the origins to the destinations, treating arrival times at origins as fixed. The key information obtained from the simulation is the time at which the items arrive at the final destinations. A measure of *lateness* is based on comparing the simulated arrival times with the required arrival times at the destinations. Movements are late because the infrastructure or the asset capabilities constrain throughput, or because time-distance relationships make realization of the required delivery dates impossible.

In summary, ELIST simulates a given movement plan to determine whether the plan is feasible relative to required delivery dates at destinations. Other movement problems which treat one or more of the fixed input parameters in ELIST as variables, such as origins, arrival times, destinations, or required delivery times, are not currently addressed by ELIST.

3 SIMULATION APPROACH

Following the work of Dahl and Nygaard (1966), recent simulation advances have emphasized using an object-oriented (O-O) approach (Rothenberg 1989). The O-O approach is more conducive to tailoring simulation components to individual applications and embedding simulations into larger systems. The initial ELIST simulation borrowed many object-oriented constructs and was written entirely in Prolog (Bratko 1990, Quintus 1991) because of the rapid prototyping capabilities of the language. Eventually, performance concerns over scaling-up the simulation to realistic-sized problems dictated a reimplementation of the simulation kernel in C. A typical movement problem consists of 30,000 or more items moving over an infrastructure network of 500 links and 500 nodes over 200 time periods. To conform to the rapid turn around requirements placed upon the system, a simulation must be completed in less than 30 minutes.

3.1 Movement Processes

The movement general process simulated by ELIST is depicted in Figure 2. Activities include unloading ships and planes at sea ports and air ports and transport along each link and through each node of a route through the infrastructure network. Queues are modeled explicitly where items wait at the end of each completed activity. Items are queued because the next activity is being utilized at maximum capability (example: road segment along a route is utilized at maximum capacity) or because resources are not available to affect forward movement (example: trucks not available to carry items over highway).

Items either arrive from outside the theater to ports or originate within the theater at pre-positioning sites. An item may have one or more intermediate theater destinations where the item waits for a specified amount of time (sojourn time) before moving onward to its final destination. When an item is stored in a queue, its attributes are used to match available resources and to determine priorities for selecting items from the queue for forward movement. Queues are assumed to have non-restricting capacities – queues exceeding their nominal capacity are reported to the user during the simulation as warnings, for determination of whether the situation represents a problem by the user.

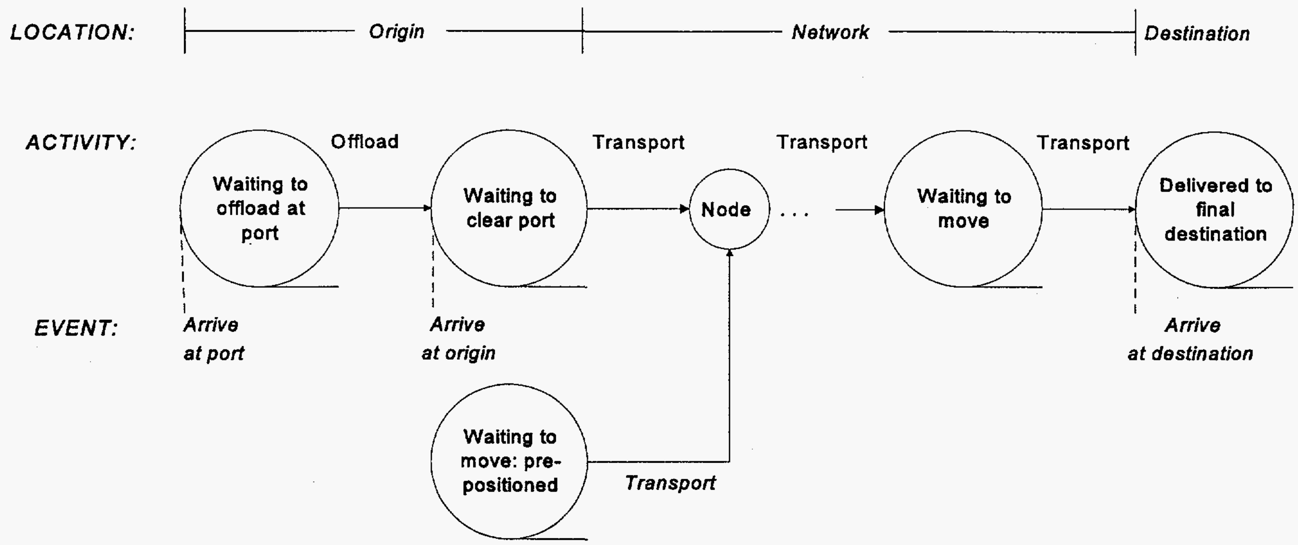

Figure 2 Movement Activity Representation

Ports are modeled at the level of detail necessary only to determine credible throughput capability estimates. This is less than the level of detail required for complex systems of interacting queues and servers, as are typically modeled with general purpose simulation development systems, for example, Pritsker and Pegden, 1979. Blocking, balking, and other complex queuing behaviors are not modeled in ELIST, given the simplicity of the queue-server representation.

The route for each origin-destination pair is determined before a movement is simulated, in a separate procedure. Mode selection including the determination of intermodal transfers, is part of the route selection heuristic. Once the resources are available to move an item from its origin to its destination, the departure from the origin and the arrival at the destination are scheduled as future events. This discrete approach to route selection and event scheduling minimizes data record-keeping and overhead processing; an artifact of this approach is that the precise location of an item traversing a route at simulation time t is not represented explicitly in the simulation. The location of an item is known only if it is at its origin or destination. As an alternative to recasting the simulation kernel to include elements of continuous simulation, inference routines have been developed which imply the location of an item en route, and are executed when this information is called for.

3.2 Components of the Simulation

ELIST can be described as a dynamic, deterministic, discrete-event, time-stepped, queuing simulation. The simulation structure contains the rudimentary elements of a discrete simulation, and has several sophisticated and useful capabilities as described in Section 3.3. The simulation kernel consists of several key components described below.

Activities. Activities process items (example: unloading a ship's cargo at a port) and are characterized by a duration time. Activity times depend on the attributes of the movement item and the attributes of the activity. For example, for the activity of a truck moving along a route, the travel time is a function of the average speed of the truck and of the distance along the route. Distance is computed by the system, based on the latitude and longitudinal coordinates of each of the links that comprise the route from origin to destination, is specified by the user, or is imported from an external database.

Resources. The resources modeled in ELIST consist of transportation assets (for example, medium truck companies, C-130 aircraft, helicopters). Static theater assets, such as terminal service companies, are not currently modeled. Resources are matched to items to begin movement activities. The concept of global resources (resources used for general types of activities) versus local resources (resources divided into pools that can only be applied to specific activities) is implemented. For example, a heavy equipment transport vehicle (HET) is a resource required to move tanks over highways. If HETs are able to move any tanks, the resource is global; if HETs which are owned by a unit can only be used to move tanks owned by the unit, the resource is local. Resources are dynamic, with availability and utilization are modeled over time. Resource levels are either exogenous input by the user or determined automatically from the arrival profile. For example, truck company assets for U.S. forces are automatically identified based on the unit type code (UTC) attribute of arriving items.

If an item requires a resource during the simulation, the resource availability is checked, and, if available, the resource is assigned to the item for the duration of the activity. For example, after a tank is unloaded from a ship, the tank goes into the queue of items waiting to clear the port. If a HET is available, it is assigned to the tank and the travel time from the current location (origin) to the tank's destination along its specified route is estimated. The arrival of the HET and tank at the destination then becomes a scheduled event. After the simulation time is updated to the destination arrival time, the tank enters the destination queue, and the HET is reassigned to the pool of available assets.

Queues. Queues store items that need to wait before they can begin their next activity. For example, ammunition waits at a port for an ammunition transporter to move over a highway.

Event File. The event file records and sorts scheduled events. The main event type in ELIST is arrival at a node having a queue (example: arrival of an item at final destination after traversing a route).

Simulation Clock and Event Scheduling. The simulation clock updates the simulation time and initiates the processing of events. The simulation is deterministic with fixed times for each specific activity. The incorporation of stochastic activity times is not precluded by the structure of the simulation, but the deterministic assumption is made due to lack of data upon which to base stochastic representations.

State and State History. The state consists of at least the minimal set of information required at any simulation time t to begin the simulation forward from t. This consists of the contents of the queues and events scheduled to occur in the future. The state is used as a basis for reporting on the status of items at the current simulation time and on the history of items moved and the resources used during the simulation. For example, the locations of a unit from the beginning of the simulation until the current time can be determined from the state information.

Practical limitations such as disk space limitations and file I/O requirements dictate that only a small subset of information generated by the simulation can be saved as part of the state history. The history is used as a basis for generating reports on simulation results and for explanations of arrival observations, such as lateness. An expanded state history would be desirable as a basis for a comprehensive explanation facility that would not only infer and explain why an item was late, but would also recommend how a plan could be improved.

Heuristic Procedures. Heuristic procedures, often called rules-of-thumb, are procedures that knowledgeable experts use to perform specific functions. Heuristics determine various types of information needed to support the simulation but which are not directly involved in the calculation of activity duration times. Examples are route selection, mode selection, sea and air port capacity calculation, ship and berth matching, road trafficability and average speed determination, and bottleneck identification.

3.3 Simulation Features

The simulation structure described above allows the simulation to have several important capabilities.

Stop/Start Capability. The stop/start capability allows a user to run the simulation to a specified time, report on the status of the system, and make a limited number of changes to the system state at that time. The simulation can then be restarted and run to see the effects of these changes over subsequent time periods. The system also processes a scenario event list during the simulation in the form of a script, which is specified before system initiation. The event list specifies a set of changes to make at specific times during the simulation, such as port closures of limited duration and link unavailability. The event script modifies the state of the system as the simulation proceeds without requiring user interaction and without affecting permanent changes to the underlying database.

Arbitrary Time Increments. With some adjustment in the definitions of unit measures for data attributes and in the logic of the scheduling algorithms, a user-specified time step of arbitrary duration has been implemented as a simulation parameter. Parameters specified by the user in tons/day are converted to their equivalent values in tons per time step. This feature is important for reporting on the status of items in-transit, in half-day or hourly increments, as has been a requirement. However, the representation of the time- varying nature of all of the input parameters to the simulation, such as separate vehicle speeds for day and night operation, has not been implemented due to the increased burden this would place on data specification.

Encapsulated Simulation Process. The stop/start capability described above and the open architecture of the implementation allow ELIST to communicate with and to be controlled by other models. ELIST is being integrated into mobility modeling systems, including the Analysis of Mobility Platform (AMP, U.S. Transportation Command, 1994), as the theater movements module. ELIST is also being linked directly with other strategic and theater models such as the Knowledge-Based Logistics Planning Shell

(KBLPS, Carnegie Group, Inc. 1993), and tied directly to standard databases. Investigations are underway into using ELIST as a node in a distributed simulation environment.

4 INFRASTRUCTURE NETWORK AND DATA

The feasibility of a deployment plan is based in part on the infrastructure capabilities. The infrastructure is represented as a network of nodes, links, and features. Nodes represent sea ports, air ports, terminals, intersections, destinations and other point features that could constrain movement. Links represent segments of road, rail, air, and inland waterway. Features include bridges, tunnels, and vulnerable points that could adversely affect movement. Figure 3 shows an example of an infrastructure network as represented in and displayed by ELIST.

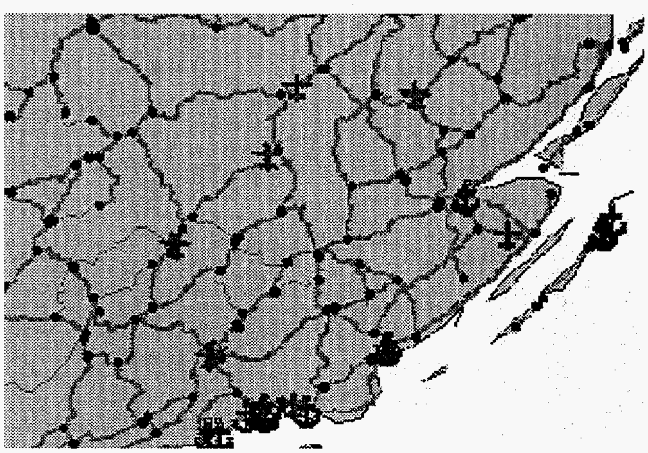

Figure 3 Graphic Display of Complex Infrastructure Network

The infrastructure data is stored in a Prolog database. Prolog is a high-level, fourth generation, language. The reasons for using Prolog have to do with the naturalness of the representation and the ease with which inferencing procedures can be embedded into the database. These factors led to rapid development of the initial ELIST prototypes.

The data representation for the infrastructure is object-oriented. General object-oriented data schemes have been developed for Prolog (Moss 1994, Schachte and Saab 1994), but the O-O features most useful to support the movement simulation are a subset of these general capabilities. These include the definition of classes and instances, inheritance of attribute values from classes to instances, and methods for computing object attributes from other attributes of the object (example: capacity of a seaport based on the berth attributes). These capabilities have been implemented in Prolog predicates which supplement ground unit clauses of the Prolog database. The Prolog database representation has proven to be very successful in its flexibility, in terms of the ease of developing data manipulation tools (for example, a truth maintenance facility), performance, and reliability. The possibility of reimplementing the database as a relational database to conform to other modeling systems has been studied, but no benefits to converting from an O-O to a relational database design have been identified.

The fact that the database is in Prolog and the simulation kernel is in C leads to a potential performance concern – data must be passed between languages through the language interface scheme, which is implementation dependent. To obviate the need to access the Prolog database for every data item that is required as the simulation progresses, and to improve the performance of the simulation, large slices of data are periodically passed from the database to temporary structures in the C routines of the simulation. For example, in scheduling a movement along a route, all of the capacity and other relevant attribute data on the links and nodes along a route are passed from Prolog to C at one time.

5 REPORTS

The simulation produces reports and presentation graphics at various levels of aggregation and are available to the user at any time during the simulation. Figure 4 is a summary graphic that indicates the overall success of a plan in terms of how well requirements are met by the capabilities of the movement system. The graphs shows cumulative requirements for closure at all destinations over time plotted against cumulative arrivals over the same period. The difference between the requirements and the arrivals at any time t is the overall shortage at the destinations and is an indicator of lateness of the movement items. Other graphs and reports can be used to identify specific items that are late and possible reasons for lateness.

6 FUTURE DIRECTIONS

ELIST has been used to support several exercises, to determine theater-destination closure profiles for operational plans, and to determine the effects of movement asset constraints and multinational asset sharing policies on force closure. These experiences have been critical for defining the requirements of a theater movement planning system, an area which has not previously received much attention. Possible areas for model enhancement and will be dictated by user requirements. These include: optimal route scheduling with foresight, optimal allocation of assets and better modeling of the theater distribution of assets, modeling commodity-specific reception and movement (example: petroleum reception and movement through pipelines, an explanation facility to automatically identify the most important simulation results and the factors responsible for late item arrivals, and automatic determination of improved plans, using response-surface or similar methods applied to the simulation results.

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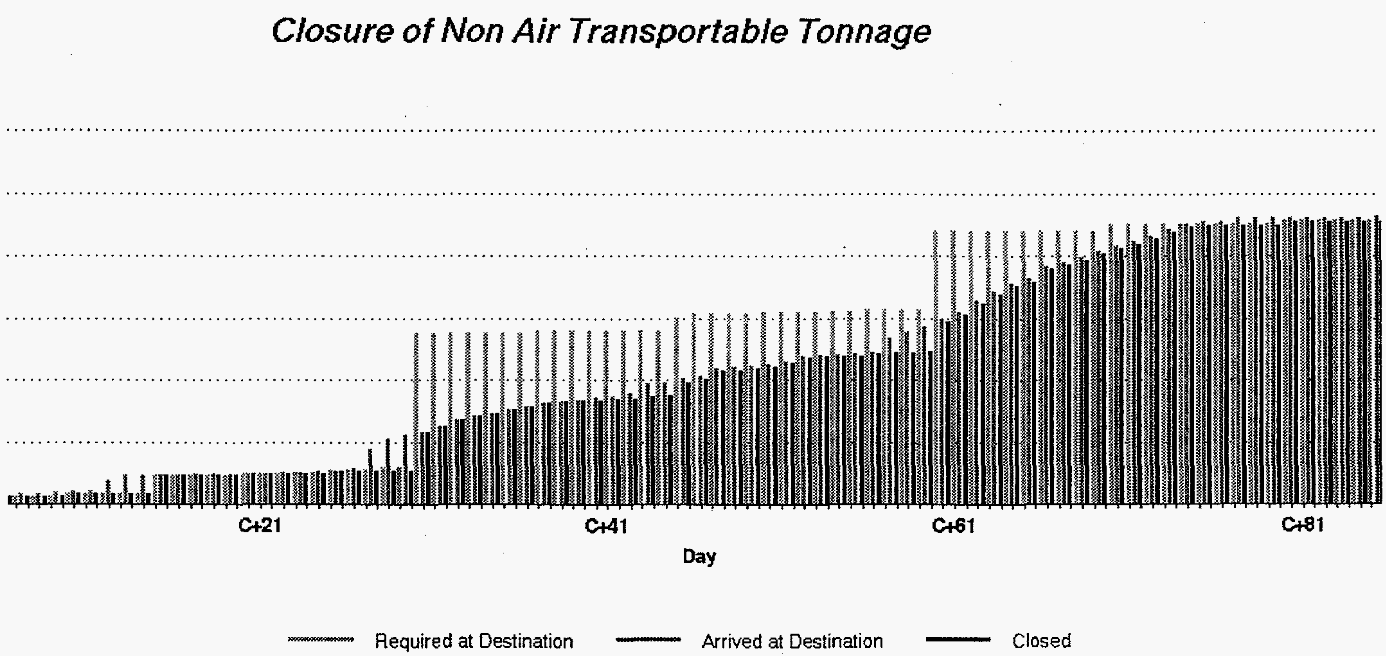

Figure 4 Cumulative Summary Closure Profile for All Destinations