A GENERALIZED MODEL FOR SIMULATING COMMODITY MOVEMENTS BY SHIP

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Abstract

The paper describes the logic structure and techniques used in a Simscript program for simulating the movement of ships through a network of locks, reaches, lakes, and ports. The program also provides for endogenous route selection between "micro-route" alternatives, i.e., parallel locks or canals, and for the endogenous scheduling of ship movements, given port-to-port commodity movement demand and fleet mix. The model is basically a general network simulation tool based on the concept of a "route map" which describes the sequence of facilities to be traversed between given points in the network. The cardinal mechanism in the model is a Movement Control Module

which monitors the route map of each ship during its voyage and sends the vessel to generalized satellite modules where the performance of locks, reaches, lakes, and ports are simulated. Attributes carried by the ship initialize the generalized modules to simulate a specific lock, reach, lake, or port as dictated by the ship's position along its route map. The model is being used to simulate the performance of the Great Lakes System for the Corps of Engineers.

Background

The model described in this paper was developed to assist the U.S. Army Corps of Engineers in thier assessment of the need for improvements to the Great Lakes and inland waterway systems. This is a third-generation model deriving from research sponsored by the Corps over a number of years. Initial research resulted in the models WATSIM [3] and TOWGEN [1] for simulating inland barge systems. The Corps subsequently sponsored the development of a model for simulating components of the Great Lakes System; this resulted in the Multiple Channel Deep Draft (MCDD) model [2,4,5]. During the development of the MCDD model, a number of powerful techniques were formulated which promised to form the basis of a generalized model to meet all of the Corps' needs in the area of systems simulation. A third and current research project was sponsored by the Corps to develop and apply such a model. The Network Simulation (NETSIM) model described here is the result of this research. As suggested by the acronym, NETSIM is basically a general network simulation tool; modules for simulating the operation of water navigation facilities are linked to NETSIM to provide the unique capabilities required by the Corps. To describe this specific formulation of NETSIM for the simulation of waterborne transportation systems, the acronym NETSIM/SHIP is used.

The Problem

The overall problem to which the model is addressed is that of simulating commodity movements between multiple origins and destinations by ships or barges through a network of navigation facilities. Some of the specific questions leading to the Corps' sponsorship of the research project are:

1. An appraisal of the need for a new Niagara Canal to parallel the existing Welland Canal in the light of increasing commodity movement and an evolving fleet mix
2. Determination of the response of different combined Welland-Niagara Canal configurations to imposed loading
3. Determination of the response of the

existing Eisenhower-Snell lock complex and possible new configurations to imposed loading

4. Determination of the response of the existing Sault locking system and possible new configurations to imposed loading
5. Identification of potential shipping bottlenecks in the Great Lakes System under various system states
6. The need to relate design and performance in planning future locks.

Network

The modeling problem can be disaggregated into four general areas:

1. Simulation of a transportation network--specifically, the ability to route a ship through a redundant network via a minimum or otherwise specified path
2. Endogenous assignment of ships between parallel facilities--a vessel may have to decide between parallel locks or between a series of locks and reaches, e.g., the Welland Canal versus the possible Niagara Canal
3. Endogenous scheduling of ship movements--specifically, the ability of an individual ship in the simulated system to react to ephemeral commodity movement demand and thereby schedule its next movement
4. Simulation of specific facilities--for the Corps' purposes, these are locks, reaches, lakes, and ports.

The first three problem areas are, in fact, general to many transport systems; and it is only the fourth which specifically orients the model to a shipping application. In a Personal Rapid Transit (PRT) application, for instance, the specific facilities might be switches, track segments, and stations, and the commodities to be transported would be people.

NETSIM Structure

The purpose of this paper is to present the conceptual basis of the model (Figure 1). This structure has been largely retained in implementing the model. NETSIM may be considered as consisting of three stages: the preprocessor, the simulation, and the postprocessor stages.

The Preprocessor Stage

The preprocessor stage is concerned with preparing and loading the data stream which consists of:

1. Run option and specification parameters--choice of Experience Data Bank or Event Log run; simulation run length; switches to select service look-ahead feature, parallel facilities, port rescheduling procedure, vessel file options, and input-output device options. Each of these terms will be defined in later sections.
2. Network description--the transport network is represented by nodes and links in the usual manner. Links represent transit facilities such as lakes,

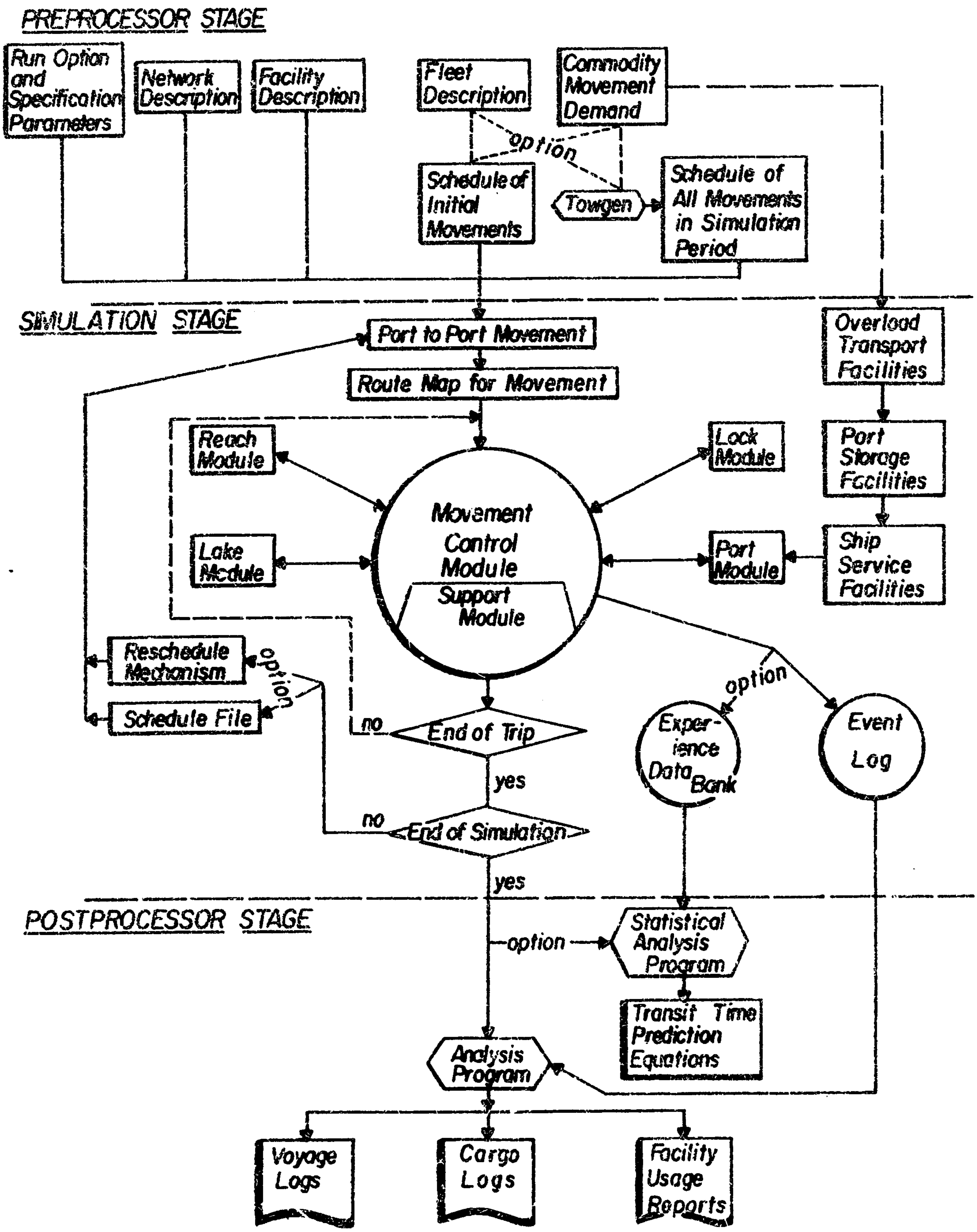


FIGURE 1 Conceptual Structure of NETSIM/SHIP.

reaches, and locks; nodes are located at facility coterminal points; and ports are also represented as nodes in the system. The actual description of the network is based on the singularity of spanning (minimum path) trees based on a given root. In effect, each port is treated as a root and heads a column which has entries for each node in the network, the column entry being the identification number of the next node in the path from the subject node to the root port. Using this formulations, one vector fully defines the route structure from any network node to a given port. A matrix of size (number of ports x number of network nodes) serves to define the route structure for the entire network. Supplementing the above "next node" table is a facility identification matrix. Since an ordered sequence of two-node numbers defines a directional link, a matrix of size (number of network nodes squared) encompasses a mapping of directional links into navigation facility code numbers. (Clearly, there exists some redundancy here since the two tables could be combined by defining the network route structure in terms of facility identification numbers; the separation is made in NETSIM to simplify data preparation.) To allow for cases where parallel "micro-route" options exist within a macro-route link, a special code is entered in the facilities identification table. This code serves to address a parallel facilities table where the sequence of navigation facilities within each micro-route are identified.

3. System facility enumeration and description--number of ports, lakes, reaches, locks, etc. and their operational and physical characteristics.
4. Commodity movement--origin-destination quantities by type of commodity.
5. Fleet description--number, type, and characteristics of available fleet.
6. Schedule of movement--movement schedules can be specified in one of two ways. If the scheduling is to be endogenous, then only the initial origin-destination movements for each vessel are required. Subsequent movements are then determined internally. It is also possible to specify exogenously the entire schedule of movements that are to occur during the simulation period. Such a schedule can be derived by using TOWGEN [2], a model which utilizes commodity movement and fleet data to give a time-ordered list of movements. Note that an auxiliary input defining multiple-port trips for specified vessels is also possible (e.g., ore-ships on committed

shuttle movements).

The Simulation Stage

Completion of the initialization of the system by the preprocessor stage signals the beginning of execution of the simulation mechanisms embodied in the simulation stage. The approach to simulation is based on the concept of a route map which describes a vessel's current trip and is unique to each vessel. In NETSIM, a vessel carries with it four route map attributes. These are numbers representing the previous node, current node, next node, and the port of destination. Once the origin and destination of a vessel are determined, the sequence of links and nodes comprising the route from the origin to the destination port is defined by the network description "next node" array. As a vessel traverses its route, the first three route attributes are continuously updated. Note that these route attributes key into the facility identification matrix, so that the sequence of facilities (i.e., reaches, locks, etc.) comprising the route is known and that the previous facility and the next facility to be traversed are uniquely identified. When the vessel's route attributes have been updated to the point where the current node and the port of destination are identical, the current trip has been completed. It is this route map concept which enables NETSIM to deal with complex networks that incorporate alternative routing options, makes possible the use of a modular approach to the structure of the model, and facilitates the rescheduling mechanism.

Each vessel's route map is monitored by the cardinal Movement Control Module. As a vessel moves along its route, the Movement Control Module identifies three characteristics of the next link to be traversed--the type and identification number of the facility which the link represents and the direction of movement through the facility, by virtue of the node number sequence. The three characteristics are, in fact, encompassed by one attribute value. The attribute is assigned to the entity representing the vessel, and the entity is passed into the appropriate facility module where the performance simulation is effected. The entity is then passed back to the Movement Control Module where the next link in the route is identified and the processes repeated. This monitoring and referral sequence continues until the end of a ship's current trip. Note that a vessel may call at intermediate ports for a given trip en route to the final port of destination if on a committed voyage.

Linked to the Movement Control Module, in satellite fashion, are the modules which simulate the performance of the different types of facilities. In NETSIM/SHIP, these are the reach, lock, lake, and port modules. It is important to recognize that the satellite facility modules are generalized logic sequences. It is the attributes carried by a vessel as it enters the facility module which direct and enable the module to simulate the operation of a specific facility. This approach is very flexible and enables additional modules to be added easily as required to simulate the operation of any type of transportation facility. These satellite facility modules are passive until activated by a vessel's routing requirements which, in turn, are dictated by the nature of the transport system being simulated.

Common to the Movement Control Module and its satellite facility modules are many routines for searching, adjusting, referencing, and stochastic sampling. To avoid duplication, seven such routines have been assembled into a Support Module which is referenced by the other modules as necessary.

Upon completion of a given vessel's trip, the need to reschedule the vessel arises. If an exogenously specified schedule is used, another trip is triggered by the scheduled event file and the process described above repeated. If an endogenous reschedule is required, the timing and destination of a vessel's next trip is a function of the location, type, and amount of commodities awaiting shipment in the system. The character of the ship also determines its suitability for transporting the available commodities. In the absence of suitable demand at the current port, a trip must be scheduled to the nearest port at which a suitable cargo is available. Since ship rescheduling is intimately associated with the port simulation module, further discussion is delayed until the logic of the port module is outlined.

The Postprocessor Stage

Upon completion of the simulation period, the third, or postprocessor, stage of NETSIM comes into effect. The function of the postprocessor is to generate system performance reports from the coded event file that is the output of the simulation stage. The event file lists in time-sequence all events which occurred in the simulated system during the simulation period. These recorded events are subsequently analyzed using a simple Fortran program to produce a set of statistical reports. This approach was adopted to minimize the time required for the actual simulation on a large computer and to provide maximum analytical flexibility. In addition, this approach enables each potential user to produce reports suitable to their own needs. It is a relatively simple matter to make appropriate changes to the existing NETSIM/SHIP postprocessor program to augment its report generation capability. The event file approach offers another advantage in that the simulation need not be rerun to obtain supplemental performance reports; it is only necessary to rerun the taped event file through additional postprocessor programs.

<u>Ship Navigation Modules</u>

The place of the reach, lake, lock, and port simulation modules in the model structure was described in the last section. Some of the features of these modules are now described.

Reach Module

The reach module represents ship transit time by sampling from a transit time probability function appropriate to the particular reach in question. The function may be derived from empirical data, or it may be a theoretical function. The module incorporates an optional reach-specific no passing rule which allows a trailing vessel to overtake but not to pass a preceding vessel in a reach.

Lake Module

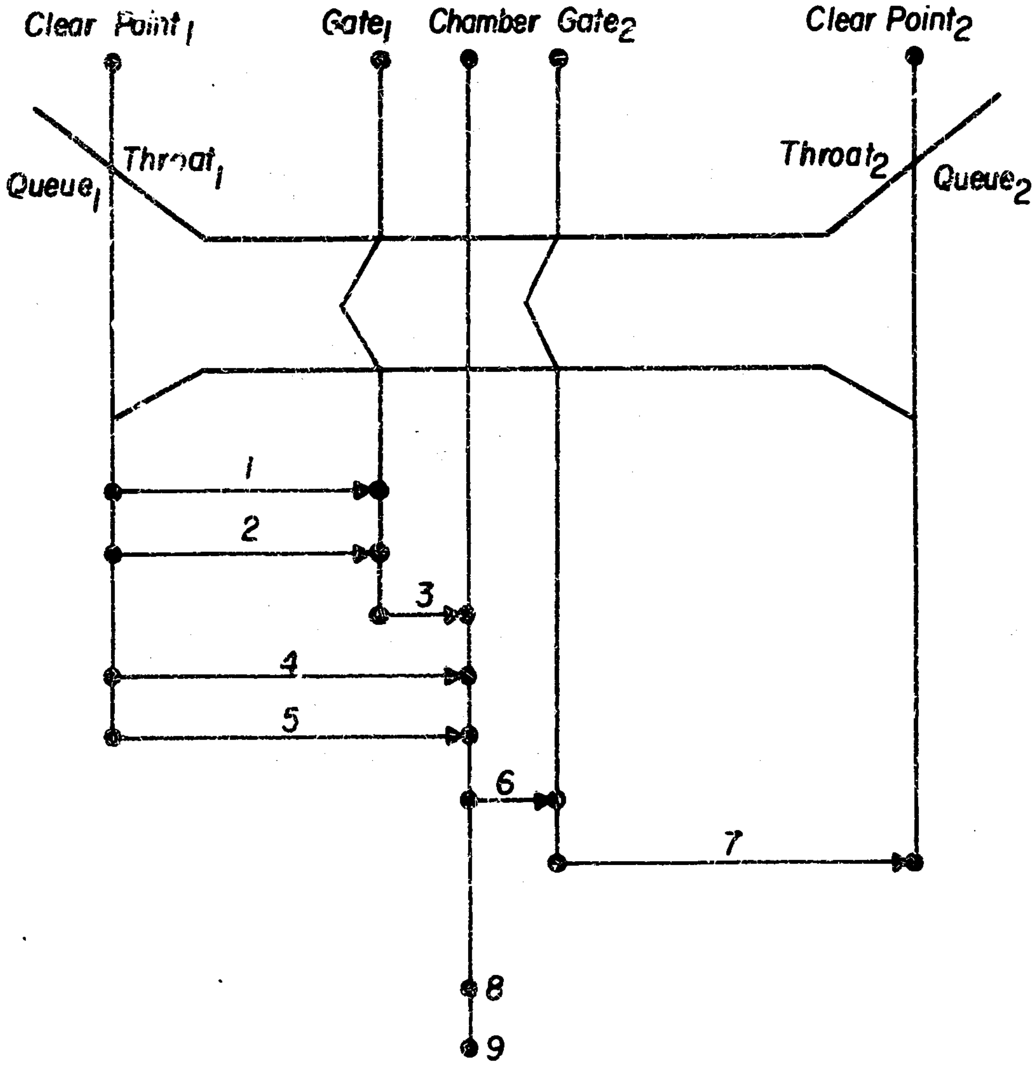
The lake module functions in a fashion similar to the reach module except that no constraints are imposed on passing. An internodal distance matrix is specified for each lake in the input stream. When a ship is to cross a lake between given node points, this matrix is referenced to obtain the appropriate distance. Lake transit times are derived by sampling from a standard cumulative density function (CDF) which is adjusted according to the distance to be traversed on the lake and the characteristics of the subject vessel.

Lock Module

The lock module has the most complex logic structure. This intricacy results from the inherently complex nature of an efficient locking operation and was dictated, in part, by the need to simulate the performance of a lock so that it is sensitive to engineering design features. Figure 2 depicts the nine time elements in relation to the physical lock configuration that are used to simulate lock operations. Five time elements are used for entry maneuvers, two for the exit maneuvers, one for chamber processing (to change water level with a vessel in the chamber), and one for recycling the lock (to change water level in an empty chamber). The entry and exit CDFs are direction differentiated and can be adjusted for differences in vessel performance.

Two service rules are included in the logic structure of the lock module, their selection depending upon conditions at the lock. When queues exist on both sides of a lock, a Serve-Opposing-Queues-Alternately (SOQA) service rule is adopted. If a queue exists only on one side of a lock, then a First-Come-First-Served (FCFS) service rule is adopted. These are standard operating procedures for locks operated by the St. Lawrence Seaway Authority and for locks under the control of the St. Lawrence Development Authority.

These service rules alone do not, however, suffice to simulate lock operations in the manner adopted by experienced lockmasters. For example, on the Great Lakes System lockmasters have radio communication with approaching vessels so that they can anticipate vessel arrivals and can make appropriate operational decisions. Such decisions are replicated by means of two "look ahead" features in the logic structure. The first of these is the "service look ahead" mechanism. Prior to making a decision to recycle a lock to accommodate a waiting or approaching vessel, the service look ahead scans the adjacent reach on the opposite side of the lock for approaching vessels. If a vessel in this reach



1. Clear point to short-entry position, moving start.
2. Clear point to short-entry position, stationary start.
3. Short-entry position to chamber.
4. Clear point to chamber, moving start.
5. Clear point to chamber, stationary start.
6. Chamber to gates-clear point.
7. Gates-clear point to clear point.
8. Process (with vessel).
9. Recycle (empty).

FIGURE 2 Schematic of Lock Time Elements used in NETSIM/SHIP.

could enter the lock chamber at its current water level before the opposing vessel could enter the recycled lock, the lock recycle is suppressed. The second feature is the "recycle look ahead" feature. In the absence of opposing traffic, the recycle look ahead adjusts the water level in the lock chamber to receive an approaching vessel directly into the chamber. If the vessel arrives before the recycling is complete, the vessel waits in the short-entry position until entry is possible.

Port Module

The immediate applications of NETSIM/SHIP envisaged by the Corps of Engineers do not require an elaborate port module. The current model, therefore, determines ship turnaround time simply by sampling from port-specific CDFs. The mechanisms to support a more elaborate module are, however, built into the structure of NETSIM/SHIP.

The logic structure of an elaborated port module has been defined with a port considered to have attributes relating to berthing capacity, ship servicing capacity (e.g., craneage), commodity-specific storage capacity, and seasonal attributes which define the opening and closing dates of the port. Each port also maintains an incoming-ship list that contains the identification of every ship that currently considers the subject port as its next port-of-call. The time spent in port by a ship is a function of berth and servicing availability and the amount of cargo to be on- and off-loaded. The commodities in a port awaiting shipment are a function of port storage capacity, inputs from the overland transportation system, and previous cargo movements from the port.

After on- or off-loading cargo, a ship must be rescheduled (under the endogenous scheduling option) and may be in one of three states. If the vessel is on a committed voyage, it will have a predefined next port-of-call, the current port being an intermediate stop. In this case, a trip to the next port-of-call is scheduled, with cargo if cargo is available or in ballast if not. If the vessel is not on a committed run, a completely new voyage must be scheduled. If suitable cargo exists in the current port, the next voyage is scheduled to accommodate this commodity movement. If no such cargo exists, a search for suitable cargo at other ports must be instituted, starting at the nearest one. To obviate sterile in-ballast trips, the incoming ship list of each port must be checked and the available cargo manifests at that port adjusted to account for commodity movements which will occur before the subject vessel can reach that port. When the location of suitable cargo is identified, a voyage to the nearest such port is scheduled for the subject vessel.

Assignment Decision Technique

In ship navigation contexts (excluding oceans), redundant networks rarely exist in the sense that alternative, nearly competitive, routes are not usually available. However, within a macro-route, alternative micro-routings may exist.

Examples are twinned locks or parallel canals, the Welland-Niagara canals being a case in point. This situation is common in many transport systems.

Decisions as to which macro-route to use are usually easily made by observation or, if need be, by a minimum path algorithm. Selecting between alternatives at the micro-scale within a macro-route usually depends upon the conditions prevailing in the micro-route alternatives. The NETSIM assignment decision technique is based on this philosophy. It is assumed that it is possible to derive an equation to relate expected transit time through a sequence of facilities to the traffic conditions prevailing in those facilities. The mechanisms to support the derivation of these equations is built into the NETSIM/SHIP logic. Prior to simulating the operation of a system containing micro-route alternatives, it is necessary to derive a set of expected transit time prediction equations for each such alternative.

The equations are derived by regression analysis of an Experience Data Bank (EDB) which is built up by simulating the operation of each micro-route alternative individually. The approach is shown graphically in Figure 3. In a simulation run to construct an EDB, as a ship passes the assignment decision point, a snapshot is taken of current traffic conditions in the subject micro-routing alternative; as the ship leaves, the actual transit time is recorded. These observations are made for each ship, differentiated by direction, and constitute the EDB.

A set of dummy transit time predictor equations of the form $E(T) = C_o + \sum_{i=1}^{n} C_i X_i$ are already built into NETSIM/SHIP. As a result of the EDB analysis, the user simply calibrates these equations by specifying the influencing variables (X_i) and assigning coefficient values (C_i).

When running a system simulation with calibrated equations, values of the appropriate traffic condition variables are automatically obtained for each micro-routing alternative when a ship reaches the appropriate assignment decision point. The expected transit time is computed for each alternative using the transit time prediction equations, and the ship is assigned to the micro-route offering the least expected transit time.

Language

Although the earlier MCDD model was constructed using IBM's General Purpose Simulation System (GPSS), it was decided to use Simscript for programming NETSIM/SHIP. GPSS was selected for the MCDD model because it could encompass the restricted objectives of the MCDD model and it offered considerable savings in programming effort. In retrospect, the selection of GPSS was correct for that purpose since it allowed the MCDD model to be programmed within severe time constraints.

While the MCDD model development had limited objectives, the generality and power of

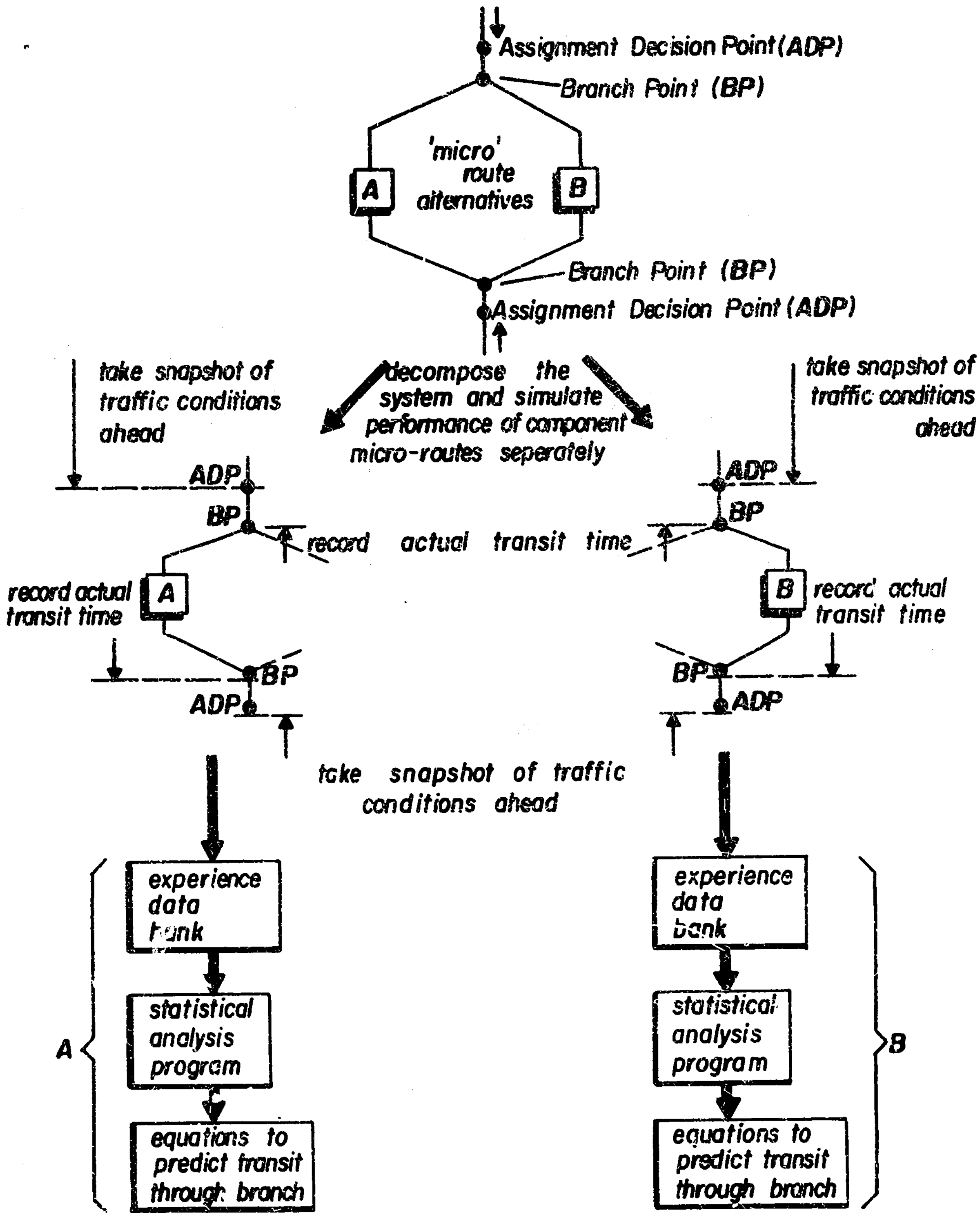


FIGURE 3 Derivation of Assignment Decision Equations.

the NETSIM concept made it impossible to pre-specify its potential uses and applications. Certainly, even in a shipping context, it is easy to envisage model capabilities beyond those actually required by the Corps of Engineers for the current research project. Simscript, being a general purpose language, was selected since it offered the inherent ability to encompass easily any developments of NETSIM. In addition, the English-like readability of the language allows a Simscript written program to virtually serve as its own documentation. This is a distinct advantage in a complex model.

In contrast to the four man-months required to program the MCDD model in GPSS, the programming of NETSIM/SHIP in Simscript has been much more protracted. A detailed model specification for NETSIM/SHIP, including logic structures and techniques, resulted from a review of the MCDD model. Some nine man-months of Simscript programming effort and four thousand dollars worth of computer time on an IBM 360/67 was subsequently required to bring NETSIM/SHIP to its present state of development.

Future Extensions of NETSIM

The completion and documentation of the NETSIM/SHIP capabilities described in this paper is currently in hand at The Pennsylvania State University's Transportation and Traffic Safety Center, and the model is being applied to the Great Lakes-St. Lawrence Seaway system. The logic structure for facility simulation modules to allow NETSIM to be applied to networks oriented to personal rapid transit, highway, traffic light, and airport systems is being considered.

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Key Words

SIMULATION, SIMSCRIPT, SHIPPING, LOCKS, GREAT LAKES, PORTS, COMMODITY MOVEMENTS, NETWORK SIMULATION