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A COMPUTER SIMULATION MODEL OF CONTAINER MOVEMENT BY SEA

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ABSTRACT

We describe a computer simulation model of ocean container carrier operations. The simulation is called SimSea and was developed through collaboration between the CSIR, a research organisation in South Africa, and the Georgia Institute of Technology (Georgia Tech). SimSea simulates the transport of containers by container vessels. Containers are transported from container depots to customers. The customers load the containers, and thereafter the containers are transported to the ports. At the ports the containers are loaded onto and offloaded from vessels, and the vessels transport the containers between ports according to the vessels' schedules. Containers are transported from the ports to receiving customers who unload the containers, and from there the empty containers are transported to container depots. Empty containers are also transported between container depots to compensate for imbalances in the flow of loaded containers.

1 INTRODUCTION

The operations of ocean container carriers are quite complex. Different types of containers, containing different types of cargo, are transported between many origins and destinations. The demand for such transport varies with time, and the detail variation is not known by the ocean carrier in advance of the receipt of booking requests from the customers. In the process, transport by road, rail, and water is used to move containers between inland locations and ports, and ocean vessels are used to transport containers between ports. Along the way the containers are loaded, transhipped at various terminals such as road-rail terminals and ports, and unloaded at the destinations.

Ocean container carriers have many decision problems for which a simulation can serve as a decision support tool. Some of these problems are of a longer term or strategic nature. Examples of such problems are which ships to order or charter, in which ports to establish facilities, and how to design the services that determine the sailing schedules of the vessels. Some of these problems are of a medium term or tactical nature. An example of such a problem is the design of the portfolio of contracts that the carrier enters into with its customers, that determine the cargo and the empty containers that have to be transported between various origins and destinations. Some of these problems are of a shorter term or operational nature. Examples of such problems are the day-to-day control of bookings, that is, which booking requests to accommodate on which sailings, and how to route the containers from their origins to their destinations when, as is often the case, the carrier can choose between various paths for a particular shipment. As mentioned, these decision problems involve aspects that are both complex and for which all the relevant data, such as origin-destination demand at each point in time, are not known at the time the decisions have to be made. Therefore a simulation would be a useful tool to estimate the performance measures associated with the types of decisions referred to above.

Simulation is not a new methodology in the ocean transportation area. Many simulation models of port operations, especially container port operations, have been developed. Tugcu (1983) used a port simulation model to aid investment planning for the Istanbul seaport. El Sheikh et al. (1987) developed a simulation model to help the planning of future berth requirements of a third-world port. Chung, Randhawa, and McDowell (1988) proposed a method that uses buffer space to reduce container loading times and optimize equipment utilization, and a simulation was developed to justify their method. Silberholz, Golden, and Baker (1991) employed simulation to study the impact of work crew schedules on container port productivity. Hassan (1993) presented a simulation to be used as a decision support tool for evaluating and improving port activities. Ballis and Abacoumkin (1996) developed a simulation with animation to simulate the operational activities of a container terminal with straddle carriers. Ramani (1996) developed a simulation to support the logistics planning of seaports. The simulation provided estimates of port performance indicators such as berth occupancy, ship output and ship turnaround times for various strategies. Merkuryev et al. (1998) used simulation to improve logistics processes at Riga Harbour Container Terminal. Nevins et al. (1998) simulated the operations of a seaport, and provided detailed statistics on seaport throughput and resource utilization. Gambardella, Rizzoli, and Zaffalon (1998) developed models of an intermodal container terminal to aid container allocation in the terminal yard, resource allocation and operations scheduling. Simulation was used to test their results. Thiers and Janssens (1998) used a port simulation model to investigate the hindrance of a river quay. Bruzzone and Signorile (1998) employed genetic algorithms and simulation to make strategic decisions about resource allocation and terminal organization. Yun and Choi (1999) proposed a container terminal simulation model using an object-oriented approach. Tahar and Hussain (2000) introduced a simulation model of port operations and provided detailed statistics on the port throughput and utilization. Legato and Rina (2001) developed a container terminal simulation model to aid berth planning and resources optimization. Shabayek and Yeung (2002) simulated Kwai Chung container terminals in Hong Kong and investigated the goodness of the simulation model in predicting the actual terminal operations. Pope et al. (1995) employed simulation to examine the impact of road traffic flows on container terminals located in cities. All the studies referred to above were concerned with the simulation of port operations, and not with the simulation of the operations of container carriers, which involve multiple ports. The following is the only reference to a simulation model of ocean container carrier operations that we have found in the literature. Lai, Lam, and Chan (1995) developed a simulation model of a carrier's operational activities to aid the search for the best container allocation policy.

Therefore we decided to develop a simulation of ocean carrier operations called SimSea. The effort involves collaboration between the CSIR, a research organisation in South Africa, the Georgia Institute of Technology (Georgia Tech), and The Logistics Institute Asia-Pacific, with technical input from various carriers and ports. The first application of the simulation is to support our own work on operations research applications in the ocean transportation industry. However, the simulation is also available to other researchers, carriers, and ports.

2 SIMSEA

As mentioned, the first purpose of SimSea is to support our research on a variety of operations research applications in the ocean transportation industry. Different applications have different requirements regarding the levels of detail at which different aspects are simulated. For example, some applications require port operations and port costs to be simulated in great detail, and other applications only need the simulation to record the number of containers that are loaded and off-loaded in each port. Also, different applications require different operational decisions to be simulated. For example, a simulation of which the purpose is to compare the desirability of different sizes of ships on various cycles may require the simulation of a simple booking control mechanism, whereas a simulation of which the purpose is to compare different booking control mechanisms requires the simulation of these booking control mechanisms in great detail. We attempted to develop SimSea to be sufficiently flexible to support such different applications. To that end, SimSea was developed in a modular fashion, consisting of a number of C++ functions that can be combined and/or modified to suit the particular application. At the moment SimSea is tailored for the simulation of ocean container carrier operations, which are typically scheduled services. The use of SimSea to simulate bulk shipping, which are typically tramp shipping services or industrial shipping services, will require some additions to the simulation. Therefore, the development of SimSea is an ongoing process. Next we describe in some more detail some of the entities, such as containers, container depots, customers, ports, and container vessels.

3 CONTAINERS

In the current version of SimSea, all cargo is moved in containers. Containers are moved between container depots, customers, ports and vessels. Containers are classified into General Purpose, Refrigerated (Reefer), High Cube, Reefer High Cube, Open Top, Flat Top, Hanger and Tank Containers. Container sizes include 20-foot, 40-foot and 45-foot. The most common combinations of container type and container size are 20-foot General Purpose, 40-foot General Purpose, 40-foot High Cube, 45-foot High Cube, 20-foot Reefer and 40-foot Reefer High Cube. Containers can be provided by the customer or by the carrier whose operations are simulated. Which of the two is the case is determined at the time the booking request is made by the customer. If the container for a shipment is provided by the customer, then the simulation keeps track of the movement of the container from the moment the container is picked up at the consignor until the container is delivered at the consignee. If the container for a shipment is provided by the carrier, then the carrier has to arrange for an empty container to be moved from one of the carrier's container depots to the consignor, and after the container has been loaded it is moved to the consignee, and after the container has been unloaded, it is moved from there to another of the carrier's container depots. The total number of carrier containers in the simulation is the number of containers at the depots, at the consignors being loaded, at the consignees being unloaded, in transit on feeder services, on the vessels, and at the ports. The values of these numbers at the start of the simulation is input to the simulation. The simulation keeps track of the location and movement of all containers that belong to the carrier from the start until the end of the simulation.

4 CONTAINER DEPOTS

Container depots hold empty containers in inventory. As mentioned, if the container for a shipment is provided by the carrier, then the carrier has to arrange for an empty container to be moved from one of the carrier's container depots to the consignor to be loaded, and after the container has been unloaded at the consignee, it is moved from there to another of the carrier's container depots. In addition, the carrier can move empty containers between container depots to compensate for the imbalances in loaded container flows. The dynamic control of the repositioning of empty containers is a challenging problem that has received a fair amount of attention in the operations research literature. Crainic, Gendreau, and Dejax (1993) developed container distribution and allocation models, in both single commodity and multi-commodity versions. They also provided a single commodity formulation which handled dynamic aspects and uncertainties. Lai, Lam, and Chan (1995) developed a simulation model of a carrier's operational activities and employed heuristics to search for the best container allocation policy.

5 CARGO

Cargo is broadly classified into four types: General Cargo, Dangerous Goods, Refrigerated Cargo, and Refrigerated Dangerous Cargo. In addition, cargo is further classified by commodity types, such as Cotton, and General Department Store Merchandize.

6 CUSTOMERS

The carrier has contracts with a variety of customers. The contracts specify the prices that the customers pay for the transportation of containers with different types of cargo between different origins and destinations. Often the prices also vary by time of the year, for example, prices are higher during peak times than during off-peak times. Also, often the carrier can transport containers along different paths between the same origin and destination. For example, the carrier can transport containers from Shanghai to Atlanta either through a port on the west coast or through a port on the east coast of the USA. The prices may vary depending on the path that is used between origin and destination. Sometimes different paths have the same price, but customers have requirements regarding the paths that are used for their shipments. For example, there may be several alternative paths through various ports on the east coast of the USA, but a customer may require that a path through a particular port be used because their customs agent has an office in the port. These customer related data form part of the input of the simulation.

7 VESSELS

Vessels are operated by the carrier to transport containers between ports. Each vessel has specified capacities for general purpose and refrigerated containers and for different sizes of containers. Other relevant characteristics of a vessel are its speed, gross registered tonnage, length and volume. The location of the vessel and the containers on the vessel are initialised at the start of the simulation.

8 VOYAGES AND SERVICES

A voyage is defined as the movement of a vessel between two consecutive ports of call on the vessel's schedule. The length of the voyage and the speed of the vessel determine the time to sail from one port to the next. The container capacity of the vessel determines the number of containers that can be booked on a voyage.

As is typical in the case of ocean carriers with scheduled services, the vessels repeat a cycle of voyages that is also called a service or a rotation. A service usually has a specified frequency of departures at each port in the cycle. The number of vessels on a service is determined by the amount of time it takes a vessel to complete the cycle of the service, and the frequency of departures scheduled at the ports in the service. For example, if it takes a vessel 6 weeks to complete the cycle, and the service has weekly departures at each port in the cycle, then 6 vessels, equally spaced one week apart in their port visits, are needed to operate the service.

9 FEEDER SERVICES

Containers have to be moved from container depots to consignors, from consignors to ports, from ports to consignees, from consignees to container depots, and between container depots and ports (for the repositioning of empty containers), in addition to the movement of loaded and empty containers between ports on the carrier's vessels. These other movements are typically performed by other carriers, called feeder services, that are subcontractors of the ocean carrier. The time taken by feeder services to move containers can vary substantially. This variation is modelled with random travel times.

10 PATHS

A path is a sequence of container moves from the origin of a shipment to the destination of the shipment. Some of the moves are performed by feeder services, and other moves are voyages between ports performed by the vessels of the simulated carrier. The flow on a path is constrained by the capacities of the vessels that sail the voyages that form part of the path.

11 PORTS

Each voyage starts and ends at a port. At the ports containers are offloaded from and loaded onto vessels. The rate of loading and offloading varies from port to port and is specified by each port's loading rate. The offloaded containers either wait at the port to be transferred to another vessel, or they are transported to their destination which is either a consignee or a depot.

The ports first offload containers from the vessels that are destined for the port. Ports can also perform vessel maintenance; if needed, maintenance is done after the offloading operations have been completed. Next the full and empty containers are loaded onto the vessel. In the current version of SimSea, if the vessel is overbooked, containers which the vessel can transport to their destination ports are loaded before transfer containers which the vessel can only transport part of the route.

12 A BRIEF DESCRIPTION OF AN OCEAN CONTAINER CARRIER'S OPERATIONS

In this section we give a brief overview of how the entities described above are involved in a typical ocean container carrier's operations. Usually a carrier operates a number of services (rotations), and each service has regular, typically weekly, departures at each port in the rotation. Each vessel is operated on a particular service, and each vessel moves containers filled with cargo and empty containers around the cycle of its service. Different services may visit the same ports. On its way from its origin to its destination, a loaded container is typically transported by one or more feeder services until it gets to a port close to the origin that is visited by a service of the carrier, then the container is carried on one or more voyages on a vessel operating on the service, occasionally the container is transferred in a transhipment port to another vessel operating on another service of the same carrier, until the container reaches a port close to the destination, from where it is again transported by one or more feeder services until it reaches the destination of the shipment. Movement of containers along each such path takes place regularly in time, for example, every week if the carrier maintains a schedule with a weekly frequency. Thus, for each path, time-stamped copies of the path are repeated regularly, for example weekly. There may also be more than one such path, involving different services, connecting the same origin-destination pair. The flows of both loaded and empty containers are assigned to time-stamped paths by the carrier. The assignment of loaded containers to time-stamped paths takes place as the booking requests are received from the carrier's customers. This assignment decision process is called booking control and is briefly discussed in the next section. Figure 1 represents the system of a small carrier. Nodes 1, 2, and 3 represent ports and nodes 4 and 5 represent inland locations. There are two services in the system, one is the directed cycle 1-2-3-1 in the bold line and the other is the directed cycle 1-3-1 in the dashed line. Four paths connect inland locations 4 and 5; for example, path 4-1-2-3-5 and path 4-1-3-5 connect location 4 to location 5.

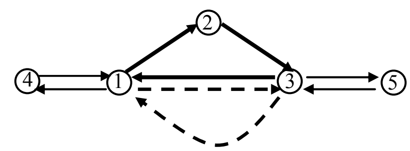

Figure 1. Operational System of a Small Carrier

13 BOOKING OF CONTAINERS

The demand for container transport is modelled as a stochastic process of which the parameters may be time varying. A demand module generates customers' booking requests at random points in time. Each booking request specifies a particular customer, cargo class, number of containers, origin, destination, desired departure time, and whether the customer or the carrier should provide the containers. The booking control module determines what path and what departure time the carrier offers to the customer for the shipment. The availability of appropriate containers at the container depots and the available space on the vessels are factors that the carrier can take into account when making booking offers. The customer may accept or reject the booking offer with a probability that depends on how well the offered departure time matches the desired departure time.

The booking control module that has been implemented for the current version of SimSea is a simple approximation of how carriers control bookings. The paths between each origin and destination are listed in order of preference from the most preferred to the least preferred. When the customer requests that the carrier provides the containers, the availability of the requested types, sizes, and number of containers is checked first. If the appropriate containers are not available the order cannot be fulfilled. If the appropriate containers are available, then all the paths between the specified origin and destination that satisfy the customer's requirements are scanned from the most preferred to the least preferred path to check if there is sufficient capacity on the voyages to transport the shipment. The carrier offers the customer the first path found with sufficient capacity for the shipment.

Customers use their own containers or containers are provided by the carrier from one of its container depots. The consignors load the containers with cargo. Thereafter the containers are transported to a port where they are stored until they are loaded onto a container vessel. One or more vessels transport the containers to the destination port where the containers are offloaded. The containers are then transported to the consignee who unloads them. If the containers were provided by the carrier, the containers are then moved from the consignee to one of the carrier's container depots.

Bookings can be cancelled by the customers. Also, often containers do not arrive at the port of departure on time for the voyage on which the container was booked. To compensate for cancellations, late arrivals, and no-shows, carriers overbook voyages. The overbooking policy forms part of the booking control module.

14 EVENTS

SimSea is a discrete event simulation. Next we describe some of the events in SimSea.

14.1 Vessel Events

The events pertaining to the vessels are the following:

- Sailing. The sailing event moves a vessel out of its current port and schedules its arrival to its next port of call (the anchorage event).
- Anchorage. Upon reaching a port of call, each vessel may incur a delay called anchorage before the vessel can enter the port (the docking event).
- Docking. The docking event moves a vessel into a port and schedules the time that the vessel will be ready to be offloaded.
- Offloading. Containers are offloaded from the vessels, and either a maintenance event or a loading event is scheduled for the vessel.
- Maintenance. For each vessel, one port of call is identified as the maintenance port of the vessel, and whenever the vessel visits the port a maintenance event takes place. The maintenance may be short routine maintenance or longer repairs.
- Loading. Containers are loaded onto the vessel, and the next sailing event of the vessel is scheduled.

14.2 Container Events

The container events include the following:

- Transport. The containers are transported by feeder services between container depots, customers, and ports. A transport event may schedule a subsequent load or unload event if the container is transported to a consignor or a consignee.
- Load. The container is loaded with cargo. A load event schedules a subsequent transport event to the first port on the chosen path for the shipment.
- Unload. The cargo on the container is unloaded. If the container belongs to the carrier, an unload event schedules a subsequent transport event to a chosen container depot. If the container belongs to the customer, the simulation stops keeping track of the container when the unload event takes place.
- Arrival. The container arrives at a port or at a container depot.

The vessel events discussed above also involve containers. For example, during the vessel loading event, containers become associated with a vessel, and they remain associated with the vessel until the container is offloaded from the vessel during a vessel offloading event. A vessel offloading event then schedules the transport events to consignees for loaded containers, or the transport events to container depots for empty containers, or transfer containers stay at the port until the next vessel loading event on the container's chosen path.

14.3 Other Events

Other events include booking requests for container movement, and the movement of surplus empty containers between container depots.

15 COSTS

Various cost functions have been incorporated into SimSea, and the user can choose between a number of different cost functions depending on the level of detail required. The two major types of operational cost for ocean carriers are the costs incurred during voyages and the costs incurred during port visits. Other costs besides these include the costs to lease additional containers and the costs to obtain additional voyage capacity from alliance members.

The costs incurred during voyages can be partitioned into the following cost components:

- Crew costs. Crew costs in turn consist of many components, including salaries and wages, overtime pay, payroll taxes, health insurance, pension contributions, and recruiting costs.
- Fuel costs. Fuel consumption is sometimes described as fuel oil consumption and diesel oil consumption.
- Stores and consumables. These include lubrication oil, spare parts, and water for boiler consumption.
- Maintenance and repairs. These include both maintenance of vessel equipment, as well as the living areas of the crew.
- Dues. These are fees that have to be paid for facilities used while on voyage, such as the fees to traverse the Panama Canal and Suez Canal, and lighthouse dues.

- Insurance. This includes both marine insurance for the vessel's hull and machinery, and protection and indemnity insurance against injury or death of crew members or third parties, and pilferage or damage to cargo.
- Cargo claims. This includes costs incurred due to loss of or damage to or delay of customers' cargo.
- Ship chartering or capital cost. This includes the cost incurred for chartered vessels if the vessel does not belong to the carrier, or the portion of capital cost assigned to the voyage if the carrier owns the vessel.

If detailed voyage cost calculations are desired, the simulation user has to supply the unit costs for each of the items above. Alternatively, the user can supply a unit cost per voyage for each ship.

Another important type of cost for ocean container carriers is the costs incurred during port visits. Before the development of SimSea, a study (Wu and Kleywegt, 2002) was done of the way various port operators calculate different fees charged to carriers. It was found that different ports calculate the fees for the same service in different ways. For example, some ports calculate the dockage fee as a function of the length of the ship and the docking time, and others calculate the dockage fee as a function of the gross registered tonnage of the ship and the docking time. In addition, even if two ports both calculate the dockage fee as a function of the length of the ship and the docking time, the formula according to which the calculation is done may be different for the two ports. And, of course, even if two ports use the same basic formula, the parameter values in the formulas may be different between the two ports. The study produced a classification of the different types of fees that port operators charge to carriers, and for each type of fee a number of the most widely used formulas were identified. These formulas were incorporated into SimSea. If such detailed port cost calculations are desired, the simulation user has to identify, for each port and each type of fee, the type of formula used, and has to provide the parameter values used by the formula. Alternatively, the user may use a simplified port cost calculation, for example, a fixed charge per vessel (the value of which may depend on the port) per visit to a port, and a charge (again, the value of which may depend on the port) per container loaded and offloaded.

The port fees are partitioned into two main categories, namely the charges against vessels and the charges against containers, and are briefly discussed next.

15.1Vessel Costs

The vessel charges include the following:

- Anchorage cost. This is the fee levied for the time that a vessel drops anchor at a port but is not berthed.
- Berthing/un-berthing cost. This is the fee charged for the berthing and un-berthing of a vessel.
- Dockage cost. This is the fee assessed for the time that a vessel is berthed at a wharf, pier, bulkhead structure, or bank at the port.
- Light dues cost. This is the toll levied on vessels for the purpose of maintaining lighthouses and light buoys around the port.
- Mooring/unmooring cost. This is the fee charged against a vessel for using ship moorings for the purpose of discharging or loading cargo.
- Overstay cost. This is the fee assessed against a vessel when it is deemed to have overstayed at a berth.
- Pilotage cost. This is the fee levied for the piloting services rendered when a vessel enters or leaves a port.
- Port dues cost. This is a charge for entering a public port or using its channels, navigation aids and other facilities to ensure safety in entering and leaving the port.
- Towage cost. This is the fee charged for the services of tug boats assisting a vessel or the act of towing a vessel.

15.2 Charges on Containers

The container charges include the following:

- Lashing/unlashing cost. This is the fee for the operations of lashing or unlashing containers onto or from the vessel.
- Lift on/lift off cost. This is the charge for lifting a container from a vehicle on the container yard onto a ship or for lifting a container from a ship onto a vehicle on the container yard.
- Wharfage cost. This is a charge for the use of a wharf.
- Gantry crane cost. This is the charge for the use of gantry cranes to stack and unstuck containers in the container yard.
- Fork lift cost. This is a charge for the use of forklifts to move empty containers.
- Demurrage cost. This is a charge against a container that remains at a wharf or container yard after the expiration of the free time allowed.

16 OUTPUT

The simulation produces an output file and a results file. The output file is a detailed report of all the events that occur in the simulation and the time of occurrence. The results file reports performance measures such as the total cost incurred during the voyages and at the ports and the total revenue generated by serving the customers. The file also reports the number of different containers at the container depots at the end of the simulation; the number of containers supplied and received by each container depot; the number of containers loaded and offloaded at the ports; and the number of containers loaded and offloaded by the vessels.

17 FURTHER WORK

SimSea is an ongoing research project and changes are continually made to the simulation. Current developments include the addition of a user interface for the simulation to improve the interaction between the user and the simulation, additional booking control modules, better demand models, models of scheduled and unscheduled maintenance, and models of delays and disruptions. The need for an animation of the vessel and container movements has been identified. A longer term objective is to provide a training tool which can be used to train industry decision makers.

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