

ON THE DEVELOPMENT OF A COMPUTER SYSTEM TO SIMULATE PORT OPERATIONS CONSIDERING PRIORITIES

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ABSTRACT

This paper describes the simulation system developed at The University of Texas at Austin for the performance analysis of port operations considering container's priority. The paper discusses the current trends toward service differentiation and provides a brief description of port operations and the historical evolution of performance analysis in this area. The conceptual and computational characteristics of the simulation system are described, as well as the calibration process. Finally, conclusions and recommendations for further research are discussed.

1 INTRODUCTION

Increasingly over the last twenty years, developments in electronics and computer control are allowing production of goods with higher added value, smaller unit size and relatively low volume. Concurrently, the growing popularity of Just-in-Time (JIT) production systems have increased the importance of the cargoes' logistic value. On the other hand, the advent of intermodalism has provided container carriers with the opportunity to target non-traditional markets. As part of these efforts, container carriers are trying to attract low-valued cargoes as a way to reduce the number of empty movements, e.g., cotton movements from Texas to the West Coast. If these attempts to attract low-valued cargoes succeed, container carriers and intermodal terminals may be handling a potentially high number of containers carrying low-valued cargoes.

The combined effect of the aforementioned trends is to increase the relative importance of both ends of the cargo value distribution. In this context, an operational policy that does not distinguish containers according to cargo value is likely to penalize the segments of users located at the ends of the cargo value distribution, i.e., the low-valued cargoes may be charged for a service that they do not need, and the high-valued cargoes may receive a quality of service below their needs. Container

carriers have responded to this new challenge by implementing "hot hatch programs," where the high priority containers are located on the ship hatches that will be unloaded first.

In this context, the implementation of priority systems will provide a level of service consistent with the container's priority. The objective of this research is to analyze the implementation of priority systems at container ports where network effects are not considered. The complexity of this problem required the research to be divided into three major areas: information systems, performance analysis and pricing policy.

This paper focuses on describing the simulation system developed for the performance analysis of priority systems. The system is able to simulate a wide range of operational policies ranging from the current "hot hatch" programs to more complex systems in which service differentiation is done at all the stages (i.e., movement to storage yard, storing yard operations, gate processing in/out of the storage yard and container retrieval).

The paper is comprised of five major sections in addition to the introduction. Section 2 presents a brief overview of port operations in general. In Section 3, the different approaches used for the performance analysis of port operations are discussed, and the needs for a simulation system considering priorities are analyzed. Section 4 is dedicated to describing the simulation system. Section 5 focuses on describing the calibration process. Finally, conclusions and recommendations for further research are presented.

2 OVERVIEW OF PORT OPERATIONS

The operation of transportation terminals is one of the most challenging tasks in the transportation industry. The amount of investment involved, the conflicting objectives of the agents involved, the ever pressing needs for increased efficiency, and the multitude of constraints that affect the operations are some of the elements that make terminal operations such a difficult task. The operation of marine container terminals is no exception.

The investment in a medium size container terminal frequently surpasses one hundred million dollars. Interacting at these expensive facilities are a number of different agents: (a) shipping companies, (b) container terminal operator, (c) railroads and motor carriers, (d) brokers, (e) shippers; (f) forwarders, and (g) regulatory agencies. Balancing the frequently conflicting objectives of these agents, and their different operational criteria is, to say the least, a difficult task.

The term "port operations" encompasses the set of service processes that takes place at marine ports. The characteristics of these processes depend upon the type of flow (e.g., import containers, export containers); the type of terminal (e.g., dedicated container terminal, multipurpose terminals), and the handling technology being used, that is frequently determined by managerial styles, financial capability and labour agreements.

Although there is not a unique way of conducting "port operations," the alternative systems share some common characteristics. In a very simplistic way, four major systems are identified: (a) marine side interface, (b) transfer system, (c) container storage system, and (e) land side interface. A "typical" U.S. terminal has the following characteristics:

a. marine side interface: two or three gantry cranes move containers to/from the ship. Since the efficiency of the gantry cranes is the single most important factor in determining ship turnaround time, maintaining a continuous operation of the gantry cranes is a primary objective.

b. transfer system: yard trucks and straddle carriers are the two most popular types of equipment. In the former case, the gantry cranes put the containers onto trailers towed by yard trucks to/from the container yard. Usually seven or eight yard trucks serve a gantry crane. When straddle carriers are used, no trailers are needed because the straddle carrier works as a mobile crane that lifts the containers from the apron, moves it to the container yard, and places it at the final destination.

c. container storage system: there are two basic schemes, i.e., stacking containers on the ground and storing the containers on chassis. In the former case, special handling equipment, e.g., yard cranes or straddle carriers are needed. In the latter, no special handling equipment is needed, though more land is required. Additionally, yard operations involve a number of supporting activities like updating container location and reorganizing the container yard.

d. land side interface: seven to ten lanes operated by clerks process related paperwork and clearances of incoming and exiting trucks. An increasing number of terminals are implementing Automatic Equipment Identification (AEI) devices and other information technologies (e.g., electronic tags, bar coded and magnetic strip cards) to facilitate the identification of vehicles and drivers, though the market penetration of these technologies is still relatively low. For a full

discussion on information technology, see Holguín-Veras and Walton (1995d and 1995e).

3 PERFORMANCE ANALYSIS OF PORT OPERATIONS

Three different approaches have been used for the performance analysis of port operations: ship distribution at ports (SDP), queueing theory (QT) and simulation (Frankel, 1987; Holguín-Veras and Walton, 1995a). Historically, the first approach used was SDP; followed by QT and simulation.

SDP relies on the assumption that the berth occupancy analysis can be performed using the observed ship distribution at ports and, consequently, the number of ships at port is an independent random variable. The weakest point of this approach is that the number of ships present at the port, at any given day, is not independent of the number of ships that were present the day before and, consequently the independence assumption does not hold. In addition, since it is assumed that the SDP remains the same, irrespective of the number of berths and the demand, the influence of the service characteristics is not properly considered. Because of these flaws, the use of SDP has been abandoned.

The use of QT was suggested in the 20's and 30's for the capacity analysis of ports, but it was not until the early 60's when it became widely used (Agerschou and Korsgaard, 1969). The first application is commonly attributed to Mettam (1967) but an earlier application by Gould (1963) was found. Mettam did demonstrate the practicality of QT by stating the basic principles of this type of application, and highlighted the potential benefits that could be obtained from it. As it was to become typical of this approach, Mettam considered only the ship-berth interface. His paper was influential in attracting other analysts to QT. In general, the majority of QT applications consider only the ship-berth interface. In these applications basic QT, i.e., birth-death processes in equilibrium, has been used to provide performance estimates. Other classes of QT models, e.g., queueing network and cyclic queues, have been only sporadically applied. For instance, see Daskin and Walton (1983).

The number of papers on simulation applications is enormous; however, the number of innovative applications is much less. Most papers do not describe the details of the models. At most, a simplified description is provided in the context of actual applications. This situation arises because most of the simulation models are developed by private companies, being for most cases, proprietary materials. Among them it is worth mentioning the simulation systems developed by August Design, Inc., Liftech Consultants, Inc., and Vickerman, Zachary and Miller. Some of the traditional models are described by Frankel (1987).

After analyzing the different methodological options, the research team achieved the following conclusions:

a. QT formulations would be extremely complicated because priorities, at the user level, translate to a subdivision of the user population that significantly increases the number of states of the system. So far, most QT models that consider priorities deal with relatively simple problems. In addition, the big differences in the service times for the different ships make it difficult to justify the assumption of a homogeneous population of users that is required by QT.

b. simulation offers numerous advantages. It allows the explicit consideration of the geometry of the system and their interactions with the operational policy. Secondly, since it is not likely that the priority systems under consideration have been implemented in practice, there is no data with which to construct the empirical distributions needed in QT models. This is not a problem for simulation because the service time can be estimated by simulating the micro-movements of the equipment.

Thus, it was decided to use simulation as the performance analysis tool to model the different operational policies. Since the available simulation systems were not able to deal with different priority levels, it was decided to develop a new simulation system, PRIOR, which is described in the next section.

4 DESCRIPTION OF THE SYSTEM

The simulation system is comprised of two programs, PRIOR, which performs the simulation, and ECON, which calculates economic indicators of performance.

4.1 Description of PRIOR

The terminal is modelled using arrays to represent the storage location (on ship and in the yard) and networks to represent travel times for the different servers. Figure 1 shows a 3-D representation of the networks. The truck

network is represented using a directed network. The yard crane and gantry crane networks are represented using non-directed networks. The program has the capability of simulating stochastic travel times, though this option was not used in the simulations. PRIOR uses the following operating principles:

String of ships: At the beginning of the simulation run, the file containing ship description, arrival time, and the fractions of high and low-priority containers is read, and the corresponding ship arrivals are scheduled. When all gantry cranes are idle and the previous ship has already departed, the queue list is scanned to begin service for the next ship.

Beginning of service (ships): When this event is processed the containers are created and the corresponding retrieval events are scheduled.

Creation of containers: The simulation system allows the user to specify the characteristics of the containers to be created (i.e., the fractions of containers of each kind and dwelling times for high and low-priority containers and the location of high-priority containers on the ship). After the containers are created, the control of the program is transferred to the subroutine in charge of simulating the unloading process.

Lot assignment: After the containers on ship have been created, the lot assignment process takes place. By virtue of this process the ship hatches are assigned to specific destination lots on the storage yard.

Gantry crane operations: The subroutines in charge of simulating gantry crane operations estimate the corresponding service times according to different operational rules. The first subroutine simulates the base case, in which the containers are evenly unloaded from top to bottom, regardless of priority. The second one simulates the operational rules for cases in which the gantry crane operator unloads high-priority containers first. Low-priority containers are unloaded only after all high-priority containers have been unloaded.

Yard truck operations: It is assumed that the yard trucks serve all gantry cranes. Whenever a gantry

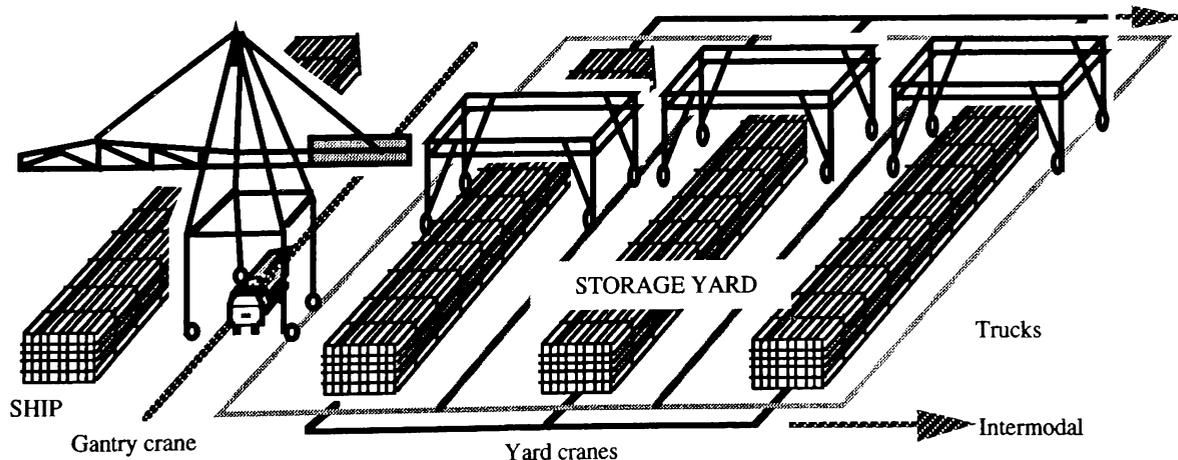


Figure 1: 3-D Representation of the Networks

crane needs a yard truck, the first yard truck of the pool of trucks moves over. When the container is loaded onto the truck, the end of service event is scheduled for the gantry crane and a beginning of service is scheduled for the truck. When processing a beginning of service event:

1. the simulation system determines the destination lot for the container.
2. a suitable slot is found in the corresponding yard lot. A suitable slot meets the following requirements: it is close to the current position of the corresponding yard crane (if present in the lot) and it is empty and not reserved for another container. When a suitable slot is found, it is reserved.
3. the links connecting the origin and destination nodes are updated to represent both the current truck location and the future container location. Then, the shortest paths are calculated from the origin node (current truck position) to the destination node (slot assigned to the container) and from the destination node to the node representing the pool of trucks. The travel times from origin to destination node will be used to schedule the arrivals at the storage yard, while the travel times from the destination node to the pool of trucks will be used to schedule the end of the truck's reposition.

Yard operations: Yard operations are quite complex because yard cranes interact with several processes. First, yard cranes are the last link of the unloading process. Secondly, they are a key component of the container retrieval process. Thirdly, they are in charge of reorganizing the storage yard. The current version of the simulation system includes only the first two roles of yard cranes.

The operational rules are the following:

1. unloading has a higher priority than container retrieval. External trucks arriving to retrieve containers are served only after all yard trucks (loaded with containers unloaded from the ship) are served.
2. service is non-preemptive. If a yard truck needs to be unloaded while the yard crane is serving an external truck, the yard truck waits until the yard crane finishes serving the external truck.
3. matching is performed to guarantee that both truck (external or yard truck) and yard crane are assigned to the same container.

Yard crane allocation rules: Two yard crane allocation rules are considered, static and dynamic. Static allocation refers to the case in which the list of lots served by a yard crane does not change over the simulation. In this case, a crane having an extremely long queue will not be helped by idle yard cranes. In the dynamic allocation scheme, idle yard cranes collaborate in tackling the longest queue. Helping yard cranes are assigned to help a needy yard crane (the one with the longest queue) provided that the queue of the needy yard crane exceeds a given threshold, and the helping yard crane is idle. In this scheme, the allocation is re-assessed at a fixed time interval specified by the user. Since

dynamic allocation produces more realistic results, it is used in all runs of the simulation system.

Gate operations (in): When an external truck arrives to retrieve a specific container, the external truck is assigned to a gate. If no gate is available, the truck is placed in a queue list. After processing the truck at the gate, it is necessary to determine if the container is already in its corresponding slot at the storage yard. If the container is in its slot, a beginning of service event is scheduled for the external truck and a request is sent to the corresponding yard crane to retrieve the container. Otherwise, the truck is placed in a queue list to wait for the corresponding yard crane.

First movement of retrieval (gate to yard): When the beginning of service event is processed, the computer system checks the container's availability. If available, the shortest paths from the gate to the storage yard and from the storage yard to the gate are calculated. The arrival at the yard is scheduled using the travel time from the gate to the storage yard. If the container is not available, the truck is placed in a queue list.

Match: Since the yard cranes are assigned to specific lots, trucks must be matched to the corresponding yard crane. Matching requires determining the identification number of the target container, which yard crane is assigned to the container lot and which truck is delivering or retrieving the target container. After both truck and yard crane are identified, it is necessary to determine their status. If one of the servers is busy or repositioning, the other server waits. By matching servers, the system is able to provide a realistic representation of port operations and it also provides useful cross-statistics, e.g., mean waiting times for yard cranes waiting for trucks and vice versa.

Container retrieval at the storage yard: Once the yard crane has been assigned to retrieve a particular container, the system simulates all necessary processes. If the yard crane is not located in the corresponding lot, a reposition event is scheduled. If the target container is obstructed by other containers, the system simulates the clearing process. Finally, the target container is loaded on the truck (after proper matching).

Second movement of retrieval (yard to gate): After the yard crane is released, the beginning of service for the movement to the gate is scheduled. The travel time (previously determined using shortest path) is used to schedule the arrival at the gate.

Gate operations (out): Upon arrival at the gate, the trucks are assigned to the different gates. If no gate is available, the truck is placed in a queue list. Otherwise the service time is estimated and departure is scheduled.

PRIOR has a hierarchy structure. The system was written in FORTRAN and is comprised of more than 16,000 instructions and more than 150 different subroutines. PRIOR is based on the next event approach. Figures 2 and 3 show some examples of subroutines at different levels of the hierarchy. The majority of the second level subroutines are in charge of processing the

different events, transferring control to the corresponding third level subroutine. The subroutines called by the subroutine in charge of processing beginning of service, for instance, estimate service times for the different service stages.

The simulation system reads the variables and parameters controlling the run from an ASCII control file. The control file is comprised of five different sections. The first section provides the program with the parameters that specify the operational policy. The second section contains the global control parameters. The third and fourth sections focus on the specification of input and output files. The fifth section contains the parameters that specify the printing interval. In its current version, fifteen different input files provide the program with the detailed information the program needs. Since most of the file's contents are self-explanatory only a brief description will be provided here.

The first file contains the ship characteristics (e.g., maximum number of containers, maximum number of containers per hatch and number of containers on deck, and the geometric information about the gantry cranes). The second file contains the characteristics of the incoming ships. The third file specifies the geometric characteristics of the storage yard. The information provided by this file is used to calculate link lengths and link travel times associated with truck and yard crane networks. The fourth file contains the list of high priority lots. The fifth and sixth file provide the morphology of truck and yard crane network, respectively. The seventh file contains the structure of the simulation network (i.e., the server's identification number, the stage to which the server belongs and the type of operation). The eighth and ninth files contain the characteristics of gantry and yard cranes respectively (e.g., job assignment, initial location of cranes). The tenth file provides the initial configuration of the storage yard, i.e., number of containers stacked at each spot. The eleventh file specifies the memory locations in which the simulation statistics and the queue list will be collected

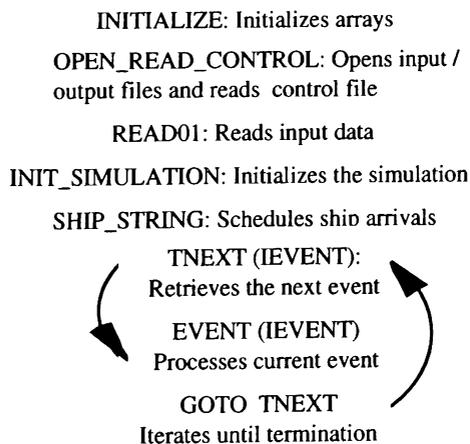


Figure 2: First Level of Subroutines (called by main program)

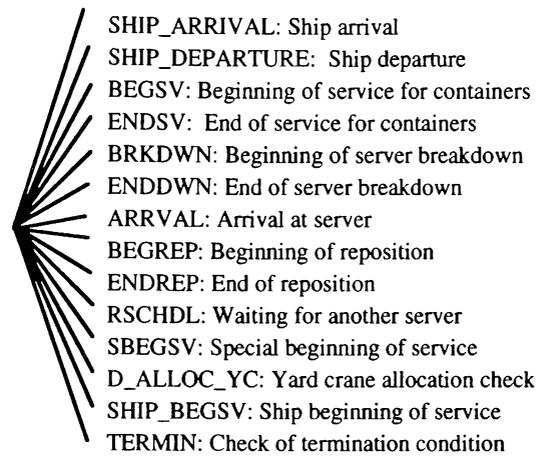


Figure 3: Examples of Second Level Subroutines

and maintained. The last three files provide the titles and headers that will be used in the printout.

The specification of the simulation output requires two sets of variables, file names and print codes. Output file names must be specified according to user's needs to avoid overwriting old outputs. Print codes specify whether or not the output file will be generated and its format. Additional parameters help to keep the output size to a manageable size, e.g., lower and upper bounds to the simulation clock.

4.2 Description of ECON

ECON is in charge of post-processing the PRIOR's output to produce economic indicators of performance. This section focuses on providing a brief description of the operational principles ECON uses.

It is important to highlight that ECON does not take into consideration the influence of labour agreements on operational costs. Instead, ECON considers exclusively the direct cost of equipment and labour. The reasons to make this decision are two-fold. First, although considering labour agreements may lead to potentially more realistic results, considering them may masquerade the relative advantage of different operational systems. For instance, it is common practice to pay the stevedors for the full shift, even if the work is finished in half an hour after the beginning. From this real-life perspective, there is no difference between an operational system that requires the gang to work for the full shift and another more efficient system in which the same job only takes half an hour. Thus, the costs estimated by ECON must be interpreted as estimates of economic costs. Second, since labour agreements vary significantly from terminal to terminal, considering labour agreements on cost calculations would impede the generalization of the conclusions of this research.

The following paragraphs provide brief descriptions of the elements considered in the cost calculations. Costs

are calculated for the different types of equipment, namely, ship, gantry cranes, yard cranes, gates (in and out), and external trucks (in and out). Additionally, costs are broken down by server status, namely, idle, busy, repositioning, waiting for another server.

Ship costs: The ship costs are comprised of the fixed cost of the ship, plus the direct cost associated with the service. The latter component was calculated by assuming that two longshoremen and two lashers are required for each gantry crane, plus one lash leader. The service and the waiting time for the ship, in conjunction with the unit ship costs and unit service costs, are used to calculate the total unit cost per container.

Gantry cranes, yard trucks, yard cranes, external trucks and gates: Using the output of the simulation system, the time the servers spend in each status is determined. The corresponding total costs are calculated by using the unit costs of operating the server (equipment + labour). Then, the unit costs for each status are calculated by dividing total costs by the output, measured in containers.

The computational structure of ECON is relatively simple. The main program initializes the arrays and reads the file containing the information about unit costs. The unit costs are stored and the input file produced by PRIOR is read, beginning with high priority containers. The data is transferred to the subroutine that calculates the operating costs. The process is repeated for low priority containers. Then the output file containing operating costs for both priorities is printed. The process is repeated for all observations. ECON uses two input files. The first one is the output of the simulation provided by PRIOR and the second is the control file containing economic information about equipment and labour costs. The unit costs for labour and equipment were taken from "Assessment of Cargo Handling Technology" (PRC Inc., 1993). The output of ECON consist of two files containing detailed costs and a summary of results, respectively.

5 CALIBRATION OF THE SIMULATION SYSTEM

The calibration of the simulation system required the use of two different approaches (i.e., combined models and empirical distributions). "Combined models" refer to models that have a systematic and a random component. The systematic component expresses service time as a function of task's characteristics, while the random component represents random noise, i.e., the non-explained component. This approach was used to model gantry crane operations, yard crane operations and yard crane movements. On the other hand, traditional empirical distributions were used in the cases in which the characteristics of the service process were not suitable for analytical modelling, e.g., yard gate operation.

The parameters of the systematic component of the service time were estimated using multiple regression. After choosing the final models, the residuals were analyzed to determine which statistical distribution can be used to describe them. In the simulation system, both components (i.e., systematic and random) are used to estimate the service time. The task's characteristics (e.g., distance travelled, type of container) are inputs to the systematic component. The statistical distributions representing the random component of the service times are used to generate random numbers that are added to the systematic component to obtain the service time. The service time models described in this section focus on the following processes: (a) yard crane service times; (b) yard crane movements; and (c) gantry crane service time. The data set was obtained from video tapes taken at the container terminals in the Port of Houston.

5.1 Yard crane operations

This model provides estimates of the service times of yard cranes. The final model is:

$$\begin{aligned} \text{Time} = & 4.42D_{hyp} + 27.38Picking - 28.87Empty & (1) \\ & (5.652) \quad (3.777) \quad (-4.278) \\ \text{Adjusted } R^2 = & 0.322 \end{aligned}$$

(t-statistics in parentheses),

Where:

Time: time to move the spreader (in seconds);

D_{hyp} : hypotenuse of the triangle formed by the vertical and horizontal distances travelled by the spreader (in ms);

Empty: equal to 1 if spreader is empty, otherwise 0

Picking: equal to 1 if picking up container, otherwise 0

5.2 Yard crane movements

This model estimates the time required by the yard crane to move from one container lot to another. The variables used were the following:

Time: travel time (in seconds);

Distance: total distance travelled (in ms);

Stop: equal to 1 if the crane stops, otherwise 0;

Turning: equal to 1 if turning, otherwise 0

The final model is:

$$\begin{aligned} \text{Time} = & 0.61Distance + 19.97Stop + 133.22Turning & (2) \\ & (9.929) \quad (4.490) \quad (15.779) \\ \text{Adjusted } R^2 = & 0.930 \end{aligned}$$

5.3 Gantry crane operations

The gantry crane operation model estimates the gantry crane's service time. The variables used are:

Time: time required to move the spreader (in seconds);
 Dx: horizontal distance of the movement (in ms)
 Dy: vertical distance of the movement (in ms);
 Empty: equal to 1 if spreader is empty, otherwise 0;
 On deck: equal to 1 if container is on deck, otherwise 0
 The final models is:

$$\frac{Time}{Dx} = 0.23 + 1.72 \frac{Dy}{Dx} - 10.76 \frac{Empty}{Dx} + 7.41 \frac{OnDeck}{Dx} \quad (3)$$

(25.734) (7.165) (3.488)

Adjusted R² = 0.856

For a comparison between the observed average service time per layer and the average service time per layer calculated by the model the reader is referred to Holguín-Veras and Walton (1995d).

6 APPLICATION

PRIOR was used to assess the performance of a set of priority systems (PS) that differ in the degree in which service differentiation was implemented. Service differentiation can be implemented in different ways: (a) locating high priority containers (HPC) on special hatches, (b) at the storage yard i.e., storing HPC on chassis, and (c) at the gates. Table 1 shows the different systems.

Table 1: Description of Operational Policies

	Location of HPCs	Yard crane operations	Yard gate operations
Base case	Random	No priority service	No priority service
PS-I	Hot hatches	No priority service	No priority service
PS-II	Random	HPC are wheeled	No priority service
PS-III	Random	No priority service	Priority service
PS-IV (I + II)	Hot hatches	HPC are wheeled	No priority service
PS-V (I+II+III)	Hot hatches	HPC are wheeled	Priority service

PRIOR and ECON were used to assess the performance of each of these systems under various combinations of demand and percentage of high priority containers. The output of the system was translated to a multi-criteria decision matrix including: total service time at unloading and at retrieval, probability of non-compliance and operating costs (for both priorities).

Using this decision matrix in conjunction with a multicriteria decision model, the range of applicability of the aforementioned systems was determined. The reader is referred to Holguín-Veras and Walton (1996b) for more details. Table 2 shows the range of values of the multi-criteria model for which each of the systems is the

preferred option. In Table 2 only the decision criteria associated to high priority containers are shown.

Table 2: Range of Applicability

Operational system	Time at unloading	Time at retrieval	Non-compliance	Total cost
	Base case	0	0	0/+
PS-III	0	0	0	0/+
PS-I	0	0	+	0
PS-II	0	0/+++	0/++	0/+
PS-IV	0/++++	0/++	0/++++	0/+
PS-V	0/++++	0/++++	0/++++	0/++++

Where:

- 0: No importance
- +: Weak importance
- ++: Essential importance
- +++ : Very strong importance
- ++++: Absolute importance

As can be seen, for the level of demand examined in this research, the base case would be the preferred option if the level of service associated with priority systems is of no importance to the decision maker. Similarly, PS-III would be the preferred option if operating costs for high priority containers are of weak importance. Systems that articulate service differentiation at different stages (PS-IV and PS-V) are the preferred options only if all the performance indicators associated with priority systems are of considerable importance to the decision maker.

7 CONCLUSIONS AND FURTHER RESEARCH

The simulation system proved to be an invaluable decision aid that provided the information needed to assess the range of applicability of priority systems. Although in its current version PRIOR is a research tool, its potential as a decision aid could be enhanced if other features are added. Among them, the developers would like to incorporate animation capabilities that would facilitate the interpretation of the output.

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