Time-Motion Analysis of Wharf Crane Operations

MAX K. KIESLING AND C. MICHAEL WALTON

Numerous queueing models are available that are appropriate for modeling wharf crane operations. When used correctly, the models provide an excellent way to assess the efficiency of container port operations. The majority of queueing theory applications assume that exponential distributions adequately describe the service and arrival processes, primarily because of the tractable solutions that result. Regardless of the assumption's simplifying effect, its suitability should be questioned before applying it to any analysis. The appropriateness of the exponential distribution for analyzing service, interarrival, and backcycle processes at container port wharf cranes is determined, and suitable distributions should the exponential distribution prove inappropriate are investigated. Interarrival and service times were recorded for all tractors servicing wharf cranes for a total of more than 30 hr at two United States ports. The formation of the data set used for the analysis, the testing procedure used to determine the most appropriate distribution, and the results of the analysis are described. It is shown that service times, interarrival times, and backcycle times used in queueing analysis should not always be modeled as exponential distributions, contrary to popular belief.

In today's competitive freight industry, where speed is required or at least desired, the ability to efficiently move freight can control how successful ports, freight forwarders, and shippers are in business. Since total transport time can be substantially increased by a breakdown in a single link, each leg of the journey must operate efficiently to ensure expeditious freight transportation. This becomes increasingly difficult in intermodal transportation where freight travels through any number of freight terminals—the primary source of excessive delays. Since terminals are the only segment of a journey in which freight is not moving toward its destination, the time spent in the terminal can make or break an efficient journey. Unfortunately, container ports are more often than not the source of long delays relative to total transport time.

Simply stated, container ports are critical interfaces in the efficient movement of international containerized freight from the viewpoint of both the customer and the shipper. A manifestation of this demand for speed is an increase in the research on container port operations, the primary goal of which is to develop and implement techniques to streamline operations and improve efficiency. In 1990, researchers at the University of Texas at Austin embarked on a series of such studies. This paper focuses on one component of these studies.

Much of the research at the University of Texas relied heavily on queueing theory to evaluate operations surrounding the wharf crane. Kiesling (*1*) analyzed wharf crane productivity at two major container ports in a three-step process. First, several statistically significant factors affecting wharf crane productivity were identified. Second, several queueing models were applied to the loading and unloading cycle associated with wharf cranes and storage yards. Third, computer simulations were developed to determine the benefits of modifying operations. This paper deals primarily with step two of the research effort and provides insight into arrival and service processes associated with wharf crane operations. Ultimately, this enables researchers to more accurately specify queueing models commonly used in analyses of port operations. This, in turn, leads to improvements in the management of container port operations by specifying improved wharf crane service configurations (such as specifying optimal number of tractors in system and their service protocol toward wharf cranes).

Most queueing theory applications are built on the assumption that exponential distributions correctly describe the service and arrival processes of the system. One reason for the exponential assumption is that the resulting models are mathematically tractable and typically result in closed-form solutions for single server and cyclic queues. Regardless of the exponential distribution's elegance, its suitability in any queueing application should be validated. (To the authors' knowledge, there have been no published works validating the assumption of exponential arrival and service processes of tractors at the wharf crane.)

Existing wharf crane performance studies generally assume exponential interarrival and service time distributions without validation. The objective of this paper is to assess the validity of that assumption. The most effective way to assess the suitability is through a time-motion study of the service facility in question. If the assumption is not suitable, it is necessary to determine what distributions can be used to accurately describe the system. Knowing this will improve the accuracy of container port operational models. In turn, it will be possible to more accurately specify the number of cranes and tractors and an operational configuration that maximizes the efficiency of ship loading and unloading.

Toward the goal of specifying correct distributions, arrival and service times were recorded for all tractors servicing wharf cranes at two major United States container ports. For anonymity, the ports will be referred to as Port 1 and Port 2, and ships will be assigned letter names (A-G). The remainder of this report documents the data collection procedure, the analysis of the data, and the conclusions that can be drawn from the analysis.

M. K. Kiesling, Department of Civil Engineering, University of California, 107A McLaughlin Hall, Berkeley, Calif. 94720. C. M. Walton, Department of Civil Engineering, University of Texas, Ernest Cockrell, Jr., Hall, Room 4.2, Austin, Tex. 78712.

EXPERIMENTAL ENVIRONMENT

Loading and unloading procedures at most container ports are conceptually similar. While unloading a containership, a cycle is formed that involves a tractor and chassis accepting a container from a wharf crane, carrying it to the storage yard where it is removed and stacked, and returning to the wharf crane where another container is received. (In the event that containers are stored in the yard on the chassis, a bobtailed tractor picks up another chassis before returning to the wharf crane.) This cycle is reversed for the loading of a containership. In general, six or seven tractors serve one wharf crane during this process. Atkins (*2*) provides an excellent description of the containership loading/unloading process.

Three elements of the cyclic queue are examined in this paper: the service process, the arrival process, and the total cycle of tractors. At the container port, the service facility is the wharf crane, and customers are the tractors serving the crane. The service provided by the single server facility is the removal of a container from the chassis of the tractor or the placement of a container onto the chassis. The service time is defined as the difference between service completions of succeeding tractors. Thus, the first tractor in queue (if a queue is present) begins service immediately after the preceding tractor completes service. The service time includes the move-up time [see Carmichael (*3*)]. Similarly, the interarrival time is the time between consecutive arrivals of tractors into a queue or at the wharf crane if no queue exists. The backcycle time is the time to complete a full cycle through the storage yard (in other words, the difference between the departure from the service facility and the arrival at the crane or queue). To identify the correct time distribution, we record the service, interarrival, and backcycle times for a large number of tractors. Given a sample of such measurements, we then test what theoretical distribution best describes the empirical distribution. This process is described in the following sections.

CREATION OF THE DATA SET AND INITIAL DATA ANALYSIS

Data for this research effort were collected at two United States container ports. Four different operating entities were represented. Two ports are privately operated and two are publicly operated. Two of the ports use chassis storage as opposed to container stacking. In each case, wharf cranes were rail-mounted, single-pick cranes with adjustable spreader bars and adequate clearance to move 48-ft containers. Yard cranes were rubber-tired cranes with clearance for stacking containers four deep and up to five container widths, or top-pick loaders capable of stacking containers three deep. The type of yard crane associated with each data file is identified later in this report.

The time-motion experiment was based on the coded events described in Table 1. The code "999" was included in the list to permit recording any nonstandard tractor or crane operations, including tractors balking from queues, hatch cover removals, lashing, movement between bays, and spreader adjustments. Such nonstandard operations were noted in the field through the use of microcassette recorders and later corrected in the actual data files. The tractor number was also recorded to permit tracking gang members through the cycle.

The exact time of events was recorded with programmable Hewlett-Packard calculators. A simple program prompted first for the tractor or crane number, then for a predefined event code. Event times were recorded to the nearest second, more accuracy than necessary since tractors and cranes often "inch" forward at the beginning or end of an event. Data were then uploaded to desktop computers and immediately transferred to spreadsheets, minimizing the potential for human error. Multiple port visits resulted in a total of 16 data files. Each filename identifies the date and time of day it was created (e.g., Feb11a.1, the first file created on February 11 in the morning). Data files created in March are associated with top-

TABLE 1 Data File Code Description

Code	Description of Event
1	Tractor enters queue. (wheels of tractor stop rotating)
2	Tractor completes move-up procedure. (wheels of tractor stop rotating)
3	Tractor departs service. (wheels of tractor begin rotating)
3.1	Placement of first container during double container moves. (tractor remains in service position)
3.2	Service completion of double container move. (wheels of tractor begin rotating)
4	Beginning of crane movement from one bay to another. (wheels begin rotating)
5	Completion of crane movement from one bay to another. (wheels stop rotating)
6.0 (6.1)	Beginning of crane idle period with zero (one) container.
7.0 (7.1)	End of crane idle period with zero (one) container.
8	A tractor that was in queue, balks.
999	Special event or comment about crane or tractor operations.

pick loaders operating in the storage yard. Table 2 provides a sample of the Jan7p.1 data file.

The 16 data files represent 31 hr 10 min of data collection. The individual data files cover time periods ranging from only 30 consecutive min to more than 5 hr. Short observation periods were caused by service interruptions such as lashing/unlashing, hatch cover removal, crane movements, mechanical failure, equipment changes, or other unexpected operational problems. Table 3 summarizes the results of the data collection effort. Seven ships are represented in the 16 data files, all of which are cellularized vessels. The crane productivity averaged 28.6 container moves per hour with a standard deviation of 6.1 moves per hour. Maximum productivity achieved was 37.1 moves per hour for the observation period of 1 hr 20 min, a substantial period of time to maintain exceptionally high productivity. Minimum productivity was only 13.3 moves per hour over a span of 1 hr 7 min. This includes at least one significant delay, which deflates the reported crane productivity (the same crane provided the fastest average service time of 40 sec/tractor).

There is a high variance of service, backcycle, and interarrival times between and within individual files. Reasons for this are as follows. First, the stowage location of the container on the ship significantly affects how quickly a container can be placed or removed. Restows on the ship can also inflate average service times. Other factors that delay service times have already been discussed. Backcycle times are controlled primarily by the distance from the ship to the yard storage location and the speed at which the container can be transferred in the yard. This will vary between ships, as well as throughout the ships' loading/unloading plan. Thus, if yard delivery locations change within the time frame of a data file, the backcycle times will also change, increasing its variance. Ideally, then, there should be more than one distribution assigned to describe backcycle times throughout the loading/unloading process. The same argument applies to service and interarrival times. It may seem most appropriate to specify several different distributions for service, interarrival, and backcycle times to describe various stages of the loading/unloading process. The result would be the ability to optimize the number of tractors in a gang for each phase in the loading/unloading process. Obviously, decisions are not made this way in practice—the same number of gang members serve a crane from start to finish. To coincide with this practice, we will focus on specifying a single distribution for service, interarrival, and backcycle times through the duration of servicing a ship. In other words, we will not try to specify different distributions for the movement of containers only on top of the hatch covers, or being delivered to one part of the storage yard. The process of testing and specifying various time distributions is presented in the following sections.

TABLE 2 Field Data Extracted from Jan7.pl Data File

Event	Tractor	HH:MM:SS	Queue	Interarrival Time	Service Time
no event	no event	14:05:14	1		
2	921	14:05:43	0	0:00	
1	952	14:08:26	1	4:51	
1	922	14:09:21	2	0:56	
3	921	14:11:25	2	0:00	5:41
2	953	14:11:46	1	0:00	
1	950	14:12:25	2	3:04	
3	953	14:13:35	2	0:00	2:10
2	952	14:14:03	1	0:00	

ERLANG DISTRIBUTION

When the exponential distribution's validity is questioned, a common alternative to consider is the Erlang distribution. The Erlang distribution is very flexible and, depending on the selection of parameters, transforms into the exponential, normal, and constant distributions, as well as many distributions "in between" [see Winston (4)]. The density of the Erlang distribution is specified by two parameters: a rate parameter R and a positive shape parameter k. The rate parameter is the inverse of the mean of the sample under consideration. The Erlang probability density function is

$$f(t) = \frac{R(Rt)^{k-1}e^{-Rt}}{(k-1)!} \quad (1)$$

where $E(T) = k/R$ and $\text{var}(T) = k/R^2$.

Inspection of the Erlang probability density function (pdf) reveals that when $k = 1$, the Erlang reduces to the exponential density. As the shape parameter k increases, the variance of

TABLE 3 Initial Data Analysis

File	Moves per hr	Service Times # Obs	Mean	St Dev	Interarrival Times # Obs	Mean	St Dev	Backcycle Times # Obs	Mean	St Dev
Jan7p.1	26.2	60	1:40	1:20	59	2:36	2:05	50	12:39	8:57
Jan7p.2	28.7	37	1:17	1:11	39	2:05	1:49	26	11:13	3:23
Feb11a.1	30.5	41	1:44	0:42	44	1:50	1:05	34	5:13	1:43
Feb11a.2	27.9	37	1:09	0:45	38	2:10	1:40	21	9:34	10:26
Feb11p.1	28.0	74	1:40	1:31	74	2:37	2:21	62	12:02	7:58
Feb12a.1	23.8	27	1:23	1:22	29	2:35	2:09	6	16:36	2:47
Feb12a.2	13.25	15	0:40	0:25	16	3:53	5:44	11	17:49	11:35
Feb12a.3	36.3	22	1:40	0:34	22	1:36	1:12	16	6:22	1:22
Feb12p.1	33.3	53	1:33	1:03	48	1:51	2:27	39	6:35	1:35
Mar7p.1	36.2	30	0:48	0:21	27	1:49	2:02	17	9:24	6:21
Mar7p.2	37.1	47	1:00	0:26	43	1:49	2:45	43	5:00	2:58
Mar8a.1	24.1	25	1:32	0:41	21	2:03	1:36	21	8:09	4:51
Mar8a.2	33.2	17	1:50	0:49	14	2:00	1:09	14	3:44	0:30
Mar8p.1	24.1	61	1:25	1:02	65	2:19	2:41	47	6:27	4:46
Mar9p.1	25.1	118	2:09	1:22	97	2:15	1:44	89	6:31	2:04
Mar9p.2	29.7	128	1:36	1:12	136	1:57	1:54	133	7:20	4:48

the pdf decreases, causing the density to behave more like a normal density function. For extremely large values of k, the Erlang density approaches a constant density (zero variance).

The shape parameter of the Erlang distribution has a powerful yet simple interpretation. Consider a process that is described by an Erlang distribution with parameter k. The process is actually composed of k exponential service phases that occur in series. Each of the k phases follows independent and identically distributed exponential random variables, each with a mean of $(1/\mu k)$, where μ is the mean service rate. Only one customer at a time is allowed in the system of phases, and each customer must complete all k phases of the system.

TESTING METHODOLOGIES AND DISTRIBUTION TEST RESULTS

The individual data files were tested two ways. Initially, the chi-square test was used to determine whether the exponential distribution was appropriate. Initial analyses indicated that this was seldom the case. The Kolmogorov-Smirnov (K-S) statistical test was used extensively to further test the distributions. The K-S test has several inherent advantages over the commonly used chi-square test for this application, including the ability to compare theoretical and empirical data by considering cumulative distributions instead of categorized data. In the remainder of this paper, the null hypothesis is that data were drawn from the tested distribution. The test is executed by comparing cumulative distribution functions of theoretical and sample distributions. The test statistic, D, is the maximum absolute difference between the two distributions. If the difference between the cumulative distributions is greater than that allowed by the test statistic, the null hypothesis is rejected.

Although the primary objective of the tests is to specify the distribution that best describes the service, interarrival, and backcycle times, other events were tested. For example, whenever double moves were captured within a data file, tests were performed on single, double, and combined service and interarrival times. Also, if two or more data files were created for the same ship, the tallied service and interarrival times were combined and the tests performed again on the new data file.

The test results are presented in Tables 4, 5, and 6, representing service times, interarrival times, and backcycle times, respectively. Each table represents statistical tests for a significance level of $\alpha = 0.05$. Note that the majority of the files tested allow several possible distributions. The best-fit distribution is considered the distribution with the smallest maximum deviation. However, the null hypotheses that the exponential, E(3), and E(4) distributions are the same as the sample distribution cannot be rejected at the $\alpha = 0.05$ significance level. Erlang distributions with shape parameters greater than seven were not considered. Such distributions become extremely laborious to analyze. If there is reason to believe that a distribution should be described by shape parameters higher than seven, a secondary shape parameter estimation procedure exists. Carmichael (*3*) illustrates the simple derivation leading to the following estimation for k:

$$k = (\text{mean})^2/(\text{stdev})^2 \tag{2}$$

TABLE 4 Service Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.175	0.144	**0.070**	0.136	0.177	0.207	0.236	0.260
Jan7p.2	0.218	0.164	0.158	**0.149**	0.176	0.205	0.2300	0.251
Feb11a.1	0.212	0.344	0.242	0.195	0.161	0.151	0.143	**0.135**
Feb11a.2	0.218	0.228	0.154	0.134	**0.120**	0.146	0.174	0.196
Feb11p.1	0.158	0.165	**0.114**	0.116	0.147	0.171	0.192	0.206
Feb12a.1	0.254	0.198	**0.178**	0.190	0.234	0.268	0.297	0.321
Feb12a.2	0.338	0.262	**0.152**	0.188	0.222	0.250	0.274	0.295
Feb12a.3	0.251	0.458	0.362	0.305	0.262	0.229	0.202	**0.198**
Feb12p.1	0.186	0.352	0.245	0.236	0.234	0.230	0.227	0.222
Mar7p.1	0.242	0.264	0.198	0.166	0.143	0.126	**0.116**	0.130
Mar7p.2	0.198	0.339	0.252	0.201	0.164	0.134	0.108	**0.087**
Mar8a.1	0.264	0.300	0.168	**0.094**	0.095	0.099	0.105	0.111
Mar8a.2	0.318	0.427	0.325	0.263	0.218	0.183	0.169	**0.165**
Mar8p.1	0.174	0.154	**0.070**	0.119	0.156	0.187	0.214	0.236
Mar9p.1-single	0.132	0.379	0.254	0.181	0.191	0.203	0.214	0.222
Mar9p.1-double	0.361	0.437	0.346	0.293	0.263	0.238	0.218	**0.200**
Mar9p.1-all	0.125	0.364	0.234	0.161	0.159	0.176	0.191	0.205
Mar9p.2-single	0.136	0.211	**0.107**	0.129	0.149	0.171	0.191	0.208
Mar9p.2-double	0.246	0.398	0.279	0.208	0.160	0.124	**0.114**	0.125
Mar9p.2-all	0.120	0.175	**0.078**	0.134	0.176	0.211	0.240	0.264
Ship A	0.138	0.169	0.165	0.218	0.258	0.289	0.315	0.338
Ship B	0.109	0.187	0.132	0.129	0.124	0.134	0.152	0.166
Ship C	0.217	0.214	**0.121**	0.184	0.232	0.268	0.297	0.321
Ship D	0.154	0.358	0.247	0.204	0.189	0.175	0.162	**0.151**
Ship E	0.154	0.280	0.157	0.086	0.063	**0.059**	0.080	0.104
Ship F	0.132	0.154	0.161	0.198	0.226	0.251	0.280	0.304
Ship G	0.093	0.245	0.106	0.101	0.111	0.125	0.138	0.162

* Boxes identify the minimum deviation between the theoretical and sample distributions.

TABLE 5 Interarrival Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.177	0.089	0.100	0.173	0.222	0.256	0.282	0.301
Jan7p.2	0.213	0.110	0.100	0.148	0.196	0.231	0.258	0.278
Feb11a.1	0.205	0.238	0.116	0.074	0.118	0.152	0.181	0.205
Feb11a.2	0.215	0.156	0.118	0.118	0.154	0.175	0.191	0.204
Feb11p.1	0.158	0.144	0.111	0.134	0.181	0.216	0.242	0.264
Feb12a.1	0.246	0.126	0.125	0.158	0.192	0.222	0.249	0.272
Feb12a.2	0.327	0.281	0.355	0.403	0.439	0.467	0.491	0.512
Feb12a.3	0.281	0.147	0.088	0.152	0.198	0.234	0.263	0.287
Feb12p.1	0.196	0.097	0.116	0.183	0.226	0.254	0.272	0.290
Mar7p.1	0.254	0.156	0.200	0.246	0.288	0.323	0.352	0.376
Mar7p.2	0.207	0.243	0.278	0.292	0.335	0.371	0.400	0.424
Mar8a.1	0.287	0.172	0.117	0.133	0.160	0.195	0.224	0.248
Mar8a.2	0.349	0.188	0.117	0.128	0.138	0.141	0.158	0.180
Mar8p.1	0.168	0.092	0.127	0.201	0.248	0.280	0.303	0.322
Mar9p.1-single	0.152	0.128	0.085	0.119	0.154	0.181	0.204	0.227
Mar9p.1-double	0.318	0.064	0.174	0.232	0.261	0.296	0.325	0.348
Mar9p.1-all	0.138	0.109	0.074	0.134	0.173	0.206	0.232	0.252
Mar9p.2-single	0.130	0.052	0.112	0.179	0.218	0.254	0.282	0.304
Mar9p.2-double	0.250	0.180	0.195	0.232	0.258	0.271	0.286	0.307
Mar9p.2-all	0.116	0.055	0.126	0.189	0.225	0.252	0.280	0.301
Ship A	0.137	0.088	0.095	0.155	0.199	0.233	0.262	0.285
Ship B	0.108	0.155	0.089	0.095	0.144	0.179	0.208	0.231
Ship C	0.202	0.158	0.145	0.165	0.213	0.249	0.278	0.302
Ship D	0.162	0.092	0.091	0.149	0.198	0.234	0.262	0.284
Ship E	0.162	0.176	0.208	0.248	0.295	0.332	0.361	0.384
Ship F	0.136	0.105	0.070	0.143	0.192	0.226	0.252	0.271
Ship G	0.099	0.081	0.084	0.149	0.185	0.214	0.242	0.265

* Boxes identify the minimum deviation between the theoretical and sample distributions.

TABLE 6 Backcycle Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.192	0.208	0.118	0.157	0.185	0.207	0.229	0.243
Jan7p.2	0.259	0.358	0.266	0.210	0.169	0.137	0.109	0.104
Feb11a.1	0.227	0.412	0.305	0.244	0.200	0.165	0.144	0.156
Feb11a.2	0.287	0.232	0.339	0.408	0.456	0.492	0.521	0.544
Feb11p.1	0.172	0.284	0.151	0.158	0.159	0.160	0.189	0.212
Feb12a.1			no test					
Feb12a.2			no test					
Feb12a.3	0.327	0.232	0.339	0.408	0.456	0.492	0.521	0.544
Feb12p.1	0.213	0.426	0.331	0.273	0.231	0.197	0.169	0.146
Mar7p.1	0.318	0.211	0.133	0.201	0.249	0.285	0.314	0.338
Mar7p.2	0.207	0.386	0.261	0.227	0.259	0.285	0.308	0.328
Mar8a.1	0.287	0.250	0.110	0.145	0.193	0.226	0.251	0.270
Mar8a.2	0.349	0.473	0.394	0.348	0.313	0.286	0.263	0.243
Mar8p.1	0.198	0.236	0.106	0.108	0.130	0.166	0.194	0.216
Mar9p.1	0.144	0.447	0.343	0.280	0.235	0.200	0.173	0.162
Mar9p.2	0.117	0.379	0.258	0.187	0.190	0.200	0.208	0.217

* Boxes identify the minimum deviation between the theoretical and sample distributions.

There are two disadvantages to estimating the shape parameter in this fashion. First, there must be prior knowledge that the process can be described by the Erlang distribution. Second, when k is estimated by the mean and variance of the sample, it is more sensitive to outliers in the sample data file. The K-S methodology, on the other hand, is based on the cumulative distribution of the sample and is less sensitive to extreme values.

Service Time Distributions

Inspection of the service time distributions indicates that there is no consistency in the shape parameters of the Erlang distributions not rejected by the K-S test. Put another way, there is no indication that the service times at wharf cranes can be predicted or modeled as one distribution. This is verified by the fact that every single distribution was rejected by at least five of the data files. More specifically, the 16 original data files indicate that the E(1)–E(7) distributions were deemed most appropriate 0, 6, 2, 1, 0, 1, and 4 times, respectively. On two occasions, no distribution tested successfully.

Two of the four files that tested successfully as E(7) distributions represented the operations of ports using chassis storage systems. It was expected a priori that these operations would result in more efficient (lower variance) distributions because of the chassis storage system. On the basis of the observed data, this is the case. The reason is that yard crane operations are avoided, reducing the opportunity for delays in queue or yard crane maneuvering. This is not to say that backcycle times are necessarily shorter; they are merely more consistent for chassis storage systems.

The data files created at Port 2 (Mar9p.1 and Mar9p.2) were categorized into single and double moves to determine whether they follow different distributions. On the basis of the differences found in the Mar9p.2 distributions, this is the case, suggesting that single and double moves should be modeled separately. It was previously mentioned that several distributions test "acceptable" for each data file in addition to the actual best-fit distribution. Note, however, that 11 of the 16 data files indicate that the null hypothesis can be rejected, since the deviation for the exponential distribution is greater than the test statistic.

To determine whether specific ships followed specific service distributions, all data files associated with the same ship were combined and tested. The results indicate that of the seven ships represented (Ships A–G), only three tested successfully with E(2), E(7), and E(5) service time distributions. The premise that service times are not necessarily exponentially distributed is supported by these tests for two reasons. First, four of the seven ships did not test successfully with any of the seven distributions. Second, the ships that did successfully test (for any distribution) did not test as exponentially distributed service times.

The last test performed was on a data set that contained all service time observations. The test was inconclusive, because no distribution was accepted as statistically similar to the sample distribution. It is possible that a hyperexponential distribution would be applicable. However, the variability in the mean service times suggests that the service time is too general of a process to be modeled with only one distribution (i.e., it is very unlikely that a single distribution could be specified that accurately describes the service process for any ship).

The major conclusion that may be drawn from the service time distribution tests is that the process is not necessarily exponentially distributed as assumed in most studies. The test results indicate that more efficient distributions (high k) or very broad distributions [exponential or E(2)] are generally appropriate to model the process. It is likely that there is a relationship between the level of congestion in the port and the service time distribution, explaining the different "groups" of distributions. Because of the inadequacy of the data to accurately quantify the congestion (*1*, Chapter 3), it is not possible to explore this hypothesis in this study. The point remains, however, that the service times are often not accurately described by the exponential distribution.

Interarrival Time Distributions

Interarrival time distribution tests were performed for the same data files as the service time distributions. The results, however, were much more consistent for the interarrival time distributions. The E(1) distribution was selected seven times, the E(2) was selected seven times, and the E(3) distribution was selected twice. No other distributions accurately modeled the empirical interarrival time distribution.

All files that were tested for interarrival time distributions tested successfully, including the two data files that did not test successfully for the service times because of the presence of single and double moves. Even when the interarrival times for single and double moves were tested separately, the same distribution as the combined times was specified. In other words, single and double moves did not have the same effect on interarrival times that they did on service times. The trend that exponential interarrival times are more appropriate than exponential service times is supported by the fact that only two of the data files that were tested can reject the exponential distribution as statistically similar to the sample distribution.

The last data file tested for interarrival time distributions combined all individual files. The test was again inconclusive; no distribution was accepted as statistically similar to the combined sample distribution. The distribution tests on individual files indicate that exponential distribution of interarrival times is a much more solid assumption than exponential distribution of service times.

Backcycle Time Distributions

Backcycle time distributions appear to be less consistent than the interarrival distributions yet more consistent than the service time distributions. Specifically, each distribution tested successfully with the following frequencies: E(1) two times, E(2) five times, E(3) zero times, E(4) zero times, E(5) zero times, E(6) one time, E(7) three times, and no distribution three times. The actual test results are given in Table 4. (Only 14 data files are included in the test results because two data files had too few observations to produce strong results.)

The three unknown distributions correspond to the files Mar7p.2, Mar9p.1, and Mar9p.2. The first of the files represents stacking operations using top-pick loaders, and the last two files are associated with chassis storage operations. However, it does not appear that there is any correlation between container storage techniques and backcycle time distributions. Inspection of the test results of these three files indicates that the Mar7p.2 and Mar9p.2 files do not correspond to any of the Erlang distributions considered in the testing procedure. However, it appears that the Mar9p.1 data file is converging toward an acceptable Erlang distribution with a high shape parameter. The shape parameter is estimated as $k \approx 10.0$.

It is somewhat surprising that several data files tested successfully for distributions other than exponential or E(2). It was expected that the backcycle times would be consistently exponential or E(2) because of the wide range of mean backcycle times given in Table 1. This wide range verifies that the backcycle time is dependent on the operations within the storage yard. Specifically, if containers are being delivered to a point in the yard that is near the wharf crane, the mean backcycle time is expected to be considerably less. The variance of the backcycle time is also expected to decrease as the point of delivery in the storage yard draws nearer to the wharf crane. This would have the effect of increasing the shape parameter of the Erlang distribution.

Visual inspection of the test results does not indicate that such trends exist. The four data files that produced the highest-parameter Erlang distributions are associated with mean backcycle times ranging from the smallest to the third largest. Mar8a.2 resulted in an E(7) distribution and is associated with a mean backcycle time of only 3 min 44 sec. Jan7p.2 also resulted in an E(7) distribution but is associated with a mean backcycle time of 11 min 13 sec. This wide range suggests that there may not be a relationship between the Erlang shape parameter and the location of storage yard deliveries, contrary to prior expectations. Obviously, there is not enough information to quantify such relationships.

It is very difficult to make any assumptions or predictions about the backcycle time distributions. It appears that the best-fit distribution may be as file specific as the service time distributions. This makes it increasingly difficult to form general models that are applicable to more than one ship.

CRITICISM OF DATA COLLECTION EXPERIMENT

The actual process of collecting, processing, and testing field data for this experiment was successful. The required information was captured, and all test results are appropriate and significant. However, the experiment could be improved in several ways.

First, this data collection effort produced time-motion studies of cellularized vessels only. As yet, the implications of noncellular vessels for time distributions have not been quantified. We can safely assume that the mean service time is larger but cannot safely assume what distribution best describes any element of the process. The only way to quantify the effects is to repeat the data collection on noncellularized vessels.

Second, it is unfortunate that visibility, logistics, and safety concerns precluded the collection of data from yard cranes where container stacking is used. Such information could be used to further analyze the variability of backcycle time distributions. It would also open the door to further decompose the cyclic queue so that transit times could be analyzed as another stage in the cycle. The collection of data in the storage yard would also allow researchers to study the impact of various storage container techniques on operational efficiency.

Third, not all events that affect service, backcycle, and interarrival time distributions could be recorded in this time-motion analysis. It would have been beneficial to have information on where containers are located in the ship, exactly where containers are placed in the yard, the reason for all crane delays, and other miscellaneous operating characteristics. Having such information would have equipped us to analyze the data more effectively and quantify the effect of such information on time distributions. Similarly, if this type of data collection effort is repeated, an account of how far a container is stored from the wharf crane should be kept during the data collection effort. This could be as basic as counting the number of bays between the storage location and the ship. Such information would help explain the variability of the backcycle time distributions and may provide an explanation for the division in the service time distribution results.

Fourth, the data collection experiment is port specific. Conducting similar experiments at other ports could yield different results, since operating technologies and strategies differ at each port. Thus, the results presented in this paper should not be blindly assumed appropriate for all ports. To investigate this issue, similar studies should be conducted at numerous other ports.

These inadequacies do not render the experiment unsuccessful or unimportant. The experiment would benefit greatly from repetition at other ports and from having full cooperation from port operators in viewing activities and obtaining valuable documentation. However, valuable and reliable information was obtained that, to our knowledge, has not been collected in the past. The experiment successfully indicated that exponential distributions are not always appropriate to describe service times (and perhaps backcycle and interarrival times), contrary to popular belief. It also provides a framework for similar experiments at other ports.

SUMMARY

This paper outlined the collection of data describing the efficiency of operations at container port wharf cranes. The data collected constitute a time-motion study of the service, arrival, and cycling processes surrounding the wharf gantry crane. Kolmogorov-Smirnov tests were used as goodness-of-fit tests to determine which theoretical distributions can or cannot be used to describe individual samples of the time-motion study. The distributions considered in the testing procedure were the exponential distribution and the Erlang(2) through Erlang(7) distributions. The range of distributions was appropriate for the majority of the samples tested.

On the basis of the results of testing 16 individual data files, this research showed that the service and backcycle time distributions are the most difficult to predict. Most important, this research showed that the service time distribution at the wharf crane is not always exponential. The arrival process, on the other hand, appears to be properly represented by the Poisson distribution.

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