

AN INTEGRATED SIMULATION MODEL FOR CHANNEL CONTENTION AND BERTH MANAGEMENT AT A MARITIME CONTAINER TERMINAL

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KEYWORDS

Logistics, simulation and optimization, container terminals.

ABSTRACT

The extension and application of a queuing network model to the management of core logistic processes at the Gioia Tauro marine container terminal is presented. Real features incorporated in the model require simulation to solve it. A manager-friendly simulator is designed for the real case study, under the constraint of guaranteeing a finer representation of: the congestion phenomenon at the port channel; the port admission policy for newly arrived vessels in the roadstead; the management of berthing slots; the assignment of cranes for discharge/loading operations. The application software is presented through a detailed discussion of its features, as these appear on panel for system definition and analysis. The simulator computes point and interval estimates for system performance measures. Statistical computations are based upon the issue of batching elementary observations either within the same run or across multiple runs. Simulation experiments are presented and discussed with the aim of recommending a cost-effective method for interval estimates in quantitative scenario analysis.

INTRODUCTION

Logistics in modern container terminals and operations management problems are exhaustively discussed in recent survey papers as (Vis and de Koster 2003; Steenken et al. 2004) and the need for both optimization and simulation models is well recognized (Bruzzone et al. 1996b). Congestion phenomena are unavoidable when facing the allocation of shared resources to random arrivals of vessels and operations whose times are affected by several causes of randomness. A basic queuing network model of the logistic activities related to the arrival, discharge/loading operations and departure processes of vessels at a container terminal has been proposed in (Legato and Mazza 2001). Some real features, such as non-standard service stations, time dependent priority mechanisms and complex resource allocation policies, prevent using any analytical approach to model

solution. The use of stochastic, discrete-event simulation as solution method is usually obliged (Bruzzone et al. 1996a). Here, starting from a process-based description of the queuing model we used a Visual SLAM environment (Pritsker et al. 1997) to quickly obtain a prototype for validating some basic modeling choices on arrivals and service times and conducting a simplified scenario analysis upon the number of berth cranes to be employed for discharge/loading operations. Here we are faced with a finer modeling of the integrated logistic processes of vessel entrance and berthing at the Gioia Tauro terminal. The entrance channel, today shared by container vessels and other traffic, could become a future bottleneck as containerized traffic increases. The explicit representation of the berth length (3.3km) in terms of berth slots for which a fixed draft may allow or prevent the assignment to some new container vessels of latest generation is also required. Finally, the complex policies by which the crane manager allocates/deallocates cranes at the same big vessel to guarantee a target on the rate of service and deploys these crucial resources along the entire berth is also asked to be represented by a decision tool. A new queuing network model is designed to satisfy the above requirements and the natural implementation of the model based on a traditional procedural language is pursued in a modern environment as (Borland® Developer Studio 2006). This suite offers a set of very useful visual objects for designing a manager-friendly tool where each single panel will be the result of an agreement with the same manager. Such an approach, clearly requires a significant programming effort. Nevertheless, it is appropriate for implementing all the mechanisms and real policies of resource allocation and scheduling defined by the terminal managers. Moreover, it is also especially fit for dealing with massive data entry and displaying a great number of non customary results for system analysis and evaluation. Particular attention has been given to the statistical methods used to analyze simulation output. The availability of credible simulation results enables the use of the model for a *what-if* type simulation based optimization approach on both the capacity planning of logistic resources and the management of logistic operations. The problem of finding a queuing system configuration that optimizes the expected value of some

measures of system performance on the long-run, such as terminal throughput and lead time, is strongly demanded. When using a simulator, this approach is known as *optimum seeking by simulation* (Law and Kelton 2000) and it requires the selection of a cost-accuracy effective method for interval estimates of average performance measures or average point estimates followed by variance estimation. In fact, at each iteration of a simulation based optimization procedure one or multiple candidate configurations need to be analyzed for comparison (Swisher et al. 2003). Thus, computational burden must be carefully considered in terms of number and length of simulation runs.

The paper is organized as follows. The queuing model of the core logistic process at the Gioia Tauro terminal is presented in the next section. The application software developed is illustrated in section 3. Methodologies for the output analysis of simulation runs are discussed in section 4. Conclusions are in section 5.

QUEUING NETWORK MODELS FOR VESSEL ARRIVAL, ENTRANCE AND BERTHING

Some queuing based simulation models for core logistic processes at real container terminals can be found in (Silberholz et al. 1991; Gambardella et al. 1998; Yun and Choi 1999; Shabayek and Yeung 2002). All these models share the common lack of attention to the waiting phenomenon that arises when an incoming vessel stops in the roadstead, first to ask for a berthing

position and then to receive one or more tugs and/or pilots, that will maneuver it to the berthing position. In principle a sort of semaphore-like queue should be considered to represent the possible stop and its random duration. In the reality of our interest, the container terminal at the port of Gioia Tauro, the holding time of the entrance channel by one vessel is becoming a non secondary congestion factor due to rising “external traffic” (e.g. other vessels visiting the port, but not the container terminal). A semaphore-like queue is shown in the leftmost part of the queuing network model proposed in this paper, as illustrated in Figure 1. In a recent paper (Legato et al. 2006) it has been shown that this modeling device can be replaced by a so called *pure delay station* with delay times distributed as a 2-phase Coxian distribution (Trivedi 2002).

The central part of the model in Figure 1 is reserved to the I/O channel model, where maneuvering resources (tugs and pilots) appear as duplicated but must be intended as subjected to a locking phenomenon issued by the vessel that has currently obtained the channel resource by the channel controller (manager). Usually, exiting vessels have priority on entering ones. Vice versa, instead of a FIFO rule, a look ahead mechanism is sometimes adopted between a newly arrived vessel in the roadstead and other important vessels about to arrive.

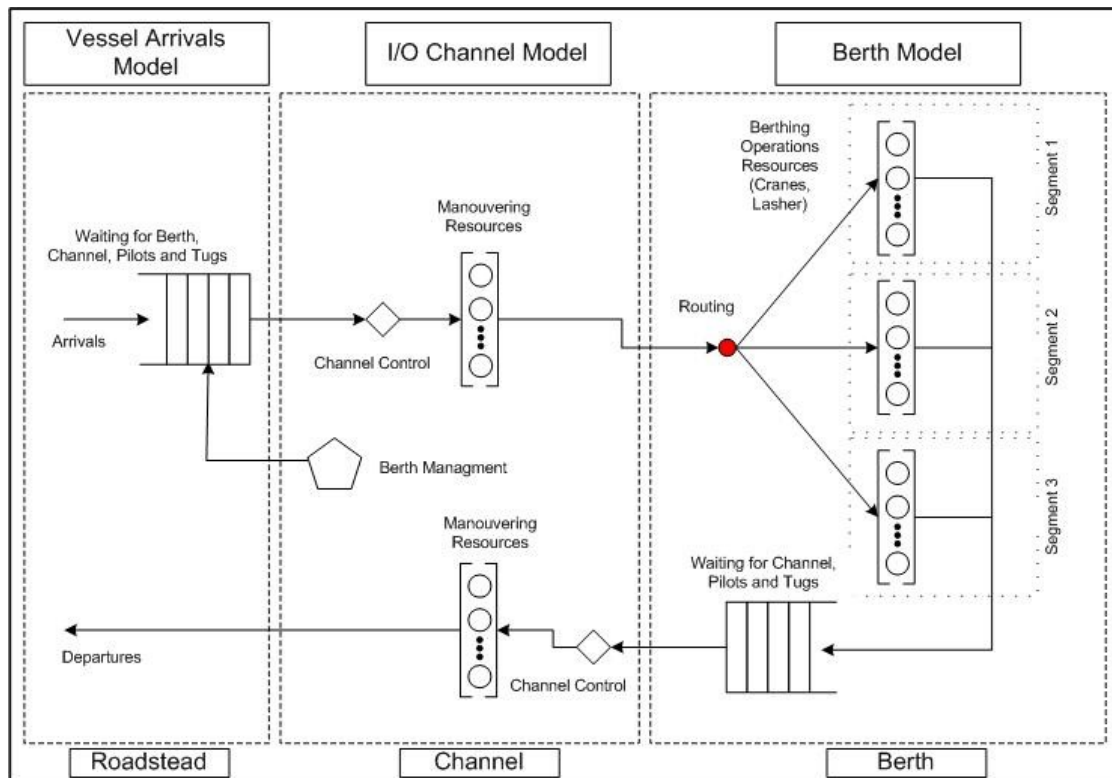


Figure 1: Queuing Model for the Gioia Tauro Port with Enhancement on the I/O Channel

The rightmost part of the model in Figure 1 illustrates the berth model. Here, the whole berth length is arranged as a variable set of berth segments whose individual length may vary as well. Precisely, each of these segments consists in a given number of berthing slots (24m) equipped with at least one crane. Each segment is assigned to a subset of shipping companies and, therefore, it results as a queuing station with multiple servers (cranes) and a limited number of places in queue. This limitation may result as a major cause of vessel stopping in the roadstead, whenever the berth manager is forced to address an arriving vessel to a fully occupied berth segment. The proposed queuing model contemplates the possibility of re-addressing the stopped vessel, provided that the new segment has a proper draft. On the other hand, the choice of berthing one vessel rather than another into a specific segment could result in a too long distance from the source/destination point of its containers in the storage yard.

The above queuing network model holds in store a wide range of useful alternative configurations to be evaluated by simulation in order to support major decisions. For example:

- what kind of admission policy should be adopted in the roadstead?
- how many berth segments should be organized for active “shipping services”?
- how many cranes - out of the total, fixed number of available ones - should be allocated for each of the above segments?
- in which segment should vessels entering the port be berthed, provided that this decision may be based on some suitable attributes shared by any given subset of the active services?

THE APPLICATION SOFTWARE

The CaLeMa software (Borland® Developer Studio 2006) is a simulation environment designed to reproduce the current MCT practice for vessel berthing and terminal operations, with a particular focus on channel contention and the management of berthing points. It is the result of a combined application-oriented modeling effort between simulationists and (MCT) policy makers which ranges from form (e.g. user-friendly panel interface, graphical/textual output display, layout, etc.) to content (e.g. identification of system specifications and assumptions, data modeling, etc.). CaLeMa is currently used as a tool for both operational management and to explore different quantitative solutions and scenarios other than those deployed by the company at present. To produce statistical results on the predetermined system of interest, interval estimates can be computed on the basis of the replicated batch means method (Andradottir and Argon 2001) as particularized and experimented in the later sections.

General Features

The simulator consists of two panel-like interfaces designed to help the user insert the proper input parameters and obtain simulation output on screen and/or file. The so-called *Main Panel* (MP) is designed for defining system resources and operational policies. The overall configuration described in this section is referred to as the “scenario”. The *Service Manager Panel* (SMP) is a friendly input panel for the physical and operational specifications that characterize the individual vessel services accounted for. The overall configuration defined in this section is referred to as the “services”. Together, the scenario and services files provide all the data for any simulation experiment. In both panels, the input parameters are specified in tab-organized screens and the system architecture is designed to minimize errors caused by a faulty data entry and/or accidental scenario-service mismatching performed by the user.

In the following paragraphs, we focus on some important channel and berth related features encoded in the related subareas of the software, rather than just present a general outline of the two major panels.

Resource Definition

The *Resources* section illustrated in Figure 2 is one of the components for data input in the *Main Panel*. It allows to account for the number and state of the resources that characterize a certain scenario. Resources include available *pilots*, *tugs*, *length of simulation run* (in days), *TEUs factor* and *crane utilization*. But most of all, this is the point in which the berth definition is initiated via the *berth segment length* sub-area. The berth deserves particular attention because it is a prerequisite for channel acquisition.

A berth segment is specified by inserting the lower bound and upper bound bollards that demarcate the segment’s physical extension (e.g. **Segment 1** 1 to 7).

Figure 2: Resource Area in the MP

Once berth segments are fixed, the *berth depth* needs definition by clicking on the proper button and entering

the number of segments. As shown in Figure 3, each segment must be completed with the boundary bollards, as well as the berth *depth*.

| | From | To | Depth |
|----|------|-----|-------|
| 1 | 1 | 18 | 11.00 |
| 2 | 19 | 22 | 11.20 |
| 3 | 23 | 44 | 13.50 |
| 4 | 45 | 57 | 14.10 |
| 5 | 58 | 71 | 14.60 |
| 6 | 72 | 82 | 13.00 |
| 7 | 83 | 91 | 13.20 |
| 8 | 92 | 107 | 14.30 |
| 9 | 108 | 123 | 13.80 |
| 10 | 124 | 139 | 15.40 |

Figure 3: Area for Berth Depth in the MP

Practically speaking, berth assignment is not straightforward. It occurs on the basis of the four yes-enabling options set by the user in the *service properties* panel shown in Figure 4. *Berth guarantee* ensures the pre-assignment of a berth segment to the associated service whose length and time location are respectively defined in the *segment priority* and *time window* fields in the *Service Manager Panel*. *Berth priority* grants the assignment of a segment with priority to a service having such benefit. In case more than one entitled service is making this request simultaneously, then berth assignment occurs on a first-come first-served basis. The *time tolerance* field represents the amount of time (in hours) that a service can wait before berth assignment when its pre-assigned berth segment is occupied. This time limit has a meaning if referred to services for which berth assignment is guaranteed. The *not used* field is currently unavailable, but its future purpose is to postpone the beginning of container discharge/loading operations to the next shift.

| Service | Berth Guar. | Berth Prior. | Time Toler. | Not Used |
|-----------|-------------|--------------|-------------|----------|
| Service 1 | | | | |
| Service 2 | | | | |
| Service 3 | | | | |
| Service 4 | | | | |
| Service 5 | | | | |
| Service 6 | | | | |

Figure 4: Service Properties for Berth Assignment in the MP

Berth and channel availability also depend on external factors. This simulator covers interruptions due to non MCT traffic and bad weather. The occurrence of these events is dealt with by inserting event frequency (i.e. average number of external vessel arrivals per week or number of days per year during which the entire terminal activity is brought to a halt), followed by a conventional “type” and “degree” of event regularity. This feature is illustrated in Figure 5.

General Parameters

☐ Enable interruptions for non MCT traffic

N° of Vessels per week

| | Avg Value | Variability |
|-----------------|-----------|-------------|
| Other Traffic 1 | 5.852 | Medium |
| Other Traffic 2 | 4.934 | Medium |

☐ Enable interruptions due to bad weather

| | Bad Weather (days/year) | Variability |
|--|-------------------------|-------------|
| | 20 | Medium |

Figure 5: Definition of External Factors in the MP

Service Definition

A service (i.e. the sequence of ports, or port rotation, to be visited by a vessel) “generates” the arrival of vessels demanding berth assignment. For complete definition, a service requires a wide range of information. The *Service Manager Panel* provides sub-areas that account for such definition and management throughout the entire service life-cycle (*new, save, modify, sort, delete*). It includes the *service name*, the *shipping company* and the number of vessel classes, meaning a group of vessels with attributes in common such as *length* and *draft*. An example of different types of vessel classes within the same service is shown in Figure 6: every class is characterized by a *frequency*, *length*, *draft*, number of *pilot(s)* and *tug(s)*, *extra bollard(s)* in compliance with security measures and *max TEU* capacity.

Service Name: Service 1 Shipping Company: Company 1 N° of Classes: 4

| Ship Code | Frequency | Length | Draft | Pilots | Tugs | Extra Bollard | Max TEUs |
|-----------|-----------|--------|-------|--------|------|---------------|----------|
| 1 | 5.32 | 90 | 10 | 1 | 0 | 1 | 2500 |
| 2 | 39.93 | 99 | 10 | 1 | 0 | 1 | 2500 |
| 3 | 21.67 | 116 | 10 | 1 | 0 | 1 | 2500 |
| 4 | 33.08 | 125 | 10 | 1 | 0 | 1 | 2500 |

Figure 6: Definition of Vessel Services in the SMP

A very original and practical schema for indicating vessel arrival is defined by selecting one of the *without*

or *with time windows* radio buttons in the *Arrivals* section. When opting for the former, the average number of vessels per week, along with the “type” and “degree” of arrival regularity must be inserted. Instead, the second option requires more details to configure the arrival pattern. As shown in Figure 7, the entry fields to complete are: the number of time windows planned for the service of interest (at the most three for every service); the day of the week and the hour of the day that define the upper and lower bound of each time window; the probability that vessel arrival will fall before, inside or after the time window.

Figure 7: Definition of Vessel Arrival in the SMP

The *Service Manager Panel* also includes additional vessel data (*GCP* – gross crane productivity, *berth moves*, *cover moves*, *maneuvering time*, *unlashing time*, *lashing time*, *other idle time*) and operational settings, which are both required to compute the sojourn time for a vessel of any given service. For example, for the service at hand:

- berth assignment is completed in Figure 8 by indicating a particular berthing preference or *priority segment*, as well as checking one or more “second choice” segments;

Figure 8: Berth Assignment to Vessel Service in the SMP

- crane assignment is defined in Figure 9 by specifying the *crane intensity* target and the number of cranes to assign during the 1st and 2nd shift - these values are used to determine the number of cranes to deploy in the (eventual) remaining shifts.

Figure 9: Crane Assignment to Vessel Service in the SMP

Simulation Output

Presentation of results is as important as their acquisition. CaLeMa offers easy-to-read data traces and reports for system performance over the entire simulation horizon.

The *Main Panel* is the primary source for data output. It is designed to offer immediate access to different kinds of data that can be summarized in the following categories:

- *global data and averages*;
- *averages per service*;
- *averages per shift*;
- *averages per segment*.

Results can be viewed directly on screen, as well as selected via button and/or menu in customized txt formats.

Many performance measures belong to more than one of the above categories. Table 1 summarizes which indices are computed in global terms (G), per single service (S), per shift (on screen – Sh; on report – ShR) and per berth segment (R). The most significant are defined in Appendix; details for every index listed below are provided in the User’s Manual (Canonaco et al. 2006).

Table 1: Performance Measure Matrix

| Performance Measure/Output | G | S | Sh | R | ShR |
|------------------------------------|---|---|----|---|-----|
| Moves | ✓ | ✓ | | ✓ | |
| Covers | ✓ | ✓ | | ✓ | |
| N° of vessel arrivals | ✓ | ✓ | | ✓ | |
| N° of vessel departures | ✓ | ✓ | | | |
| TEUs - twenty equivalent units | ✓ | | | ✓ | |
| N° of vessels in roadstead | ✓ | | | | |
| N° of vessels in berth | ✓ | | | | |
| GCWH - gross crane working hours | ✓ | ✓ | | ✓ | |
| Shift utilization | ✓ | | | ✓ | ✓ |
| Simulated time | ✓ | | ✓ | | |
| N° of cranes | | | ✓ | | ✓ |
| N° of gangs | | | ✓ | | ✓ |
| Service name | | ✓ | | ✓ | |
| Crane intensity | | ✓ | | ✓ | |
| GCP - gross crane productivity | | ✓ | | ✓ | |
| Waiting in roadstead (and cause) | | ✓ | | ✓ | |
| Waiting in berth (and cause) | | ✓ | | ✓ | |
| Berth segment | | | | ✓ | |
| Bollards per berth segment | | | | ✓ | |
| Length per berth segment | | | | ✓ | |
| Moves per berth segment | | | | ✓ | |
| TEUs per berth segment | | | | ✓ | |
| TEUs/m per berth segment | | | | ✓ | |
| Berth occupation per berth segment | | | | ✓ | |
| GCP per berth segment | | | | ✓ | |
| Shift number | | | | | ✓ |
| Overall productivity | | | | ✓ | |

An important output source produced by the simulator that deserves special attention is the trace. In general, a

trace is a file that records all the “relevant” events for simulation (i.e. an event determines a change in the state of the system) - in brief, it is a compact representation of the system behavior described by activity progress in time. The role of this program feature is twofold: on one hand, it is used by simulationists to detect errors committed during the design and development stages; on the other, it is employed by the end-user to perform tailored statistics regarding particular system performance measures not accounted for in the default output (on-screen or text-file) support functions.

In the current version of the simulator, the trace is composed by a set of lines where every line contains fields that provide a complete description for every vessel-occurrence. These fields range from specific physical attributes (i.e. *vessel code*, *service name*, *class*) and operational characteristics (i.e. *vessel GCP*, *crane intensity*, *container moves* and *covers*) to vessel service recording (*manouvering time*, *unlashing time*, *lashing time*, *idle time*, *arrival time*, *berthing time*, *labor ashore time*, *un-berthing time*, *departure time*); from berth position (i.e. *from-to* bollards) to global and specific waiting times in both the roadstead and berth.

As a result of the detailed design of its structure, the trace can also be used to create graphical outputs (e.g. berth plans) and smoothly moving depictions of the terminal activities characterized by constantly changing states (e.g. operations). These post-processed results can provide static graphic layouts to be used alone or in optimization procedures (e.g. in a cutting stock optimization model for the weekly berth plan as shown in Figure 10), as well as dynamic audience-oriented presentations (e.g. 2D or 3D animations).

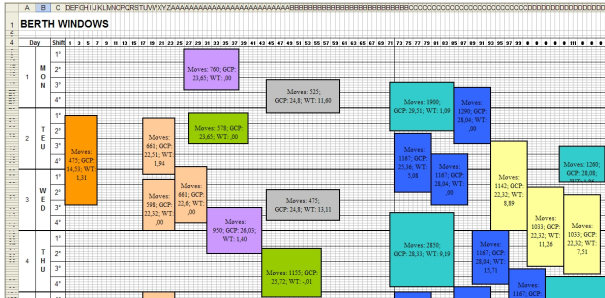


Figure 10: The Weekly Berth Plan

OUTPUT DATA ANALYSIS

At the opposite sides of the simulation based methodology for the analysis of a queuing system there are the two choices of (1) producing one very long sample path of the stochastic processes representing the performance measures of interest or (2) producing multiple, independent, sample paths (Whitt 1991). Queue occupancy (*number in*), time in queue (*delay*) and the counting process of jobs at the system exit point (*throughput*) are typical performance measures whose mean values are usually evaluated by one single replication (simulation run) or multiple, independent,

ones. Interval estimates for average measures or variance estimates - to be produced for purposes of ranking and selection (Goldsmann and Nelson 2002) of different queuing configurations - are based upon the issue of batching elementary observations either within the same replication or across multiple replications. Grouping (dependent) observations into batches and then working with batches (Schmeiser 1982) is the consolidated method to achieve (at least approximately) the independence property among realizations of the statistic to be used, as required by theory (Alexopoulos and Seila 1998). The first batching mode is aimed to minimize the initialization bias throughout the gathered observations at the price of dealing with correlations among them, while the second batching mode is aimed to do the vice versa. Nevertheless, finding the optimal compromise between the number of replications and the number of batches per replication is a problem still focused in some recent papers (Alexopoulos and Goldsmann 2003).

The study of key convergence properties of the classical steady-state simulation analysis method of the non overlapping batch means (i.e. batching within one single run) is usually referred to a restricted number of stationary processes such as the first order autoregressive process, the exponential autoregressive process and the simple M/M/1 queuing process, due to the choice of dealing with a known covariance function (Song and Schmeiser 1995; Goldsmann et al. 1997; Wilson and Steiger 2001). Vice versa, our practical interest is in analyzing stochastic processes arising in complex queuing networks as the one in Figure 1 underlying the developed simulator, where no explicit form exists for the covariance function and, furthermore, the impact of transient (initialization bias) on simulation mean and variance estimators has to be evaluated. This motivates an empirical analysis of the coverage properties of different batching modes with reference to the practical queuing system in Figure 1.

Interval estimates by batches and replications

In CaLeMa interval estimates are computed as follows.

A set of m , independent, replications is obtained with m , independent, random streams. From each replication we take one or multiple batches, each grouping n (dependent) observations of the performance measure of interest. The first l observations may be discarded to limit the bias effect of transient. The sample means (statistics):

$$\bar{X}_1(n), \dots, \bar{X}_j(n), \dots, \bar{X}_b(n)$$

corresponding to the resulting batches (b , $b \equiv m$, under one batch per replication) become normally distributed as $n \rightarrow \infty$, with μ as the common mean and, moreover, they become independent even though some batches are taken from the same replication.

On the other hand, using classical notations, the following result (Steiger and Wilson 2001):

$$\bar{X}_j(n) \xrightarrow{D} Z(\mu, \sigma^2(n)/n), \quad \text{for finite } n, \quad \forall j$$

in conjunction with the use of only one batch per independent replication $b \equiv m$, guarantees that:

$$\frac{S_{\bar{X}(m)}^2}{\sigma^2(n)/n} \xrightarrow{D} \frac{\chi_{m-1}^2}{m-1}$$

and, hence,

$$\frac{\sqrt{m} (\bar{\bar{X}}(m) - \mu_X)}{\sqrt{S_{\bar{X}(m)}^2}} \xrightarrow{D} T_{m-1} \quad (1)$$

Observe that we may use half of the replications for computing the sample variance and the second half for computing a stable estimate of the sample mean, thus respecting the basic (independence) assumption underlying (1). Whatever the choice, we use the following to get an interval estimate:

$$\mu_X \in [\bar{\bar{X}}(m) \pm H] \\ \text{with } \text{prob} \equiv (1 - \alpha)$$

where

$$H \triangleq \frac{t_{m-1, 1-\alpha/2}}{\sqrt{m}} \cdot \sqrt{S_{\bar{X}(m)}^2}.$$

Usually, the independence assumption between the sample mean and the sample variance is ignored and their respective estimates are obtained by a sequential execution of all the batches on the same unique long run of simulation. The resulting “batch means” method introduces a second error upon the estimate of the sample variance, due to the correlation among batches. The only way to limit these errors relies upon the possibility of using sufficiently large batches on a sufficiently long run of simulation for each configuration of the queuing system to be analyzed. This could introduce an intolerable computational burden in a simulation based optimization procedure.

Numerical Experiments

In this section we report on our empirical experience in queuing model simulation. We investigate how output observations can be organized in batches and replications and then evaluate the resulting coverage properties of any batch-based interval estimator of a given output process.

In particular, we produce and compare interval estimates by using 30 batches in two different cases: (1) all batches taken from a unique replication (classical batch means method) are used to compute both the sample mean and the sample variance; (2) 15 batches taken from the same replication estimate the sample mean, while 15 additional batches are taken from 15

further replications to obtain an independent estimate of the sample variance. We also investigate the number of observations required per batch to achieve normality of the batch sample mean.

Finally, we exploit all the possible combinations of replications and batches per replication (e.g. 5 runs per 6 batches, 3 runs per 10 batches, etc.) by conducting extensive numerical experiments. As a result of these experiments, we realize that there is no substantial difference in terms of quality for the coverage property.

Numerical results reported in the following refer to a queuing network where some not important details from the model in Figure 1 are neglected (Legato et al. 2006).

By fixing a batch duration to a relatively small value (803 job departures at the sampled queuing station), one may verify, in Figure 11, the expected violation of the normality assumption upon the batch means. In particular, results are shown for batch number 15 (the last one, to minimize the bias effect due to the transient period). Observe that, as shown in Figure 12, almost 4000 departures are needed to feel a bit safe about the satisfaction of the normality assumption on the sample mean under investigation!

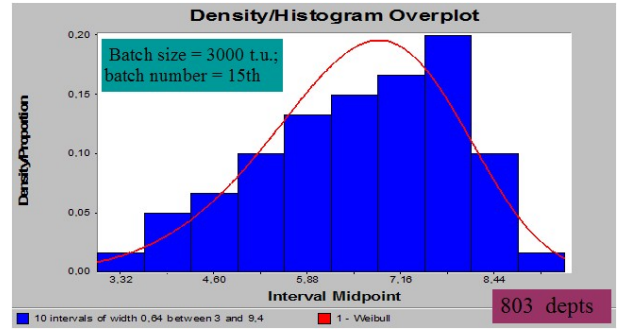


Figure 11: Verification of the Normality Assumption at a Bottleneck Station

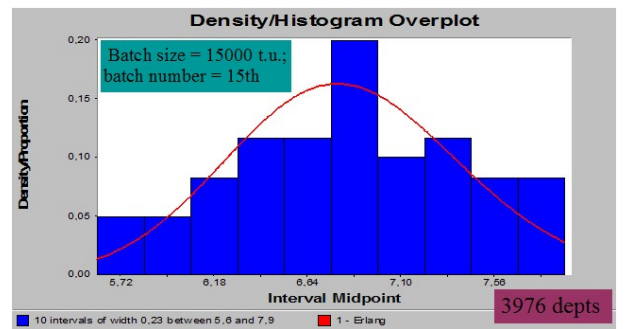


Figure 12: Improvement with the Increased Sample Size

Results become worse when moving to a non bottleneck station, where the effect of the distribution of what stands here for a service time (time spent in the roadstead for admission to the port) becomes more important. Again, we show the effect of increasing the batch size of output observations (simulated departures from the sampled queuing station) from 2067 in Figure 13 up to 9939 in Figure 14. This means that the user

would have to fix, as sample size, the number of observations that guarantee the normality assumption at the light-loaded queuing stations.

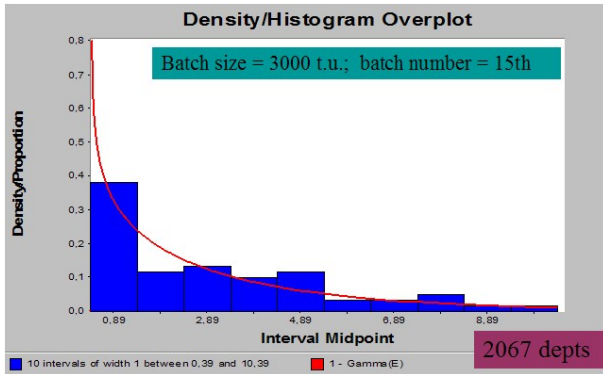


Figure 13: Verification of the Normality Assumption at a non Bottleneck Station

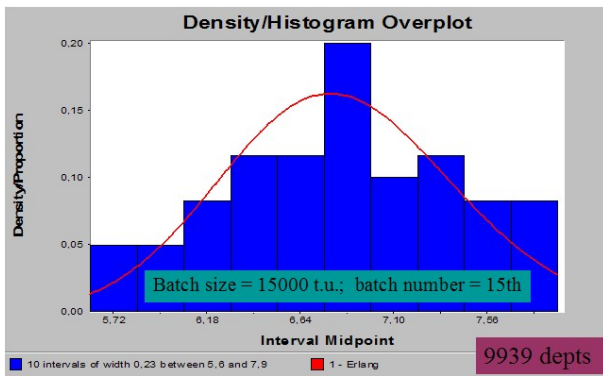


Figure 14: Improvement with the Increased Sample Size

Coverage behavior for cases (1) and (2) described earlier are now examined. A yellow line in Figure 15 indicates the sample mean estimate obtained by a very, very long run of simulation that, obviously cannot be recommended in simulation based optimization procedures. Looking at coverage results at a non bottleneck station, shown in Figure 15 with reference to the average number of jobs present (vessels berthed in a given segment), it seems that, despite the violated normality assumption upon the batch mean statistics, the quality of coverage is indistinguishable from the classical implementation of the batch means method, i.e. the implementation where the 15 batches for variance estimation are taken from the same, unique replication used for sample mean estimation.

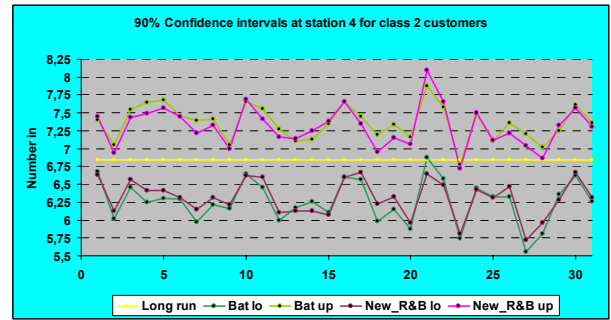


Figure 15: Coverage Results for 30 Interval Estimates under Batch Sizes of 803 observations.

In order to verify the possibility of producing narrow interval estimates and also more uniformly located around the yellow line of reference, larger size batches (3976 observations) are used next. Under this number, Figure 12 indicates that the normality assumption upon the sample mean is approximately satisfied. The results shown in Figure 16 confirm the quality improvement.

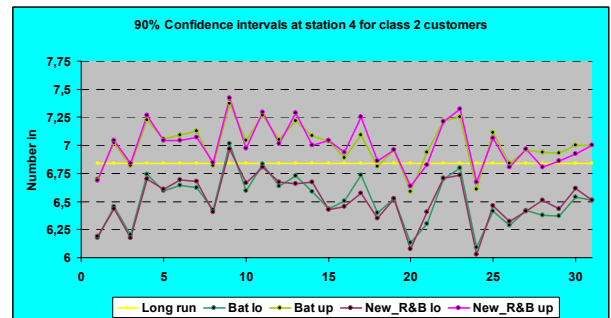


Figure 16: Coverage Results for 30 Interval Estimates under Batch Sizes of 3976 Observations.

For completeness, numerical investigation on coverage properties has been repeated at a non bottleneck queuing station that, in this scenario example, corresponds to the entrance channel and it is characterized by a hyperexponential distribution for delay times suffered by vessels.

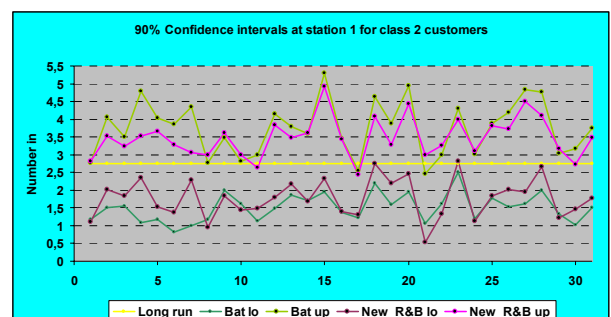


Figure 17: Coverage Results for 30 Interval Estimates, under Batch Sizes of 2067 Observations.

The results on quality of coverage are reported in Figures 17 and 18. These are obtained, respectively, under batch sizes fixed according to Figures 13 and 14. Once again, the substantial robustness of the coverage properties, with respect to the possibility of distributing batches among replications or concentrating these batches into a unique replication, is confirmed.

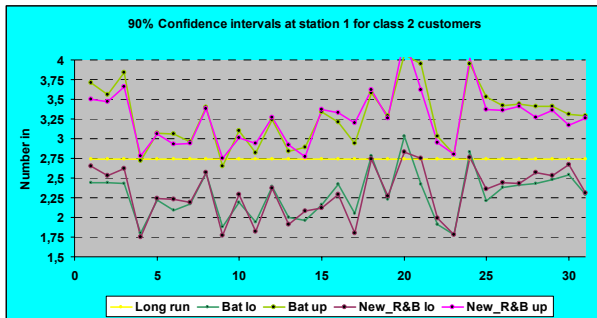


Figure 18: Coverage Results for 30 Interval Estimates, under Batch Sizes of 9939 Observations.

In conclusion, correlation among batches does not seem to generate significant errors when producing interval estimates for a mean performance measure; on the other hand, one could avoid this correlation by estimating the sample mean using short, independent replications.

CONCLUSIONS

A manager-friendly simulation environment has been designed to answer a real problem formulated by MCT SpA, the company that manages the container terminal in Gioia Tauro (Italy). Its functionality has been illustrated in detail, according to the requisites fixed with the terminal manager. The simulator is based on a queuing network model representing the integrated management of the entrance channel to the port and the berthing segments dedicated to the flow of container vessels. The simulator is a significant case of application of queuing, simulation and statistical methodologies as decision supporting tool for evaluating quantitative indices of performance in simulation based optimization studies. The replicated batch means method for interval estimates of the above indices has been investigated via numerical experiments, in order to assess its practical accuracy and, hence, provide some guidelines to the users.

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APPENDIX

A brief description of the most significant performance measures recalled in the present paper is provided below.

Berth occupation per berth segment - time-weighted use of a berth segment divided by the time-weighted capacity of the berth segment.

Covers - number of container moves to be performed in order to open/close vessel hatch covers.

Crane intensity - weighted number of cranes assigned to the vessels belonging to the same service.

Crane utilization - simultaneous use of two or more cranes on the same vessel is likely to reduce these resources' efficiency; a 100% value in a field indicates full operational conditions for the corresponding crane.

GCP, gross crane productivity - number of container movements per hour performed by cranes assigned to vessels of the same service.

GCWH, gross crane working hours - number of the total crane working hours.

Moves - number of container moves to be performed during vessel discharge/loading.

Overall productivity - number of container movements and covers performed by the cranes assigned to vessels of the same service.

Shift utilization - time-weighted use of a shift divided by the time-weighted capacity of the shift.

TEU, twenty equivalent units - unit for measuring container length.

TEUs factor - ratio used to convert TEUs to containers.

Waiting in berth - time a vessel spends in its berth slot before it can exit the port (it depends on the availability of pilot(s), tug(s) and channel)

Waiting in roadstead - time a vessel spends in the roadstead before it can enter the port (admission depends on the availability of pilot(s), tug(s), berth, and channel).

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