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A Queuing Model Study of Port Performance Evolution

The main purposes of the paper are to describe port performance evaluation by queuing models (QMs) based on the nature and applications of the models, state of the art survey based on the classification and identify considered problems and the applications of the existing QMs. There are number of benefits to be gained from QMs for port performance evaluation, among them are: faster development, greater flexibility, less data required and it is easier to understand and interpret the results.

Keywords: *queuing models (QMs), port performance evaluation*

1. Introduction

Queuing models are used to analyze complex dynamic and stochastic situations and to understand issues for port system decision making. This methodology is applied successfully to several experimental examples and is shown to deliver competitive results much faster compared to conventional models in a stochastic environment. The progress of port QMs from their early days is charted with a particular focus on recent history. Specific developments in the past 50 years include analytic formulations and formulae, analytic formulations and numerical solutions, simulations models and integration of simulation-optimization framework for the performance evaluation of port systems. Potential changes in QMs development, QMs use, the domain of application for QMs and integration with other modelling approaches are very important.

The organization of this paper is as follows. Sections 2 gives a brief description of port system performance. The classification scheme of the available literature on QMs applications in port system are described in Section 3. Section 4 presents state of the art of port QMs development and different modelling approaches to port performance evaluation. The final Section 5 gives concluding remarks.

2. Port system performance

The term Port Systems (PS) is often used to refer to systems with multiple components that need to cooperate to achieve a common goal, trying to make efficient use of available resources. In general case, PS consists of many interacting sub-systems performing various planning and control functions. Designing of PS presents a special challenge for the designer, because of the more complex systems with different level of links between elements (from very slack to very rigid), and with mutual influences which could be deterministic or defined by stochastic values. During research numerous references have been used, and most of them are emphasized ([1] – [7], [10] – [34], [36], [38] – [45], [47] – [68] and [70] – [75]). Some of PS characteristics are [74]: multicriteria goal (vector goal function is not a simple linear combination of its components); system boundaries (often not clear in relation to the environment, determined by experience); sub-systems (in achieving local goals optimization is undergone to additional constraints, which come from other sub-systems or from higher level); and components (a great number of components and state coordinates; hierarchy organization, structural and control).

The complexity of PSs requires particular methodology for model choice. Analytical models which are frequently used (models of queuing theory) for analysis of global solutions could estimate the PS performances. However, even with the simplification and decomposition of system, it is not always possible to adequately set the corresponding analytical model.

Many operations research models have been used for the purpose of modeling various operation situations in port. Queueing models (QMs) play an important role in modeling and analysis of port systems, especially, of the new port's terminals. In the literature various QMs, from simple queues to a complex queuing network models (QNM) have been suggested and studied for different types of port operations like analyzing movement of ships in port, ship traffic modeling, mechanism of congestion occurrence, cost composition and congestion cost, measurement of total cost, optimum use port facilities and equipment by imposing congestion charge, optimum number and capacity of port berths, evaluation method for determining the optimum number of berths, optimum allocation and size of port, optimal berth and crane combination in port, average cost per ships served, ship turn-around time at the port, analysis of time spent at berth, measurement of delay to ships in the queue, distribution of berth occupancy, berth planning by evaluation of congestion and cost, optimum port capacity related to congestion and berth occupancy, handling equipment assignment and deployment, and so on. There is a rapidly increasing literature in the applications of QMs to port systems and it is the intent to attempt a classification, literature review and identify possible future directions of research.

PSs have been very often considered as QMs and network of queuing links. These systems consist of berths with ships waiting to be served in queues. Berth throughput capacity was estimated based on experience from existing ports without giving much thought to the effect of the size of the port, measured by the number of berths. Some ships are berthed and are being unloaded and loaded at one or more berths. Port QNM can be represented by a single-service channel for a single-berth port and by multiple-service channel for a multiple-berth port.

A PS consists of one or more berths, an arrival process, and a service process, along with some additional assumptions about how the system works. The number of ships in the PS at any given time will equal the number of ships in the queue plus the number of ships at berths. These numbers will vary over time as ships come and go, so they are formally stochastic processes. If there is a limited amount of anchorage area, or for any other reason ships are prevented from joining a queue once it reaches a certain level, then the queue or PS has finite capacity.

From the viewpoint of designing practice, deterministic approach is more simple, but the possibility of its application is limited. Stochastic approach describes more realistic process and its dynamic character. Knowledge of these behavior laws, guide to adequate description of material flow, and the data base is used as a source of knowledge in systems modeling [74]. The particular problem presents the selection of the QMs. References ([13], [25] and [69] among other) give different types of theoretical QMs but there are no indications of adequate use in problem solving and the difference between the theory and practice. To analyze this problem we have to start with the classification scheme ([35], [46] and [69]), given as (x/y/z):(u/v/w), where the symbols are presented in Table 1.

Table 1. The symbols

A convenient notation of queueing system			
x	arrival or interarrival distribution	u	service discipline
y	service time distribution	v	max number in the systems
z	number of service channels	w	size of the population
The arrival and service distribution notation			
M	Poisson or equivalently exponential distribution	*D*	deterministic process
GI	general independent distribution	E_k	Erlang distribution with *k* phases
G	general distribution	HE_k	hyper exponential distribution with *k* phases
The service discipline notation			
FCFS	first come first served	GD	general service discipline
LCFS	last come first served	HELPF	full help between the servers
SIRO	service in random order	HELPS	partial help between the servers
SETA	standardized estimated arrival time	GOSBEA	global optimization of speed channel (berth), and equipment allocations

3. Port queuing models and performance evaluation

In the literature, it has been shown that QMs can be used to adequately model port operations. We presented here a general review on this literature. Namely, a brief review of queuing theory is presented in order to give some basic information about QMs from sea-port literature.

Queuing time at single and multiple berth facility is considered in [32]. They presented the ratios of average waiting and average service time of ships as function of number of berths and expected occupancy rate and studied problems of applying regression analysis to queueing time functions. Also, described a two-stage, multichannel QM.

In [25] a survey of various applications of QMs was presented in order to determine the port performance evaluation. He analyzed port QMs a favorite tool in the planning and modeling of ports. Considered a single and multiple berth models, introduced a berth assignment routine, and computed the berth utilization, average ship waiting time, average number of ships waiting, as well as other ship or berth operating performance measures. Explained procedure for determination of the optimum number of berths and berth planning by evaluation of congestion and costs. Criticism of the distribution assumptions in berth planning models has been presented. Application of M/M/S queue in port berth planning is discussed. Capacity bottleneck analysis using QMs and estimation of navigational channel capacity using time-space diagram with QNM have been described.

The analytical solutions for determination of facilities requirements related to berths and the capacity concept is studied in [1]. They presented queuing analysis solutions for exponential, Erlang and constant service time of ships. Through simulation the effectiveness of their procedure is established.

In [13] $M^{X=\text{constant}}/M/c(\infty)$, $M^{X=(1-a)a^{m-1}}/M/c(\infty)$ and $M^{X=\text{constant}}/D/c(\infty)$ queues are discussed. Also, the nonstationary, multichannel QM has been developed, $M^{X}/M/n/m$. This QM has the following characteristics: waiting areas are finite and given, unit bulk arrival into the system is assumed, and arriving ships or barge tows are not allowed into the system if $k > (n+m)-s$, where k is the number of ships or barge tows arriving at the same time. For all cases, some explicit results are presented. Analytical expressions are obtained in closed form for the state probabilities of a nonstationary system. The conveniences of these methodologies are the simple application in the estimates of existing conditions and the planning of berth requirements, port management, and better decision making according to the former methods.

Queuing theory is one of the most commonly used modelling techniques for the operation planning of PSs until 1995. Since the earliest days of port QMs in the 1960s, their continued developments have helped to place it near the top of the modelling technique. The past 50 years have seen many changes in the ways that QMs are developed and used. In addition, the classification of the approaches to port queue modeling is given. The available academic papers have been classified as shown in Table 2 [16], based on different methodologies to describe port systems as QMs. The purpose of using this particular classification is to identify the gap between various approaches, and to understand the research on QMs applications in PSs.

Table 2. Classification of the approaches to port queue modelling

Approaches to port queue modelling	Grouped references from 1961 to 2010
Single server versus multi-server versus infinite server (see Table 2); Analytic formulations and formulae; After 1980 used Cosmetatos' approximation - CA ([8] & [9]); Used the non-exponential assumption (other distributions of service times and interarrival times). The steady state solution follows an integral equation.	[7], [10], [11], [18], [20], [21], [22], [23], [24], [27], [28], [29], [33], [36], [42], [49], [50], [52], [53], [54], [55], [56], [58], [65], [66], [66], [67], [71], [72] and [70]
QM simulation (developed in ANSI C).	[47]
Cyclic QMs. Markovian decision process. Markov theory.	[34], [38] and [48]
Analytic formulations and formulae. Compared with developed simulation models (SMs) of CT. Used CA & refining CA [37].	[12], [13], [14], [19], [26], [30], [31], [39], [41] and [73]
Integration simulation and optimization with QNM. Descried QM by discrete-time equations.	[64] and [45]
Analytic formulations & numerical solutions of bulk arrival queues based on [6]; Compared with SM [40].	[40], [59], [60], [61], [62] and [63]
Steady state versus time-dependent. Studied the steady-state system probabilistic and port throughput. Multichannel bulk and single channel arrival QM with finite waiting areas.	[3], [4], [43], [44], [57] and [75]
QNM. Discrete-event simulation. The closed QNM.	[5] and [51]

4. Different modelling approaches to port performance evaluation

Development of queuing models for PS performance evaluation based on various mathematical approaches such as: queuing formulae, analytic formulations and formulae and comparison with simulation models, integration simulation and optimization with queuing network models, cyclic QMs and Markovian decision process, analytic formulations and numerical solutions of bulk arrival queues, steady state versus time-dependent among other.

In recent papers [16] and [17] described port system modelling by QMs based on the nature and applications of the models, state of the art survey based on the classification and identify considered problems and the applications of the existing QMs. According to the considered problems and research results, some observations are made about various features of the application in this paper.

Here we discuss the degree to which modelling complexity affects port performance of older QMs. We used to propose various mathematical approaches to queue modelling, ranging from the classic mathematical formulae of queuing theory to simulation, Table 3 [17].

Table 3. Comparison of the mathematical approaches to PS queue modelling

Mathematical approaches to PS queue modelling (from the classic mathematical formulae of queueing theory to simulation modelling)					
Queuing formulae	Analytic formulations & formulae, & comparison with simulation models	Integration simulation & optimization with queuing network models (QNM)	Cyclic QMs & Markovian decision process	Analytic formulations & numerical solutions of bulk arrival queues	Steady state versus time-dependent

Queuing formulae: These formulae can be divided into two types, single server and multi-server and they are available in the literature. These basic formulae have been modified to improve their output for specific cases. The most widely-used modifications are approximation formulae which explained in [17]. The following papers are available in the academic literature which used an analytic formulations and formulae for PSs operations modelling ([10], [20] – [23], [27] – [29], [36], [42], [65] – [68] and [70]).

Analytic formulations and formulae and comparison with simulation models: There are other ways of showing that queuing theory is becoming a more popular technique for PS operations modelling. The next papers look at the variety of modelling structures available for port QMs ([12], [14], [15], [26], [30], [31] [39], [41] and [73]). Port QMs together with simulation are becoming an increasingly popular activity and so this area of application is covered here. It is quite clear that the software support of QMs should expect and will be increased and improved considerably in the near future.

Integration of simulation and optimization with QNM: The PS performance evaluation and optimization are research issues that have received, recently, increasing attention to present a general framework to support the operational decisions for PS modelling using a combination of simulation techniques and an optimization model. As a matter of fact, PSs are very complex systems involving a variety of modelling, designing, planning and control problems. Integration of simulation and optimization with QMs are used to analyze complex dynamic and stochastic situations and to understand issues of PS decision making. The short survey and analysis related to following papers given here ([5], [45] and [64]) are intended to provide guidance on achieving PS efficiency, raise productivity of PS and accuracy in the modelling and calibration of SMs and QMs.

Cyclic QMs and Markovian decision process: A collection of papers on the application of Markov decision processes and the cyclic queue model are classified according to the use of PS operations modelling ([34], [48] and [51]). Some observations are made about various features of the applications.

Analytic formulations and numerical solutions of bulk arrival queues: Although the number of papers reviewed here is small, it is clear that some queuing systems where customers arrive in batches rather than singly have many applications in practice, such as the analysis of containers flow in PS ([40] and [59] – [63]).

Steady state versus time-dependent: An insight of the investigations on waiting lines shows that there is considerable amount of papers on queues in steady state versus time-dependent condition. Closed form expressions for the state probabilities in transient state are extremely difficult to obtain. The time-dependent behaviour of many queuing systems can be expressed in terms of differential equations. The extensive theories associated with differential equations can be used to provide understanding and insights into the behaviour of queuing systems that are modelled in this way ([43], [57] and [75]).

5. Conclusions

QMs are normally developed for the PS performance evaluation of main port link like as seaside operation planning because a PS is too complex to be represented only by this way. When systems modelled are complex, the QMs themselves must involve some level of complexity, although at the level of abstraction from the PS. It may, therefore, not be the QMs that are difficult to use, but the PS that are being modelled are difficult to represent. The QMs also addresses issues such as the performance criteria and the model parameters to propose an operational method to develop methods for adapting sensible model design (conceptual modelling) and training users accordingly.

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