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**A Categorized and Annotated Bibliography
to the Performance Analysis of
Port Operations**

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16. Abstract This report reviews the literature related to the analysis of port operations and intermodal transportation of containers in three chapters. The first one is dedicated to a general discussion of the bibliography. The contributions of the papers are analyzed on perspective, showing the evolution of the methodological approaches and how they compare to each other. In addition, the bibliography is categorized by model used and area of application. Based on this categorization, opportunities for research and innovative applications are discussed. This analysis reveals a concentration of applications of standard Queuing Theory (QT) to the optimization of the number of berths. Other approaches, such as markovian queues, cyclic queues and simulation, have not been used as often as it would be expected, thus allowing some room for innovative applications and theoretical developments. The second chapter is comprised of annotations to a selected group of papers that intend to highlight their methodological contributions and limitations, by providing additional technical information. The third chapter presents a synthesis of the literature review and brief description of the papers.					
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**A CATEGORIZED AND ANNOTATED BIBLIOGRAPHY TO THE
PERFORMANCE ANALYSIS OF PORT OPERATIONS**

by

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and
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Interim Report SWUTC/95/721912-1

**Southwest Region University Transportation Center
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Austin, Texas 78712**

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EXECUTIVE SUMMARY

This report reviews the literature related to the analysis of port operations and intermodal transportation of containers in three chapters. The first one is dedicated to a general discussion of the bibliography. The contributions of the papers are analyzed on perspective, showing the evolution of the methodological approaches and how they compare to each other. In addition, the bibliography is categorized by model used and area of application. Based on this categorization, opportunities for research and innovative applications are discussed. The second chapter is comprised of annotations to a selected group of papers that intend to highlight their methodological contributions and limitations by providing additional technical information. The third chapter presents a synthesis of the literature review and brief descriptions of the papers.

The following are some general conclusions that came out of the literature review:

a) Historically, the first approach used was Ship Distribution at Ports (SDP); followed by applications of Queuing Theory (QT) and simulation. Fairly recently, the interest in QT has been renewed thanks to the works of Carlos Daganzo in the US, and M. Noritake and S. Kimura in Japan.

b) In almost all the applications of SDP and QT, the analysis concentrates on the ship-berth interface. The exceptions to this rule are the papers by E. Koenigsber and R.C. Lam; M. Daskin and C.M. Walton; Mounira Taleb-Ibrahimi, Bernardo de Castilho and Carlos Daganzo; and Castilho and Daganzo.

c) The applications of simulation tend to consider the other service processes as well as making an explicit consideration of the particular conditions of each port (e.g., yard geometry).

d) Consultants tend to prefer simulation because of the reasons given above. At the same time, it is observed that academicians tend to use QT formulations more frequently.

e) The perception about the accuracy of simulation has changed over time. More than twenty years ago, simulation was considered to be "approximate" and QT "exact." In today's context, the big differences in the service times for the different ship sizes and ship types make it difficult to justify the assumption of a homogeneous population of users that is required by QT. It is widely accepted that, if the model specification and calibration process are adequate, simulation would provide more accurate results than QT.

The analysis of the published literature revealed a concentration of applications of standard QT to the optimization of the number of berths. Other approaches, such as markovian queues, cyclic queues and simulation, have not been used in this area, thus allowing some room for innovative applications and theoretical developments.

ABSTRACT

This report reviews the literature related to the analysis of port operations and intermodal transportation of containers in three chapters. The first one is dedicated to a general discussion of the bibliography. The contributions of the papers are analyzed on perspective, showing the evolution of the methodological approaches and how they compare to each other. In addition, the bibliography is categorized by model used and area of application. Based on this categorization, opportunities for research and innovative applications are discussed. This analysis reveals a concentration of applications of standard Queuing Theory (QT) to the optimization of the number of berths. Other approaches, such as markovian queues, cyclic queues and simulation, have not been used as often as it would be expected, thus allowing some room for innovative applications and theoretical developments. The second chapter is comprised of annotations to a selected group of papers that intend to highlight their methodological contributions and limitations, by providing additional technical information. The third chapter presents a synthesis of the literature review and brief description of the papers.

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INTRODUCTION

This report reviews the literature related to the analysis of port operations and intermodal transportation of containers (PO/ITC) in three chapters. The first one is dedicated to a general discussion of the bibliography. The contributions of the papers are analyzed on perspective, showing the evolution of the methodological approaches and how they compare to each other. In addition, the bibliography is categorized by model used and area of application. Based on this categorization, opportunities for research and innovative applications are discussed. The second chapter is comprised of annotations to a selected group of papers. These annotations intend to highlight their methodological contributions and limitations, by providing additional technical information. The third chapter presents a synthesis of the literature review. A brief description of the papers is provided. The objective of this chapter is to provide the reader with a general idea about the topics covered by the reviewed papers. If more detail is required, the reader is referred to Chapter II (Annotations) in which the technical aspects of the most relevant papers are discussed.

Throughout this report a distinction will be made between optimization models (i.e., models in which searching for an optimal solution is the main objective) and performance models (i.e., models in which the main objective is to quantify system performance according to a given metric).

The performance models that traditionally have been used in this area are ship distribution at ports (SDP), queuing theory (QT) and simulation. In order to make some distinctions about the type of QT model, this category is further subdivided into four sub-categories: a) standard QT (birth-death queuing processes in equilibrium); b) markovian queues (mainly queuing networks); c) cyclic queues (service processes in which the server rotates its efforts among a set of users); and d) contributions to QT (a generic heading that encompasses additions to QT related to port operations).

In addition, the models were classified according to the area of application. The following areas of application were considered: performance analysis, optimization of number of berths and optimization of other service processes. The optimization of the number of berths was considered as a separate sub-category because of the relatively large number of papers dedicated to this topic.

CHAPTER I. DISCUSSION OF BIBLIOGRAPHY

The following are some general conclusions that came out of the literature review regarding performance models (such as SDP, QT and simulation):

a) Historically, the first approach used was SDP; followed by QT and simulation. Fairly recently, the interest in QT has been renewed thanks to the works of Daganzo (DAGANZ89A, DAGANZ89B, SADAG89, PEDAG90, DAGANZ90A, DAGANZ90B, TACADAG90, CASDAG91A, CASDAG91B) in the US, and Noritake and Kimura (NORKI83, NORKI90), in Japan.

b) In almost all the applications of SDP and QT, the analysis concentrates on the ship-berth interface. The exceptions to this rule are the papers by Koenigsber and Lam (KOELA76); Daskin and Walton (DASWA83), Taleb-Ibrahimi, Castilho and Daganzo (TACADAG90) and Castilho and Daganzo (CASDAG91B).

c) The applications of simulation tend to consider the other service processes as well.¹ In addition, simulation allows an explicit consideration of the particular conditions of each port (e.g., yard geometry).

d) Consultants tend to prefer simulation because of the reasons given above. At the same time, it is observed that academicians tend to use QT formulations more frequently.²

e) The perception about the accuracy of simulation has changed over time. More than twenty years ago, simulation was considered to be "approximate" and QT "exact."³ In today's context, the big differences in the service times for the different ship sizes and ship types make it difficult to justify the assumption of a homogeneous population of users that is required by QT.⁴ It is widely accepted that, if the model specification and calibration process are adequate, simulation would provide more accurate results than QT.

¹ A consequence of the availability of powerful computers and flexible simulation languages.

² Maybe because of its potential for generalizations.

³ MILLE71.

⁴ The practical range of container ship sizes goes from something more than 1,500 tons of Dead Weight Tonnage (DWT), transporting 80 TEU's, (the first generation of containerships), to the post-Panamax vessels of over 100,000 DWT that transport more than 3,000 TEU's. In addition to size variability, there are at least five different types of containerships, each one with different service characteristics.

SHIP DISTRIBUTION AT PORT (SDP)

This approach relies on the assumption that the berth occupancy analysis can be performed using the observed SDP. A typical SDP application involves the use of a Poisson distribution to obtain the number of days/year that a number of ships ($n = 0, 1, 2, 3 \dots N$) would be present at the port. The parameter of the Poisson distribution represents the average number of ships present at the port at any time. Using the Poisson distribution, the number of hours the berths are vacant are calculated and compared with the number of hours the ships are present. Then, the cost for waiting ships are calculated and added to the fixed costs of the facilities. The optimum number of berths is obtained as the one that minimizes the total cost.

The weakest point of this approach, as it pointed out by Miller (MILLE71), is that the number of ships present at the port, at any given day, is not independent of the number of ships that were present the day before and, consequently, assuming a Poisson distribution is incorrect. In addition, since they assumed that the Poisson distribution remains the same, irrespective of the number of berths and the demand, they did not properly consider the influence of the service characteristics on the performance measures (i.e., waiting times). The works by Fratar, Goodman and Brant (FRGOBR61), Plumlee (PLUML66) and Nicolau (NICOL67)⁵ are typical examples of this approach.

QUEUING THEORY

The use of QT was suggested in the 20's and 30's for the capacity analysis of ports, but it was not until the early 60's when it became widely used (AGKOR69). It is difficult to say what was the first QT application in PO/ITC. The first application is commonly attributed to Mettam (METTA67) but an earlier application by Gould (GOULD63)⁶ is recorded in the list of references. Mettam (METTA67) did demonstrate the practicality of QT by stating the basic principles of this type of application to port planning, and highlighted the potential benefits that could be obtained from it. As it was to become typical of this approach, Mettam considered only the ship-berth interface. His paper was influential in attracting other analysts to QT.

In general, the majority of QT applications consider only the ship-berth interface. In these applications standard QT has been used to provide performance estimates. Other type of QT models (e.g., queuing network and cyclic queues) have not been used as often as their potentials seem to suggest.

⁵ Nicolau, responding to Mettam's criticisms to his paper, wrote a closure note to the discussion that is based on a QT formulation (NICOLAU69) in what appears to be a recognition of the limitations of SDP.

⁶ Unfortunately, we have not been able to find Gould's paper.

After an extensive search, only one paper using queuing networks (DASWA83) was found. The opinion about queuing networks is that it is a "useful approach" but very difficult to implement at complex ports.^{7,8} Despite this, Frankel (FRANK87) gives an example of this type of application in a hypothetical situation.⁹

Cyclic queues have been used to model systems in which the server rotates its efforts among a set of users. The formulations developed by Koenigsber (KOENIG58) and Gordon and Newell (GORNEW67) provide the foundation for this type of application. Applications by Koenigsber and Lam (KOELA76) and Daskin and Walton (DASWA83) are the only ones using cyclic queues, though its potential usefulness is recognized. Daganzo (DAGANZ90B) examined the properties of this type of queuing system.

SIMULATION

The number of paper on simulation applications is enormous; however, the number of innovative applications is much less. Most papers do not describe the details of the models. At most, a simplified description is provided in the context of actual applications. This situation arises because most of the simulation models are developed by private companies, being for most cases, proprietary materials. For evident reasons, these companies are not interested in making the public know about the operating details in their models. This situation imposes a big limitation at critically reviewing literature in port operations.

Some of the most important simulation models are described by Frankel (FRANK87). He described three models: MIT Port Simulation, PORTSIM (World Bank) and UNCTAD Port Operations Model. In what follows, the main features of those models are summarized, as described by Frankel.¹⁰

The MIT Port Simulation Model is a general model that can be used to analyze multipurpose ports. It is able to handle different types of cargoes and ships. It simulates all service processes that take place in ports.

PORTSIM was developed by the World Bank for the economic appraisal of port infrastructure investments. For that reason, little attention was given to the service processes that take place back of the berths (e.g., shed operations).

The UNCTAD Port Operations Model was developed to analyze the efficiency of alternative strategies of port operations. It is very comprehensive, allowing a very detailed analysis of the different service processes and port operation policies; however, it does not consider multiport systems.

⁷ FRANK87, pp. 178.

⁸ THODA80.

⁹ FRANK87 pp. 362-363.

¹⁰ FRANK87, pp. 375 -395.

The different approaches that have been described (i.e., SDP, QT and simulation) have different features and theoretical implications. Their applicability can be summarized in Table 1.¹¹ As can be seen, the observed applications of simulation extend to many different areas, except those directly related to the physical layout. In contrast, QT and SDP show a more restricted set of applicable areas. SDP can only provide some guidance, if any, with respect to the number of berths (under the heading "machinery"). However, QT allows an explicit consideration of the loading capacity of the berths.

Table 1: Approaches to Performance Analysis and Observed Applications								
Method	Predict or	Machinery			Storage capacity:		Area required	Layout and arrangement
	Optimize	Number	Type	Capacity	Operational	Inventory		
SDP	P	YES	NO	NO	NO	NO	NO	NO
Queueing theory	P	YES	NO	YES	YES	NO	NO	NO
Simulation	BOTH (1)	YES	YES	YES	YES	YES	YES	NO

Note: 1) Probably in conjunction with a search logic.

Table 2 contains a summary of the advantages and disadvantages of using the different approaches. In general, QT and SDP are easier to apply; but the realism of their results is limited by the fundamental assumptions of both approaches. On the other hand, simulation is considered much more realistic, but it is more difficult to implement.

¹¹ This table was originally made by Frankel (FRANK87, pp. 269) for a comparison of the different approaches for port design. It was expanded to include SDP.

Method:	Advantages:	Disadvantages:
SDP	Simple. Easy computation.	Not applicable when number of berths is small and waiting time is significant. Does not consider the characteristics of service processes.
Queueing theory	Relatively simple to use. Easy computation. Easy parametric variation. Easy to explain and visualize.	Limited set of solutions. Restrictive, sometimes unrealistic assumptions. Limited applicability to continuous systems. Complicated systems must be separated into sub-components losing some of the systematic interaction.
Simulation	Easy to explain and understand. Most features of the system. can be modelled to detail required. Easy parametric evaluation.	Requires computer. Larger effort involved to make computer work less to studying the problem. Random variable in answer.

CATEGORIZED BIBLIOGRAPHY

Table 3 shows the categorization of the bibliography by model used and area of application. Each of the different combinations of model area of application constitute a niche. The papers were sorted by niche and publication date. Since the niches are not exclusive, some of the papers appear more than once.

Four different types of models were considered: SDP, QT, simulation and operations research (OR). In addition, the QT models were further subdivided into: standard QT (i.e., birth-death processes in equilibrium), markovian queues, cyclic queues (i.e., queues in which the server rotates its efforts among several users), ¹² and a general heading called "contributions to QT" that includes new additions to QT related to the analysis of port operations.

¹² Though cyclic queues could be classified as a birth-death process in equilibrium, it is going to be placed in a separate sub-category because of the particularities of its formulation, that make it different from the former.

The following areas of application were considered:

a) Performance analysis includes all applications that intended to assess performance according to some metric (i.e., waiting times) without translating them to economic units.

b) Optimization of the number of berths considering only port costs considers all applications in which port performance is assessed and translated into economic units. The objective function only includes the port costs.

c) Optimization of the number of berths considering port costs + inland costs includes all applications in which port performance is assessed and the objective function (total cost) includes port and inland costs. The inland costs are estimated using OR formulations (i.e., transshipment problem).

d) Optimization of other service processes includes all papers related to the application of optimization techniques to processes different from the ship-berth interface.

As can be seen in Table 3, the majority of published papers are related to performance analysis (mainly ship-berth interface). Also evident is the fairly high level of acceptance that standard QT enjoys. Standard QT has been used as a performance model with and without optimization models (i.e., minimizing port cost and minimizing port costs plus inland costs). The other QT categories (e.g., markovian queues and cyclic queues) have not been used in conjunction with optimization models, though extensions of these models to economic analysis are fairly easy to develop. It is possible that some of these models were used to quantify economic impacts, but the results were not reported in the papers.

The use of these "non-standard" formulations as the performance model, in an optimization framework, offers a lot of opportunities and challenges for research. In this context, these models could be used to estimate the different components of port costs, thus enhancing the quality of the estimates by adding more realism to the performance model. It seems possible to model the different stages (i.e., unloading from the ship, movement to storage yard and final storage) using a set of linked models in a queuing network formulation.

Cyclic queues offer some interesting possibilities as well, from the theoretical and practical sides. From the theoretical perspective, an area of potential research is related to how to use service distributions other than the negative exponential.¹³ From the practical standpoint, a number of service processes that seems to be suitable for cyclic queue formulations (i.e., truck operations moving containers from the berth to the storage yard), have not been modeled using this type of model.

The opportunities for innovative applications are not limited to the type of model used. The objective function used to make decisions about the number of berths offers some possibility for improvements as well. Traditionally, two different perspectives have been used to define this objective

¹³ Negative exponentials are required for the current formulations to be tractable.

function: a) port operator perspective and b) national (or regional) perspective. In the former case, the objective function includes only what is relevant to the decision making process, the port costs. Examples of this approach are the applications by Miller (MILLE71) and White (WHITE72). Regarding the latter, since a national or regional planning agency is likely to be concerned with the system impacts of port investments, the inland portion of the trip is considered as well as the port costs. Applications by Chang (CHANET75) and Frankel (FRANK87) are typical examples of this group.

In the current intermodal environment, an additional perspective (i.e., intermodal carrier's perspective) is taking a growing importance. In this context, the maritime portion of the trip cannot be neglected. In fact, container carriers decide what ports to use as a function of the total cost, in which the maritime portion plays a big role. To the author's knowledge, no applications have been reported in the literature from this particular perspective.

Table 3: Categorized Bibliography

Type of model:	Area of application:			
	Performance analysis	Optimization of number of berths:		Optimization of other processes
		(only port costs)	(port+inland costs)	
SDP	FRGOBR61	PLUML66 NICOL67	Not worth to pursue this line of research	Not worth to pursue this line of research
QT	a) Standard QT METTA67 JONBL68 NICOL69 MILLE71 WHITE72 (1)	AGKOR69 BUCGO74 WEIRA74 WOOD82 (7) NORKI83	CHANET75 SHNEE81 NORKI90	Potential for new applications and research
	b) Markovian queues DASWA83 (2)	Easy to extend to this area	Potential for new applications and research	Potential for new applications and research
	c) Cyclic queues KOELA76 (3) DASWA83 (2) DAGANZ90B	Easy to extend to this area	Potential for new applications and research	Potential for new applications and research
	d) Contributions to QT SADAG89 DAGANZ89B DAGANZ90A DAGANZ90B CASDAG91 (3b)	Easy to extend to this area	Potential for new applications and research	Potential for new applications and research
Simulation	DANVO80 FRATA80 KAWEN80 THODA80 BOESE83 (4) DUBE83 (5) GOLWO83 (6) WOGRCU83	Easy to extend to this area	FRANK87 Potential for new applications and research	Potential for new applications and research
Operations research	Not applicable	Not applicable	CHANET75 SHNEE81 NORKI83 NORKI90	DAGANZ89A (8) PEDAG90 (9) TACADAG90 (10)

Notes:

- 1) Loading capacity improvements.
- 2) Lightering operations for very large crude carriers (VLCC).
- 3) Fleet operations in closed systems.
- 3b) Quantification of amount of effort according to different storage strategies.
- 4) Rail-truck interface.
- 5) Piggy-back terminals.
- 6) TOFC terminals.
- 7) Priority systems at the ship level.
- 8) Application of integer programming to crane scheduling.
- 9) Application of Branch and Bound to crane scheduling.
- 10) Quantification of impacts of handling and storage schemes.

CHAPTER II. ANNOTATIONS

This chapter includes annotations for a selected group of papers. Because of the inherent weaknesses of the SDP approach, none of the papers that used this approach was annotated.

There were a number of different reasons to include a paper in this chapter. The first reason is the historical significance of the paper (i.e., by influencing other authors). METTA67 and MILLE71 were included for that reason. A second group of papers were included because of their methodological contributions, either because they made innovative applications of known techniques (i.e., CHANET75, DASWA83) or because they developed new formulations to analyze port operations (i.e., DAGANZ89B and SADAG89).

Mettam (METTA67) is recognized for having stated the basic concepts that guide QT applications to port operations. His paper was influential in motivating other researchers and practitioners to use QT formulations. In general, Mettam described how standard QT theory could be used to determine the optimum number of berths. Mettam's approach is conceptually valid and practically useful when it is used for berth planning in situations in which schedule arrivals do not represent a significant portion of the port demand. If schedule arrivals represent a significant portion of the demand, the assumption of a Poisson distribution is no longer valid.

Miller (MILLE71) analyzed the three different approaches to performance analysis of port operations, namely SDP, QT and simulation. His paper correctly points out the main deficiencies of SDP and at the same time it discusses the advantages and disadvantages of QT and simulation. He considered simulation to be "approximate."¹⁴ In contrast, Miller considered QT to be "exact" provided that: a) ships arrive at random and b) service times are independent of each other and of the number of ships waiting. Assumption b) is reasonable and, probably, can be justified in a wide range of applications. However, the validity of assumption a) cannot be taken for granted because, nowadays, an increasing number of ships have fixed schedules, though not punctual. If QT is used in such a situation, it would provide conservative estimates for waiting times. At the time of stating these conditions, Miller failed to recognize the fact that ships are not homogeneous. In fact, their characteristics (i.e., ship size and service times) have high variability. This poses a limitation for QT applications because QT relies on the assumption of a homogeneous population of users.

Chang, Yang and Vandervoort (CHANET75) described a useful application of nonlinear programming. The objective function included inland and port costs. They used separable programming

¹⁴ He performed a manual simulation for a case study. Maybe for that reason he considered the results of this approach as "approximate." Nowadays, simulation is considered to be a realistic approach that, if properly used, is able to provide more exact results than QT.

techniques to linearize the nonlinear harbor cost functions and to be able to use linear programming (LP) techniques. They used standard QT formulations to estimate the waiting times for the different harbor configurations and its corresponding costs. Since they determined the optimum number of berths using Benefit/Cost ratio, it is not clear if they correctly dealt with the inconsistencies associated with this estimate. As they did not use mixed-integer programming, the consideration of time-phasing (i.e., when to expand a berth) and project size were made by trial and error assisted by judgment. They use the LP output to provide estimates of the marginal social costs, a key element in determining port charges.

Daskin and Walton (DASWA83) developed a model based on queuing networks for the analysis of lightering operations for very large crude carriers (VLCC). They developed a set of queuing models linked by a model of VLCC service times. The models considered were: a) lightering ship movement model in which, by assuming that the service times were exponentially distributed, they were able to use the model for cyclic queues developed by Koenigsber (KOENIG58) and Newell (GORNEW67); b) VLCC delay model, where they used an approximation for the model $M/E_k/S$; and c) VLCC service time model in which they used an iterative procedure to solve simultaneously the VLCC delay model and the VLCC service time model. The system of models was applied to a case study and different scenarios were tested.

Sabria and Daganzo (SADAG89) analyzed a single server queuing system in which the customer arrivals are scheduled, though not punctual. Tardiness (i.e., the difference between scheduled and actual arrival time) are modeled as the outcome of independent identically distributed random variables. A recursive formulation was obtained for the cumulative distribution of the departure times, in terms of the cumulative distribution of arrivals and the cumulative distribution of service times for the previous customers. This recursion allows obtaining transient solutions for a given set of initial conditions. In addition, analytical expressions for light traffic were obtained. Results provided by these expressions were compared with the ones provided by other approaches (i.e., Bloomfield and Cox's model and simulation), finding, in general terms, a good agreement.

In two separate projects, the amount of handling effort related to moving export and import containers was quantified. The former research was conducted by Taleb-Ibrahimi, Castilho and Daganzo (TACADAG90) and the latter by Castilho and Daganzo (CASDAG91B).

Taleb-Ibrahimi, Castilho and Daganzo (TACADAG90) developed formulations to quantify the handling effort (defined by the number of moves) associated to moving export containers. They considered two types of space allocation strategies: static and dynamic. The former describes the case in which the slots at the marshaling yard are reserved for a ship as soon as the first container arrives, requiring considerable space. The latter describes the strategies in which the assignment of slots at the marshaling yard is postponed to a given time before ship arrival. In this way, space needs are reduced, but

an extra cost (i.e., by moving containers) is added. This formulation is used to analyze the strategy that yields a minimal handling effort given a fixed amount of space. Because of the combinatorial nature of the problem, they used a heuristic approach to assign the slots.

Castilho and Daganzo (CASDAG91B) developed expressions to quantify the handling effort associated to move import containers (i.e., the expected number of moves required to retrieve a single container) following two strategies: a) trying to keep the stack height constant and b) segregating containers by ship arrival. Regarding the former, they obtained an expression for the expected number of moves that is a function of the initial and final average stack height and the variance of stack height that was estimated using simulation. Since they assumed that all containers are equally likely to be retrieved, the expression obtained can be interpreted as a lower bound. They also developed an upper bound for the expected number of moves by assuming that shuffled containers (i.e., the ones that have been moved to clear the way to the target container) are always returned to their original position. The aim of the second strategy (i.e., segregating containers by ship arrival) is to reduce the number of moves. They developed expressions for the expected total number of moves (i.e., the sum of the expected number of retrieval moves and the expected number of clearing moves). Both strategies were compared in an idealized situation, concluding that the segregating strategy tends to perform better provided that land is scarce and containers are stacked high.

The optimization of crane scheduling has been the subject of three different research projects (i.e., DAGANZ89A, DAGANZ89B and PEDAG90). Daganzo (DAGANZ89A) discusses the application of optimization techniques to crane (i.e., gantry cranes) scheduling. He identified two classes of problems: a) static (i.e., when a collection of ships, already present at the port, are going to be served); and b) dynamic (i.e., when ships arrive when the cranes are in use). In both cases the objective is to minimize the sum of the ship waiting times. The static problem can be formulated as an integer programming (IP) problem provided that the size is small. Using the resulting IP problem, he derived a set of three principles that should guide the crane assignment. The applications of these principles lead to a near optimal solution, without the computational burden of trying to solve a combinatorial problem. He compared the total time resulting from this assignment with the minimum obtained by using Branch and Bound. No significant differences were found among them. The dynamic case was also analyzed, concluding that the three principles still apply and, if modified, its use is still attractive.

Daganzo (DAGANZ89B), building on his previous works (DAGANZ89A and PEDAG90) developed steady-state equations that assess the impact of crane scheduling strategies upon the maximum throughput and ship delay. The fundamental assumptions used in this paper are similar to the ones used in his early works (DAGANZ89A and PEDAG90). The keystone of this formulation is the equation that links cargo throughput to the expected number of busy cranes and crane capacity (i.e.,

cargo throughput = expected number of busy cranes x crane capacity). The only unknown in this equation (i.e., expected number of busy cranes averaged over time) is estimated as the minimum of two values: the number of cranes, C, and the number of active holds, A. ¹⁵ Then, by assuming that the number of active holds present at the berth at a random time has the same probability distribution as the number of holds requiring attention for S ships randomly sampled from the queue, Daganzo was able to estimate the minimum of A and C by means of a truncated normal variable.

The crane productivity model is then used to assess the impact of crane allocation method upon the cargo throughput. Two different strategies were considered. The good strategy, G, assigns the cranes in the most cost-effective way (i.e., in decreasing order of ship cost to workload ratio). The bad strategy, B, assigns the cranes in the opposite way (i.e., in increasing order of ship cost to workload ratio). The results showed that there is not a significant difference in the cargo throughput between the two strategies.

In addition, the relation between ship delay and crane allocation methods was studied, for the same strategies. The analysis concluded that there is a significant difference between the ship delays associated to each strategy. In some cases, switching from the "bad" strategy, B, to the "good" could reduce ship delays by 25%.

Daganzo (DAGANZ90A) analyzed the productivity of multipurpose ports. Two different types of ships were considered: liners (i.e., ships with scheduled arrivals and high loading priority) and tramps ¹⁶. Three different berths assignment strategies A, B and C, were discussed. ¹⁷ Daganzo analyzed the properties (i.e., expected value and variance) of the tramp overflow when strategy C is implemented. Using the expected value of the overflow, Daganzo developed expressions to calculate the productivity of the multipurpose terminal (i.e., the maximum flow that can be handled without affecting liner operations).

¹⁵ An active hold is defined as a hold being served by a crane.

¹⁶ In the maritime industry, liners are those ships with scheduled arrivals. Tramps have random arrivals and the lower priority, these are regularly used to transport low valued cargoes.

¹⁷ Strategy A assigns each tramp to the unassigned berth that has been available the longest. Strategy B assigns each tramp to the unassigned available berth that is to become unavailable next. Strategy C assigns each tramp to the berth that is to become available next.

CHAPTER III. SYNTHESIS OF THE LITERATURE REVIEW

This chapter provides a brief description of the papers reviewed not annotated in the previous chapters. The papers are classified according to the approach used. The description follows a chronological order.

SHIP DISTRIBUTION AT PORT (SDP)

Fratar, Goodman and Brant (FRGOBR61) wrote the first SDP application. They used a Poisson distribution to predict the maximum berth occupancy. This paper attracted other analysts to this type of application, in spite of the flaws in the basic assumptions.

Plumlee (PLUML66) extended Fratar's approach to include the assessment of the economic benefits (i.e., in reduction of ship waiting costs) and the costs (i.e., berth fixed costs) and derived the optimal number of berths accordingly.

Nicolau (NICOL67), following Plumlee's assumptions, provided guidelines to determine the optimum number of berths, according to the economic characteristics of the system (i.e., ship operating costs, berth costs).

QUEUING THEORY

Jones and Blunden (JONBL68) applied different queuing models to the port of Bangkok. Like Mettam, they considered only the ship-berth interface. They analyzed several models, trying to determine which of them produced the most realistic results.

Agerschou and Korsgaard (AGKOR69) pointed out some of the weaknesses of the SDP approach. They analyzed the role of systems analysis, establishing the general objectives of economic analysis in the PO/ITC context. They also analyzed the implications of using simulation and mentioned some of its early applications.

White (WHITE72) used QT to analyze the economic feasibility of loading capacity improvements. Weille and Ray (WEIRA74) expanded White's approach to determine the optimum number of berths and the optimum loading capacity. They analyzed the different approaches that can be taken, depending on the availability of information. They used $M/E_k/S$.

Robinson and Tognatti (ROBTO73) analyzed the literature related to performance analysis of port operations.

Buckley and Goneratne (BUCGO74), using different queuing models to estimate congestion, derived formulae to obtain the "unique optimal flow." ¹⁸ Their analysis is quite interesting, but it has some limitations. They estimated the benefits for a system with inelastic demand. This limits their approach to rehabilitation projects and minor investments that do not have a large impact on the total demand. The second limitation regards the assumption that they made about the salvage value and maintenance costs.

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Koenigsber and Lam (KOELA76), using Newell's (GORNEW67) approach to cyclic queues, developed a formulation to analyze fleet operations in closed systems. They extended previous works in this area to deal with the particularities of this application. They obtained a closed form solution for the case of exponentially distributed stages, and performed simulation to analyze the effects of other distributions. They compared their results with a case study.

Shneerson (SHNEE81) used QT in a Dynamic Programming formulation to analyze investment in a port system, involving how best to distribute the cargoes among ports. He considered the investment costs plus queuing costs, plus inland transportation costs. Shneerson's approach is an extension of Devanneys's (DEGOTH72).

Wood (WOOD82) made an interesting integration of QT and economics. He analyzed the economics of priority systems for the berth assignment of two different classes of users: cruises and freight ships. He applied his formulation to a case study.

Noritake and Kimura (NORKI83) developed a procedure to determine the optimum number of berths and the volume of cargo that can be handled by different port configurations (defined by the number of berths). They used Cosmetatos' approximation (COSME75, COSME76) for the waiting times of the M/Ek/S/infinite model.

Easa (EASA87) analyzed the influence of tug services on congested harbor terminals. He modeled this problem as a queuing system with M identical servers (tug boats) and N identical customers (berths). He derived the distribution of the number of berths in the system for two conditions, for large M, for which the distribution can be approximated by a binomial model; and for small M for which an approximate model was developed. The approximation is based on the works of Newell (1980). He used the G/G/m/n model.

¹⁸ The traffic flow that minimizes the total discount cost (congestion cost plus capital cost minus salvage value plus maintenance cost).

¹⁹ They assumed that the reduction of the salvage value equals the increment in maintenance costs, such that their sum is constant over time. Even when this assumption makes sense in the context of some applications, it is not likely to be a general statement.

Daganzo (DAGANZ90A) analyzed the influence of the priority scheme on port productivity, for the case in which there are two groups of users, liners and tramps. He estimated an approximate expression for the tramp overflow when the tramp flow is heavy.

Daganzo (DAGANZ90B) examined the properties of single server systems in which the server rotates its effort among several users, i.e., group of containers to be loaded/unloaded. He derived expressions for the first and second moment of the queue length and the mean waiting time.

Noritake and Kimura (NORK190) proposed a model to analyze port networks that follows closely Chang et al's formulation (CHANET75). The objective function they defined considered two cost components (i.e., the inland transportation costs and the port costs). To deal with the nonlinearities of the port cost, with respect to the throughput, they used separable programming. Again, they used Cosmetatos' approximation (COSME75, COSME76) to the waiting times of the model $M/E_k/S(\infty)$ model.

SIMULATION

Frankel and Tang (FRATA80) defined the different components of the port systems and developed a conceptual model, based on activity and storage links. They used this model in applications to the planning of typical tanker terminals, using GERT (Graphical Evaluation and Review Technique).

Thompson and Davis (THODA80) described the model validation process adopted by Exxon. Kaplan and Wentworth (KAWEN80) analyzed the features of the software developed by Bechtel. Daniell and Vora (DANVO80) described the simulation model used by Fluor Ocean Services, based on GPSS. Wong, Grant and Curley (WOGRCU83) described the software that is supported by SRI International.

Frankel (FRANK87, pp. 416-424) describes a Regional Port Strategy Model that can be used to optimize systems of ports. This model was used in the "Venezuela Port Study." The model minimizes the total transportation costs (inland + port), and it uses simulation to estimate the ship delay function.

Other papers describe the simulation of different aspects of the container movements. As an example, Dube (DUBE83) describes the simulation of piggyback terminals; Golden and Woods (GOLWO83) describe the application to TOFC terminals; and Boese (BOESE83) analyzes the railroad-truck interface.

OTHER PAPERS

Goss (GOSS67) motivated the economic analysis of port investments. He discussed economic theory and how it could be applied to ports. It contains a fairly detailed list of the early references to the subject.

Warwar (WARWA80) proposed a simplified methodology to estimate port capacity, based partially in the works by Mettam and the experience of PRC Harris in port planning.

Bobrovitch (BOBRO82) analyzed the implications of decentralized planning in a national port system. He developed a simple model of a two port system, demonstrating that competition of profit-maximizing ports leads to a sub-optimal allocation of resources.

Hatzitheodoru (HATZI83) estimated the cost for different container handling schemes (i.e., stacked and wheeled), concluding that wheeled operations are more economical provided that: a) containers remain in port for a short period of time; b) cost of land is small; c) containers are long (40') and d) the efficiency of container handling equipment (i.e., top loader) is low.

Daganzo (DAGANZ89A) analyzed the crane scheduling problem using integer programming to obtain an exact solution for small problems. For larger problems, he presents optimality principles to guide the decision. ²⁰

Peterkofsky and Daganzo (PEDAG90) analyzed the crane scheduling problem proposing the use of the Branch and Bound algorithm to minimize the delay at ports. They analyzed different priority schemes and the computational efforts involved in the optimization. Because of the complexity of the formulation, they restricted their analysis to the static case (as defined in DAGANZ89A).

Castilho and Daganzo (CASDAG91A) analyzed the pricing schemes for transit sheds at ports. They analyzed two different schemes: non-discriminatory ²¹ and discriminatory.

²⁰ He analyzed two cases, the static case (when all the ships to be served are already present) and the dynamic case (when some ships arrive when others are being served).

²¹ Prices as a function of volume and time; the same for all users.

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