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Modeling Port Congestion Using Queueing Theory: The Case of the Autonomous Port of Conakry

Abdoul Karim Diallo[1], Coumba Diallo[2], Karamoko Sita Diallo[1,3], Papa Ngom[2]

[1]Department of Mathematics, University of Labe (UL), Labe, Guinea Conakry
[2]Department of Mathematics and Computer Science, University of Cheikh. A. Diop, Dakar, Senegal
[3]West African Institute of Mathematics of the Gamal Abdel Nasser University of Conakry (IOAM/UGANC), Conakry, Guinea
Email: abdoul-karim.diallo@univ-labe.edu.gn, coumba16.diallo@ucad.edu.sn, karamoko-sita.diallo@univ-labe.edu.gn, papa.ngom@ucad.edu.sn

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Abstract

This article highlights the relevance of queuing theory as a decision-making tool for solving congestion problems in Guinean ports, particularly of the Autonomous Port of Conakry (APC). Port congestion, which often causes delays and additional logistics costs, is a major obstacle to economic development. Using an analytical approach and numerical simulation, the study proposes a realistic model of the operation of the APC container terminal based on the GI/GI/c general queuing model, adapted to complex systems where the distributions of arrivals and services are not necessarily exponential. The Statistical tests performed on empirical data from the year 2023 revealed that ship inter-arrival times follow a Weibull distribution, while service times are well described by a Gamma distribution. Integrating these distributions into the GI/GI/c framework enabled realistic simulation of the port system's behavior. The simulation results show an average waiting time of about 1.4 days, a berth occupancy rate of 43%, and a high probability that the system is empty, indicating good operational fluidity. The average observed service rate, estimated at 0.033 ships/hour, demonstrates the port's ability to efficiently handle vessels without generating congestion. These performances confirm the positioning of the Autonomous Por3t of Conakry, through its container terminal, among the most efficient in West Africa in 2023. The methodological approach developed in this paper, combining probabilistic modeling and simulation, can be extended to other ports in the region for comparative analysis, to support strategic planning of port infrastructure, and to guide decision-making regarding investment and capacity optimization.

Keywords

Queuing Theory, Autonomous Port of Conakry, Container Terminal, Port Congestion, Queue Modeling

1. Introduction

Port congestion is a global issue that makes an impact on the provisioning channels and the local economies. In Guinea, the Autonomous port is an outstanding infrastructure of trade, and the extended delays of ships provide some high costs. Basing our studies on some similar cases, particularly those of Nigeria, this research suggests the use of the queuing theories to model the arrivals and the ships services in order to find some solutions to improve the flaw of the port traffic. Basing our studies on some similar cases, particularly those of Nigeria, this research suggests the use of the queuing theories to model the arrivals and the ship services in order to find some solutions to improve the flaw of the port traffic. The overcrowded port is a recurring phenomenon that makes an impact on the performance of naval infrastructures, particularly in the developing countries where the logistic abilities are often limited in front of an increase in traffic. This manifests itself in delays in the processing of ships, congestion of goods, increased overtime costs, and a decline in the competitiveness of ports. In West Africa, many studies have made proof of the economic drawbacks of this congestion, particularly in Nigeria where the ports in Lagos and Tin Can Island have suffered significant losses due to a lack of planification and unfitting infrastructure [1]-[4]. In Guinea, the Conakry Autonomous Port represents a strategic infrastructure, guarrantying near of 90 % of the exportation of the country. Meanwhile the efforts of modernisation undertaken these last years, the question of the flow of the naval traffic and the ability of the port to absorb the flux remain central in the discussions held on national logistic performance. In response to this question, this study proposes an analytical approach based on queuing theory to model the operation of APC container terminals and evaluate their operational performance. Queueing theory, introduced in diverse logistic contexts [5] [6] and later formalized by [7], provides a mathematical framework to represent arrival and service processes within a system, while accounting for variations and operational shifts in port activities. The classic models M/M/1 and M/M/c, though useful lay emphasis on exceptional hypothesis distribution often unrealistic in the african context. That is why this study copes with the GI/GI/c model, generally, allowing the integration of empirical laws, such as the Weibull law for the inter-arrival ships and the law of Gamma for the time of services of the quays. The main objective of this research is to analyse the performances of the terminal of containers of the PAC based on the real data collected in 2023, in shaping the behavior of the port system in realistic conditions. It is to identify the key indicators of performance such as the medium time of queuing, the rate of occupation of the quays, the probability of congestion and the flow of the system in order to suggest the best planning of ressources and an optimization of operations. The methodological approach combines the statistical tests of adequation (Kolmogorov-Smirnov (K-S), Akaike's information criteria (AIC) and Bayesian information criteria (BIC)) to determine the law of more fitting probability and a mathematical simulation grounded in Python to reproduce the dynamic function of the Port.

The article is articulated as such: after this introduction, the section 2 presents a review of literature on the application of the queuing theory in ports, while putting forward the used models and the obtained results in different contexts. The section 3 goes into details through the fitting methodology, made up of the GI/GI/c model, the adequation tests and the estimated parameters. The section 4 is focused on the case study of the Conakry Autonomous Port, through a description of the infrastructure of data collected and the statistical caracteristics of the flaws. The section 5 displays the results of the numeric simulation, the performance indicators and the associated probabilities to the system functioning. At last, the conclusion summarizes the principal teaching of the study and suggests some perspectives for the extension of this approach to other ports of the region.

2. Literature Review

The theory of queuing is used in several sectors to manage the flaws and optimize the services, particularly in the ports, where it allows for dwindling the congestion by analysing the rate of ships' arrival and their time of service. The pioneering work on queuing theory introduced probabilistic models that remain highly relevant for modeling port queuing systems [7]. In literature it exists several grounded models including: The systems M/M/1 (Markovien for arrivals and services with just one server) [8] The systems M/M/c (several parallel servers) [9], Queuing with priority [10], etc.In addition, this review summarizes the key works on the use of queuing theory to analyze and optimize various systems, particularly in the fields of road traffic, port logistics, and supply chain management. Many studies have explored the application of queuing theory to real-world cases. Maduka (2004) and Onwumere (2008) examined Nigerian ports and highlighted that persistent congestion has caused significant economic losses due to delays and cost overruns [1]. Similarly, Zhang *et al.* (2008) analyzed West African ports and showed that inadequate infrastructure contributes to frequent congestion [10]. Sanish (2007) has studied the port of New Mangalore, displaying that the exponential traffic queuing leads to an unefficient use of port setting. Adedayo *et al.* [11] have applied these principals in the port contexts to model the queuing flaws of services.

This theory permits to analyse the process of stochastic in which some "custommers" (ships in the case of port) arrive at random and are served by some "servers" (post of quay, cranes, etc.). In a global context, some studies as those of Tu-Cheng *et al.* (2006) on Taïwan region ports and Beškovnik (2008) on terminals of containers have underlined the importance of the theory of queuing in order to improve the performance of the ports of containers by optimizing the ships flaws and containers and dimunishing the costs which are linked to the delays [12] [13]. Several researchers have applied these models of queuing to simulate the performances of ports and suggesting some improvements. For instance Sharma (2008) and Radmilovich (1992) have developped some models of services multichannels to forsee the queuing et estimate the number of optimal mooring posts [14] [15]. The modeling of queuing to maximise the traffic and minimize the time of queuing has been explored by Chen-Hsiu and Kuang-Che (2004), who have demonstrated its efficiency on the asian ports highly congestionned [16]. Several authors have applied the queuing theory to the ports: Noritake, M. and Kimura, S. (1983) [17], has been one of those who have modelized the ports terminals as some multiservers systems with arrival times and services offered at random. Talley, W.K. (1988) [18], has introduced some non-exponential distribution. to represent the time of services down the ports. Song, D.-W. and Cullinane, K. (2006) [29], have studied the impact of some priorities of ships ont étudié l'impact des priorités de navires (for example, containers ship vs bulk carriers) on the congestion. Onyemechi, C., *et al.* (2018) [20], have examined the contributing factors to the congestion at five african ports. They use some statistic analysis to demonstrate the significant relation existing between the freight volume and the indicators of the ports performance underlining the importance of plannification and efficiency to reduce the congestion. Gidado, U. (2015) [21], have analyzed the negative impacts of the port congestion on logistics and the supply chain in Africa, highlighting the financial losses and operationnal unefficiencies drawn from them.

Xu Jingjing et Liu Dong (2021) [6], have explored in what extent the model of queuing may be used to optimize the services of handlingg in port terminals, reducing the waiting time while improving the global efficiency We recall that, it does exist several. techniques to evaluate the performance in the port Hector-articularly the DEA method. Diallo, K.S., *et al.* (2022) [22], have used the DEA method in order to evaluate the Dakar Autonomous Port performancy. Otherwise, diverse authors have studied the specific factors that contribute to the congestion of ports. For instance, Kalavaty (2007) has highlighted the effect of olding insfrastructures and operational unefficiency on queuing training in ports. of customs process, and the lack of mechanization leading to a queuing process and increasing the mooring delays, what is confirmed by the studies on the West African port [23]. For more information related to the review of literature on this domain for instance ([24]-[26]). The modelisation of ports systems is well documented. The classic models M/M/1 ou M/G/1 have often been used, but tthey suppose some exceptional less realistic. The model GI/GI/c, in general, allows to better represent the observed behaviors in the port, particularly with empiric distributions as Weibull et Gamma [27].

3. Methodology

The development of queuing methods include: the integration of the addiction or dependance to the state in models such as ([27]) and hybridation with approachs of hidden simulation in order to catch the real systems complexities. The port cogestion refers to the accumulation of ships or merchandise in the port providing some delays, a loss of productivity and an increase of logistic costs. It is more of the time occured bu an ill plannification of infrastructures or either uneffient process. The theory of queuing offers a mathematical area allowing a modelisation of the arrivals, the treatment, the waiting of services of units (ships, containers, trucks, etc.) in a system. It remains widely used in port logistics studies in order to simulate and optimize the ports operations. Kolmogorov-Smirnov (K-S) test is a statistic not parametric permitting the comparison of the empiric distribution of a sample to a given theoric distribution (adequation test) or either the comparison two free samples (homogeneity test). This test lays on the empiric dividing function and measures the maximal gap between comparing distributions. In this study, we use the general queuing model $GI/GI/c$, where: GI: designs a general law (here the Weibull law) which modelise the inter arrival time of ships; GI: represent also a general law (here the Gamma law) which describes the time of services of ships at the quay; c: corresponds to the number of services, meaning the quays or discharging available posts. The simulation has been done from some real datas of the port exploitation with the for prelimiinery estimation of the retained probabilty law.

3.1. Data Management: Inter-Arrival Time of Ships and Service Time of Ships at Berth

The KS test measures the highest difference between the function of empiric dividing and that of the tested law. The more, the statistics (*KS_stat*) the more the goodness-of-fit is weak, and the more the goodness-of-fit is better the more the statistics is high In our study, we proceed to the test of goodness-of-fit of Kolmogorov-Smirnov of our datas (the inter-arrival of lost ships) on different laws (the Normal law, the Exponentielle law, Poisson law, Weibull law, Gamma law,) toward a simulation withh the Python software in order to know the law of probability which modelise the inter-arrival time of our datas. Table 1 presents the results of the goodness-of-fit test of inter-arrival time of ships to different probability laws. The Kolmogorov-Smirnov (KS) test allows to evaluate the compatibility between the observed datas and the theoric distributions. A weak value of the KS statistic accompanied by a p-high value, indicates a good adjusting. In that sense, Weibull laws and that of Gamma present the best performances with repective KS statistics of.0404 et 0.0497, and of p-value not significative (0.7866 et 0.5428), suggesting that the hypothesis naughty from adequatation can t be rejected. Otherwise, the exceptional law, normal of Poisson show some very weak of p-value indication a worse adjustment of datas. Akaike's information criteria (AIC) and Bayesian information criteria (BIC) are used to evaluate and compare several statistic models while taking into account at the same time the quality of adjustment and that of the complexity of the model. Some weakest values of that criteras translate un better compromise between the precision of the adjustment and the simplicity of the model. In this present case, the Weibull law shows some weakest values of

AIC (2290.05) and of BIC (2297.11), indicating that it offers the more satisfying among all the tested laws. In fact, Weibull law appears as the most appropriate one to modelise the inter-arrival times of ships in the operational context of the container termina of the Conakry port.

Table 1. Results of the test to determine the suitability of ship arrivals for different models.

Modèle	KS_stat	KS_pval	AIC	BIC
Weibull	0.0404	0.7866	2290.05	2297.11
Gamma	0.0497	0.5428	2290.77	2297.84
Exponentielle	0.1039	0.0078	2303.13	2306.66
Normale	0.1334	0.0002	2420.49	2427.55
Poisson	0.4527	7.19×10^{-48}	6725.77	6729.30

Table 2 presents the results of the test of Kolmogorov-Smirnov (KS) apllied to the simulated datas to the time of service of ship a the docks, while comparing them to five laws of prbability: Weibull, Gamma, Exponentielle, Normale et Poisson. The criteras of intervention used are the statistics KS, by p-valeur associated, and even the criteras of information of AIC and BIC. The statistic KS measure the maximum gap between the function of empiric reparation of datas and that of the theoric model. More the statistic is weak, the best is its adjustment. In this case, the law of Gamma presents the weakest statistic KS (0.0445), followed by that of Weibull, (0.0607), that indicate that both laws are well fitting the datas than the others. The p-value allows to juge the signification of this gap. A high p-value (superior to 0.5) means that we can t reject the hypothesis according to which follow the teste law. The law of Gamma shows the biggest p-value (≈0.679), followed by the law of Weibull (≈0.295), what strenghthens their good adjustment. Otherwise, the exceptional laws, normal and that of Poisson are clearly rejected (very weak p-values). The criteras AIC et BIC, that affect the complexity of the model, confirm these results. The law of Gamma obtains the weakest values q (AIC = 2081.70, BIC = 2088.78), what indicate that it offers the best compromise between the quality of adjustment and simplicity. The law of Weibull follows directly, but with some values slighly higher.

Table 2. Résultats du test d'adéquation du temps de service des navires aux différentes lois.

Modèle	KS_stat	KS_pval	AIC	BIC
Weibull	0.060695	2.946863×10^{-1}	2098.833420	2105.908089
Gamma	0.044508	6.785916×10^{-1}	2081.701180	2088.775848
Exponentielle	0.258710	1.752782×10^{-15}	2245.943886	2249.481220
Normale	0.105137	6.728125×10^{-3}	2149.264208	2156.338876
Poisson	0.302875	3.605688×10^{-21}	3383.228920	3386.766254

3.2. Motivation for Choosing the General Model

By combining the results found in Table 1 and Table 2, we can conclude that the **Weibull law** is more adapted to modelise the les **time between arrivals** of ships, owing to its performence on the criteras KS, AIC and BIC in the one hand. In the other hand, the **loi de Gamma** is relevant to modelise the **time of service** of ships on docks, as it presents the best global performences on all the indicators The differenciated choice allows to conduct a realistic model of the port system, while taking into account some specificities of the statistics of each item of the process. It is particularly useful for some applications in simulation of the queuing, in logistic optimization or in evaluation of port performance..

3.3. Weibull Law

The Weibull law is a continued law of probability highly used in reliability analysis of surviving and modelization of extreme phenomenon (as in wind and rain). It is defined by two parameters: a parameter of $k > 0$ form and a scale. parameter $\lambda > 0$. Its density is given by 1

$$f(t;\beta,\sigma) = \frac{\beta}{\sigma}\left(\frac{t}{\sigma}\right)^{\beta-1} \mathrm{e}^{-\left(\frac{t}{\sigma}\right)^{\beta}}, \quad t \geq 0. \tag{1}$$

The expectation is given by the relationship 2

$$\mathbb{E}[T_a] = \lambda\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

In which $\Gamma(x) = \int_0^{+\infty} t^{x-1}\mathrm{e}^{-t}\mathrm{d}t$, for $x > 0$ is the function Gamma. The relations 3 and 4 repectively designate lhe change and the coefficient of the variation.

$$\mathrm{Var}[T_a] = \lambda^2\left[\Gamma\left(1+\frac{2}{k}\right) - \left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right], \tag{3}$$

$$CV_{T_a} = \frac{\sqrt{\mathrm{Var}[T_a]}}{\mathbb{E}[T_a]} = \sqrt{\frac{\Gamma\left(1+\frac{2}{k}\right)}{\left(\Gamma\left(1+\frac{1}{k}\right)\right)^2} - 1}. \tag{4}$$

The parameter k makes a control on the form of distribution (for example, for $k = 1$, the law of Weibull corresponds to an exponential law) and the parameter λ determines the temporal scale. This law used in analysis of a length of life, in reliability of systems in the study of phenomenon of break or damage. It is flexible and can adopt to various behaviours owing to its parameter of form.

3.4. Gamma Law

The law of Gamma is a continous law of probability defined for $t > 0$ and caracterised by two positive parameters of form k (ou α) and a scale of parameter θ (or intensity $\beta = 1/\theta$).

The density of probability is given by the relation 5. The relations 6, 7 and8 repectively designate the hope, the change and the coefficient of variation.

$$f\left(t\mid\alpha,\beta\right)=\frac{\beta^{\alpha}}{\Gamma\left(\alpha\right)}t^{\alpha-1}\mathrm{e}^{-\beta t},\ t>0 \tag{5}$$

$$\mathbb{E}\left[T_{\mathrm{s}}\right]=\frac{\alpha}{\beta}, \tag{6}$$

$$\mathrm{Var}\left[T_{\mathrm{s}}\right]=\frac{\alpha}{\beta^{2}}, \tag{7}$$

$$CV_{T_{\mathrm{s}}}=\frac{\sqrt{\mathrm{Var}\left[T_{\mathrm{s}}\right]}}{\mathbb{E}\left[T_{\mathrm{s}}\right]}=\frac{1}{\sqrt{\alpha}}. \tag{8}$$

This law oftenly useed to moderate the positive changing phenomena through the time, particularly in analysis of survival and reliability.

3.5. General Models

Starting from the analytic results of datas presented in the section 3.1, it appears that the gaps between the arrivals of ships follow a law of Weibull, while the length of service to both quays of the terminal obey to a law of Gamma. These observations show significant variability in arrival intervals and service times, which allows the operation of the container terminal at the Autonomous Port of Conakry (APC) to be modeled using queuing theory, adopting a general GI/GI/c model rather than traditional exponential assumptions. This model is based on the following assumptions: inter-arrival times are independent due to the diversity of shipping companies, external hazards affecting each ship separately, and the absence of correlation detected in the data, and follow a general law with a mean of $1/\lambda$, service times are also independent, as they depend mainly on the characteristics specific to each ship and standardized procedures, with no significant influence from one service to another, and follow another general law with a mean of $1/\mu$, and service discipline is first-in, first-out (FIFO). The system has c servers, corresponding to the available berths. The system is considered stable when the occupancy rate defined by relation 9 is strictly less than 1.

$$\rho=\frac{\lambda}{c\mu} \tag{9}$$

The classic carateristics of the system can be expressed as followed, where the relation 10 to 13 respectively designate the average number of ships in the system, the average number of the ships in the queuing.

$$L=\lambda W, \tag{10}$$

$$L_q=\lambda W_q, \tag{11}$$

$$W=W_q+\frac{1}{\mu}, \tag{12}$$

$$W_q\approx\frac{CV_{T_{\mathrm{a}}}^{2}+CV_{T_{\mathrm{s}}}^{2}}{2}\cdot\frac{\rho^{\sqrt{2(c+1)}-1}}{c\left(1-\rho\right)}\cdot\frac{1}{\mu} \tag{13}$$

Two important probabilities allow the evaluation of the flaw of the system and tthe average of time in queuing.

The probability off the system is empty, aproximated by tthe model $M/M/c$, is defined by the relation 14.

$$P_0 = \left(\sum_{k=0}^{c-1} \frac{(c\rho)^k}{k!} + \frac{(c\rho)^c}{c!} \cdot \frac{1}{1-\rho} \right)^{-1}. \tag{14}$$

While the probability that all servers are occupied at the arrival of a ship is defined by the relation 15.

$$P_a = \frac{(c\rho)^c}{c!} \cdot \frac{P_0}{1-\rho}. \tag{15}$$

This modelisation allows the rigorous analysis of the performences of the terminal and the anticipation of the risks of congestion, while offering and extended spot to other ports contexts.

4. Application of the Autonomous Port of Conakry

This study targets to analyse the operation of the termina of containers of the Conakry Autonomous Port, laying emphasis on the management of the ships flows, the queuing and the operational performences of the quays. This study lays on real collected datas at the level of the harbormaster office, particularly the inter-arrival of ships and timing of service (uploading). These datas have allowed to modelise the system owing to the adapted statistic distributions (Weibull law for the inter-arrival and Gamma law for the time of service), and apply the theory of queuing to evaluate the congestion and suggest some ways of optimization. This case of study offers a concrete application of tools of stochatic modelization in the port context with the aim of improving the planning of the materials and the flow of the operation within the terminal.

4.1. Presentation of the Autonomous Port of Conakry

Located at the peninsule of the atlantic coast, in front of the Tumbo island and the Loos island, the Autonomous Port of Conakry (APC) benefits from a natural site location favorable to the port activities. It remains one of the principal trade centers in West Africa Africa, trating a wide variety of cargos, going from containers to the raw materials such as the bauxite. It constitutes a strategic link of the logistic and economic system of Guinea and the principal naval port, guaranting near 90% of the exterior trade of the country. The naval access is made by a West-South channel jalonned of 13 international buoys, long de 5000 m, wide of 150 m and deep of 10 m, crossing the lighthouse of Boulbinet located at 1000 m of the entry of the basin. The port owns a basin of 10 m of depth, protected by a breakwater of 4500 m that limits the situation. The Autonomous Port of Conakry constitutes a strategic point for the Guinean economy, with a capacity of increasing investment in modernisation. The terminal of containers of the Conakry Autonomous Port shows the port modernisation in Africa and West Africa, Built in1989 and 1992 with an initial area of 80,000 m^2 et un quai (PQ10) of 270 meters of length 10.5 meters of depth, it experiences an major expantion owing to the public and private partnership between the port authorities of Groupe Bolloré. This partnership has allowed a creation a the quay PQ12, long of 340 meters and deep of 13 meters dedicated to the traffic Ro-Ro and to containers. Today, the terminal is extended on 200,000 m^2 with a linear quay of 610 meters, able to welcome simultaneously two ships. It plays a strategic role as a regional logistic termina, offering some complete services of supply, of loading and uploading, of security, of check of stocks management. In addition to the terminal of containers, the port has several other specialized installations. The aluminiers posts (PQ0 et PQ01) together 346 meters of quay with a depth of 10 meters, destinated to the aluminium, the clinker and raw materials. The conventional posts (PQ02 à PQ05) are spread on 493 miles, with depth variying from 8 and 8.5 miles: PQ02-PQ03 measure 300 miles with 8,5 miles of depth, while PQ04-PQ05 font 193 miles with 8 moles of depth. The required bulk posts (PQ08 and PQ09), dedicated to the traffic of bauxite offer 296 miles of quay with a depth of 11 miles. At last the gaz quay, long of 190 miles and deep of 11.5 miles, is equipped of eight ducks of Albe (four mourring and four accostage). Built during the second port project (1989-1992), it can welcome some moreover than 45,000 tones and is exploited by the Société Guinéenne des Pétroles (SGP). It is related to some ground bins located at 800 miles across the network pipelines. The Autonomous Port of Conakry has esstablished several port concessions with some strategic partners in order to modernise its infrastructures and improve its regional networking. The conventional terminal has been trusted to a turkish Albayrak group, charged to the modernisation and the following-up of aging settings. The terminal of contaainers, as itself has been conceded to Bolloré Africa Logistics in 2011. This partnership has allowed some important investisments, specially the extension of areas of land on 120,000 m^2, the buiding of a new quay of 340 miles with a depth of 13 miles and the acquisition of modern equipments such as gates and storage installations. Otherwithe, the mineral terminal, particularly dedicated to the traffic of bauxite and alumine, is managed by Rusal Guinea. This enterprise ensure the maintenance, the loading, and exploitation of specialized installation. These different concessions witnesses the will of the PAC to lean on public prive partnership to reinforce these operational capacities, attract morover the trade flaws and impose as a major logistic hub in West Africa (**Figure 1**).

Figure 1. Some parts of the autonomous port of Conakry.

4.2. Data Collection

In the case to this study, some datas have been collected at the level of the harbor-master's office of the Conakry Autonomous Port, principal logisttic hub of Guinea. These datas lay concern to the ships having accosted to the terminal of the year 2023, and including specifically the time of inter-arrival between the ships as well as the time of service (time of uploading or treatment).

The aim of this section is to present through a synthetic way the caracteristic statistics of the datas, in order to better understand the port system such as in the following Table 3.

Table 3. Statistical analysis of data.

Statistics	Arrival Time	Service Time
N valid	253	254
Missing	1	0
Average	34.7324	30.4843
Median	25.1	26.225
Mode	42.50	14.43
standard deviation	28.75192	16.54353
Variance	826.673	273.688
Minimum	0.50	3.13
Maximum	157.30	125.67

5. Results and Discussion

At the aim at evaluating the operational performences of the terminal of containers of the Autonomous Port of Conakry a numeric simulation has been realized from statistic datas observed on the year 2023. This simulation lays on the modelisation of the port system as a matter of queuing multi-servers, with both quays of accostage and activities. The time between the arrivals of ships has been adjusted to the law of Weibull, while time of service have been modelized by the law of Gamma, in accordance to the results of the tests of adequation. The retained model is a system is $GI/GI/c$, type with a politics of service following the rule of the first arrival, fisrt served. The arrivals are supposed proveded from an endless source, what allows us to simulate a continous flow of ship. The simulation has been settled in Python, integrating thhe estimated parameters from the real datas. It has allowed us to analyse several indicators of performance, specially the average time of waiting of the ships before treatment, the rate of occupation of the quays, the level of congestion of the system as well as the distribution of queuing at the length of the time. This appraoch allow the reproduction of the dynamic behavior of the terminal in a selected environment and identifying the conditions likely to to generate some delays or some congestions. **Table 4** presents some fondamental parameters of the system of queuing modelizing the functionning of the terminal of containers of the Autonomous Port of Conakry. The rate of arrivals of ship is estimated at $\lambda \approx 0.0283$ ships per hour, what means in the average, a ship arrives all around the 35 hours. This rythm of arrival is relatively moderated, relating a mastered pression on the port infrastructures. The rate of service per quay is of $\mu \approx 0.0330$ ship per hour, either an average time of treatment of around 30 hours per ship. This rate being superior to the rate of arrival, it indicates the quays are able to treat the ships at a faster rythm than the arrival, what represents a sign of good measurement of the system. The rate of occupation of quays, defined by the report $\rho = \lambda / \mu \approx 0.4286$, indicates that the quays are used in around 43 % of their capacity. This level of occupation is wel inferior at the critical of saruration threashold ($\rho = 1$), what means the system is functionning in a spot of stability. In other words, the port installations have a sufficient room of manoeuver to absorb the variations of traffic without occuring congestion. According to the theory of queuing, particularly the works of [28], a system with $\rho < 1$ is stable, and the average number of custommers (here, the ships) pending is over. This means thhat the ships arrive at a system of compatibility with an ability of the quays treatment, assuming a fluid and efficient functionnement of the terminal. This situation is favorable to the performance port logistics and at the reducing of the pending, what remains essential to the competitivity of APC of the region.

Table 4. Model parameters.

Ship arrival rate	$\lambda \approx 0.0283$ ships/hour
Service rate per dock	$\mu \approx 0.0330$ ships/hour
Dock occupancy rate	$\rho \approx 0.4286$

Table 5 presents the key indicators of performence of the port system of queuing. These indicators allow to evaluate the operational efficiency of the terminal of containers of the Conakry Autonomous Port (CAP). The *average waiting time in rade*, noted $W_q \approx 3.21$ hours, represents the average duration in which a ship is waitting before being taken in charge by a mooring post. This value relatively weak indicates that tthe ships do not experience important delays at their arrival, what is a sign of flaw in the management of queuing. The *average time of the system*, $W \approx 33.48$ hours includes at the same time to the pending and the time of service. This means that a ship goes in the average a little more than 33 hours in the port, of its arrival at its departure. This duration is coherent with a capacity of treatment observed and reflect a good master of the port operations. The *average number of pending ships*, $L_q \approx 0.091$, is very low, what confirm that the queue is generally empty or very short. This reinforce the idea that the system is not overloaded and that ressources are sufficient to meet the current demand. Finally, the Textit average number of ships in the system,

Lapprox 0.9483, indicates that on average, fewer than one ship is present in the system at any given time (either waiting or being processed). This result is consistent with the previously observed quay occupancy rate ($\rho \approx 0.43$) and confirms that the system operates within a stable area. Pending or in progress. This result is consistent with the previously observed dock occupancy rate and Overall, these indicators show that the APC container terminal is well sized in relation to the current flow of ships. The system runs smoothly, lead times are controlled, and queues are almost nonexistent, which is favorable for logistic performance and port competitiveness.

Table 5. Performance characteristics.

Average waiting time in the harbor	$W_q \approx 3.21$ hours
Average waiting time in the system (port)	$W \approx 33.48$ hours
Average number of ships waiting	$L_q \approx 0.091$
Average number of ships in the system	$L \approx 0.9483$

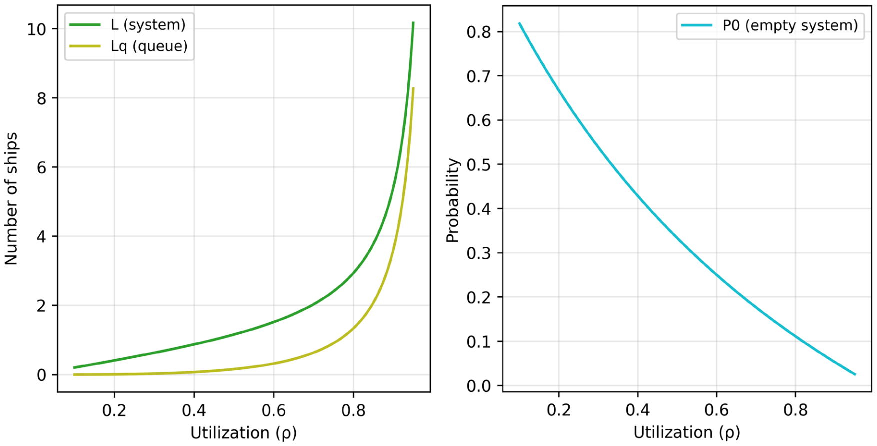
Table 6 presents two fundamental probabilities for the analysis of the operation of the terminal container at the Conakry Autonomous Port, with the framework of a queuing model. The probability $P_0 \approx 0.3999$ represents the probability that the system is empty, that is, no ship is present either waiting or being processed. This means that of the terminal is completely free, which reflects excellent flow of port operations. Such a situation indicates that the resources are sufficient to meet the current demand, without chronic overload. The pending probalility, noted $P_{\text{pending}} \approx 0.2572$, corresponds to the probability that all docks are occupied upon a ship's arrival, thereby causing a waiting period. Although this probability is not negligible, it remains moderate, suggesting that queues are occasional and generally short. This confirms that the system operates in a stable zone, with sufficient capacity to absorb fluctuations in maritime traffic. Overall, these probabilities confirm the previous results: the APC container terminal is well-sized, with good traffic handling capacity and a low probability of congestion.

Table 6. Probabilities.

Probability that the port is empty	$P_0 \approx 0.3999$
Probability of waiting (all platforms occupied)	$P_{\text{wait}} \approx 0.2572$

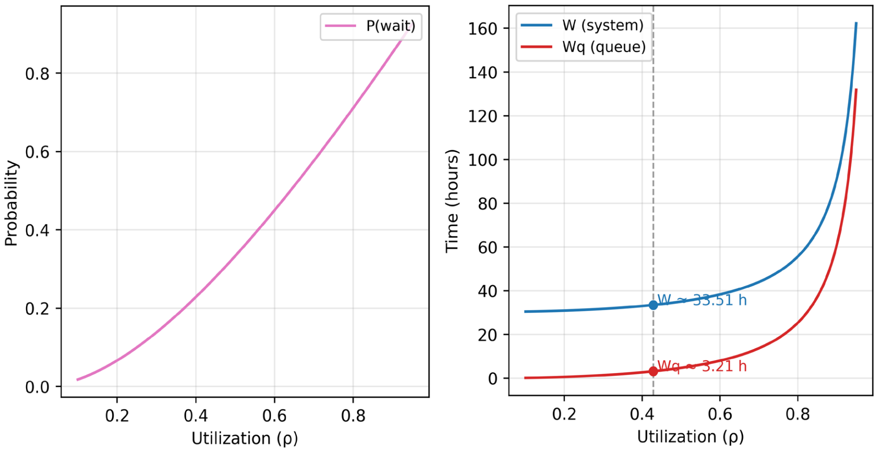
Figure 2 and **Figure 3** provide an overall view of the evolution of queue performance indicators for the $GI/GI/c$ model as a function of utilization ρ. These figures clearly demonstrate that system performance deteriorates significantly as ρ approaches 1, illustrating the classical congestion effect: higher utili-

zation leads to longer delays, larger queues, and reduced system availability. **Figure 2(a)** shows the average times in the system (W) and in the queue (W_q). Both remain relatively low for moderate utilization levels but increase sharply near saturation. This indicates that waiting times become critical when ρ exceeds approximately 0.8. **Figure 2(b)** presents the average number of ships in the system (L) and in the queue (L_q). These values follow a similar pattern: minimal for $\rho < 0.5$ and rapidly growing beyond $\rho \approx 0.8$, confirming the congestion effect. Turning to **Figure 3(a)** illustrates that the probability of an empty system (P_0) decreases rapidly as ρ increases, meaning the port becomes almost constantly occupied under saturated conditions. **Figure 2(b)** shows that the probability that a ship must wait (P_{wait}) rises significantly with ρ, reaching nearly 100 Overall, these results highlight the importance of maintaining the utilization rate below approximately 80% to avoid excessive queues and ensure smooth port operations.



(a) Average times vs utilization (b) Average counts vs utilization

Figure 2. Performance indicators (time and counts) for the GI/GI/c queue as a function of utilization.



(a) Empty system probability vs utilization (b) Waiting probability vs utilization

Figure 3. Probability-based performance indicators for the GI/GI/c queue as a function of utilization.

6. Conclusions

The study demonstrated that port congestion at the Conakry Autonomous Port APC container terminal is currently almost nonexistent. This favorable situation is explained by the combination of sufficient quay capacity and effective operational management provided by the concessionaire, Conakry Terminal. Significant investments have been made to strengthen the infrastructure, including the acquisition of four new yard cranes, adding to the eight already installed in 2018 and 2020. These pieces of equipment have contributed to speeding up handling operations, thereby improving the overall productivity of the terminal.

According to the model parameters, the arrival rate corresponds on average to one ship every 35.34 hours (approximately 1 day and 11 hours), which indicates a relatively low flow and traffic intensity. This situation provides a substantial margin to accommodate daily variations. The performance indicators analysis shows that the traffic intensity, measured by the occupancy rate $\rho \approx 0.43$, remains moderate and well below the critical saturation threshold. This reflects good operational stability, a very low risk of congestion, and an available margin of approximately 57% to absorb seasonal traffic fluctuations, delays due to maritime conditions, and equipment failures. However, a low occupancy rate may also indicate underutilization of infrastructure, lower-than-optimal economic performance, and high fixed cost per handled vessel. The average time spent by a vessel in the system is estimated at $W \approx 33.48$ hours, confirming the absence of significant queues. Likewise, the average number of vessels in the system $L \approx 0.9483$ indicates that the terminal generally accommodates fewer than one vessel at a time. This demonstrates efficient capacity utilization, with a stable and moderate occupancy rate ensuring balanced operations. Moreover, the probability that the system is empty ($P_0 \approx 0.40$) is relatively high, indicating smooth operations and a low likelihood of congestion. Given these performance results, expanding the berths does not appear to be an urgent priority. The current utilization rate is low, and constructing an additional berth would be economically unjustified in the short term. However, in the long term, such a decision should be supported by traffic growth forecasts, seasonal peaks, and arrival variability. This study highlights the relevance of queueing theory as a decision-making tool for port management. The approach based on the **GI/GI/c** model enabled a realistic representation of terminal operations, accounting for the empirical variability of arrivals (Weibull distribution) and service times (Gamma distribution). The combined use of analytical methods and numerical simulations made it possible to accurately evaluate system performance and anticipate saturation risks. Ultimately, this approach provides port decision-makers with a rigorous framework for monitoring and optimizing operations. It may also be extended to other regional ports to support inter-port comparison and strategic planning at the regional level.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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