

The Application of Queuing Network in The Warehousing System: A Literature Review

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Abstract. This review delves into the application of queuing networks within warehousing systems, highlighting their significance in optimizing operations amidst inherent stochasticity. The paper systematically evaluates existing literature, focusing on methodologies such as open, closed, and semi-open queuing networks. It underscores the necessity for developing more sophisticated analytical algorithms to handle general service time distributions and complex correlations. The review advocates for the integration of realistic distributions and empirical validation to enhance model accuracy. Ultimately, it posits that queuing network models are pivotal for advancing warehousing efficiency and innovation, emphasizing their transformative potential in the logistics sector.

Keywords: Queuing Network, Warehousing System, Order picking.

1. Introduction

Queuing network is a classical topic in the field of mathematics. A queuing network can be defined as a framework that uses stochastic processes to model and analyze waiting lines. The main components are Arrival Process, Service Process, Queue Discipline, Number of Servers, Queue Capacity, Performance Metrics, Stability Condition, Little's Law.

In recent years, warehousing systems has attracted a lot. The development of warehousing systems is marked by the rapid adoption of automation and intelligent technologies, such as automated warehouse management systems and robotic picking. The integration of IoT, big data analytics, and cloud computing has enhanced operational efficiency and accuracy. Concepts like green warehousing and intelligent logistics have also been introduced to make storage management more flexible, eco-friendly, and efficient. In addition, supply chain integration, personalized services, mobile technology, and security compliance are key areas of development, which together drive modernization and innovation in the warehousing industry.

Many researchers used queuing networks to explore warehousing systems due to their stochastic nature. The environment of a warehousing system is considered to be stochastic because of various unpredictable factors that significantly

impact its operations. These factors are as following: fluctuating demand influenced by seasons, promotions, and market shifts; uncertainties in supply due to factors like weather, transportation issues, and production challenges; the necessity for flexible inventory management strategies to adapt to change market and supply conditions; operational efficiency affected by workforce skills, equipment performance, and workflow processes; the continual need to adapt to technological advancements such as automation and artificial intelligence; policy and regulatory changes that affect business strategy; unforeseen emergencies, such as natural disasters or public health crises; and customer behavior, which are influenced by numerous factors hence it is hard to predict. With these factors in mind, warehousing systems must be flexible and adaptable to take advantage of their inherent randomness to optimize their performance and efficiency.

The arrival of orders typically follows a certain distribution, such as Poisson distribution. However, in practical situation, especially within the E-commerce environment, the arrival of orders often follows a more general distribution. As a result, the queuing network cannot be

accurately represented by a stable Markov process. Consequently, the queuing network lacks a product form solution, making it challenging to solve.

As more and more researchers employ queuing networks to explore warehousing, it becomes necessary to review relevant literature and provide insights for scholars in this domain. Our systematic literature review focuses on papers utilizing queuing networks to investigate warehousing systems and offers the following contributions:

1. We review the paper which use queuing network to investigate the warehousing system.
2. We analyze the related papers from a viewpoint of the research items and solutions.

The rest of the paper is organized as following: In Section 2, we outline the scope of this review and we analyze the related papers in Section 3. Section 4 discusses the future directions of our work.

2. Scope of review

While queuing network is widely used in various domains such as healthcare and telecommunications, our review specifically targets the warehousing system. This focus is justified, as the warehousing system is a relatively recent development that has gained a great deal of attention.

We review a number of works and we choose the following keywords "warehousing system", "order picking system" and "queuing network" to search in the Google scholar. Although several related papers are found, we whittled it down to 11 papers, most of which were published in A+ journals such as Operations Research, the European Journal of Operations Research.

3. Literature Analysis

Few methods are widely used in this field, such as open queuing network, closed queuing network model and semi-open queuing network model to solve problems. Table 1 analyze the related papers based on the methodology and research items. In [2], the author put forward a software tool that uses open queuing networks to quickly analyze and compare different design options for SBS/RS warehouses, estimating their key performance metrics. [9] created a performance estimation and a design algorithm for the SBS/RS. The performance estimation is based on a queuing model. They found the optimized solution under given requirements of throughput, container capacity, and order cycle time. Authors in [3] introduced a method that used second-moment approximation to calculate the variance of the time between job departures in a single-stage Semi-Open Queuing Network (SOQN). This calculation is crucial as it provides the necessary input to connect and evaluate the performance of multi-stage SOQNs. A SOQN to evaluate the performance of a robotic mobile

fulfilment system was proposed in [1], and the arriving of the order follows the general distribution, while [6] establish integrated methods which combine the queuing network and Markov decision process to optimize the operational process. In [5], the authors proposed a SOQN to analyze the system performance, including maximum order throughput, average order cycle time and robot utilisation and so on. An OQN is established [10] to different operational policies applied in the system. [11] recommend assigning robots to pickers by taking into account the speed at which pickers handle items, and they introduce a local search algorithm to identify this allocation. They utilize a SOQN to assess the effectiveness of different strategies for assigning robots to pickers. For multi-class semi-open queuing network, [8] individually model each tier and the vertical transfer mechanism using a multi-class semi-open queuing network and an open queue, respectively. [7] extended a semi-open queuing network model and showed that the end of the aisle is the optimal cross-aisle location for the system. And [4] studied how a class-based storage policy affects the cycle time of an AVS/R system using a closed queuing network.

Their works indicated that implementing this storage policy can alleviate cycle time concerns associated with vertical storage while maintaining the efficiency of random storage.

Based on the works above, we conclude that

1. Due to the complexity of solving queuing networks, the number of papers in this field is still insufficient. Usually, a Markov process is needed to solve the queuing network. However, analyzing Markov processes for complex queuing networks is challenging.
2. The arrival of the orders follow the general distribution. The first and second order moments are always used to solve the related queuing network. Some studies use the Coxian-m distribution to approximate the general distribution, and then they found the transition state and state probability of Markov decision process, which is quite difficult.
3. Queuing network model can be widely used in system performance evaluation, operation process optimization, strategy evaluation and decision optimization.
4. Queuing network models are extensively used for evaluating system performance, optimizing operational processes, assessing strategies, and enhancing decision-making because they provided a mathematical framework to represent and analyze the stochastic nature of real-world systems.
5. Arrival and service processes are modeled using probability distributions that accurately predict key performance metrics such as throughput and wait times.
6. Their analytical solutions for the queuing network enable the comparison of operational strategies and identification of optimal resource allocations. This aids in strategic planning and decision-making, enhancing system efficiency and effectiveness.

Tab. 1 The analysis of the papers

Reference	Methodology	Research item
Ekren and Akpunar(2021)	OQN	System evaluation
Wu et al. (2020)	OQN	System design and evaluation
Kumawat and Roy (2021)	SOQN	Facility planning and design
Lamballais et al. (2022)	SOQN	Policy comparison
Lamballais et al. (2017)	SOQN	Performance evaluation
Duan et al (2020)	SOQN	Performance evaluation
Yuan and Gong (2017)	OQN	Policy comparison
Zou et al. (2017)	SOQN	Robot allocation
Tappia et al. (2016)	SOQN and OQN	Optimal system design
Roy et al. (2015)	SOQN	Operational policy
Kuo et al. (2008)	CQN	Operational policy

7. Future directions

1. For queuing network with general allocated service time, more analytic algorithms need to be proposed. Although we have found a number of articles on queuing network issues with general distribution times, most of these articles have focused on specific areas. In addition, there are many application areas, such as service times, operational efficiency issues, which are affected by more complex factors. It is necessary to find the analytic solution of complex queuing network.
2. It's essential to improve the stochastic models to incorporate more realistic distributions, such as heavy-tailed for arrivals and service times, and to account for correlations within these processes.
3. A deeper analysis of the queue length distribution will help to understand system capacity and congestion risk. Investigating the influence of rare events is essential for comprehensive risk management, and empirical simulation and validation against real-world

data will ensure the accuracy and reliability of models in real-world decision making.

4. From the works above, we need to develop more advanced analytical algorithms to address the complexity of queuing network with service times following general distributions. These algorithms need to accurately model and predict system behavior under different service time distributions, while also being robust enough to handle the inherent uncertainty and variability in service times. They should be designed for solving the computational requirements of large-scale networks efficiently and integrate seamlessly with existing queuing network models and simulation tools

5. Combining with machine learning techniques makes it possible for these algorithms to learn and optimize from historical data, thereby enhancing their prediction accuracy and reliability over time. They must undergo rigorous testing and validation to ensure effectiveness across various situations.

6. The Conclusion

Incorporating queuing network models into warehousing systems provides a robust framework for analyzing and optimizing intricate logistical operations. As evidenced by this review, queuing theory application is not just a theoretical pursuit but a vital tool for enhancing operational efficiency, minimizing wait times, and enhancing decision-making amid uncertainty.

Although significant progress has been made in applying queuing networks, there is still ample opportunity for advancement. The critical focus lies in developing more sophisticated analytical algorithms capable of addressing the general distribution of service times and the complex correlations inherent in warehousing processes. By integrating heavy-tailed distributions and accounting for the stochastic nature of real-world operations, these models can attain greater fidelity and practical applicability.

Furthermore, the analysis of queue length distributions is essential for a comprehensive understanding of system capacities and the potential for congestion. This insight is invaluable for strategic planning and for the mitigation of bottlenecks that can impede operational flow. The examination of rare events is equally critical, as it informs risk management strategies and ensures that the models are equipped to handle unexpected disruptions.

Future research must include empirical simulation and validation using real-world data, as these are indispensable components. These practices are vital for confirming the accuracy and reliability of queuing network models, ensuring they serve as reliable guides for decision-makers navigating the dynamic and evolving terrain of warehousing logistics.

In summary, the potential of queuing network models to revolutionize warehousing operations is vast. Through ongoing research and refinement, these models will not only offer deeper insights into system performance but also stimulate innovation, propelling the warehousing industry to new levels of efficiency and effectiveness.

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