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Yetkin Ekren, Banu; Akpunar, Anil; and Lerher, Tone, "A Performance Calculator for Shuttle-based Storage and Retrieval System Design" (2018). *15th IMHRC Proceedings (Savannah, Georgia. USA – 2018)*. 18.
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A Performance Calculator for Shuttle-based Storage and Retrieval System Design

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***Abstract*— In this study, we present an analytical model based tool that can estimate critical performance measures from a pre-defined shuttle-based storage and retrieval system (SBS/RS) design. SBS/RS is relatively a new automated storage and retrieval technology and mostly used for mini-load material handling. In this study, we develop an open queuing network model based tool estimating critical performance measures: the mean travel time of lifts/shuttles, utilization of lifts/shuttles, amount of energy consumption and energy regeneration per transaction, waiting times and number of jobs waiting in queues, etc., from a pre-defined SBS/RS design. By the developed tool, one can evaluate an SBS/RS design's performance promptly by changing the input design parameters (e.g., distance between two adjacent bays/tiers, velocity of vehicles, acceleration/deceleration of vehicles, number of tiers, number of bays, number of aisles, arrival rates, weight of totes, etc.) in these systems.**

Keywords—SBS/RS, automated warehousing, queuing network, queuing performance of SBS/RS

I. Introduction

Warehouses play critical role in meeting multi-objective supply chain targets. The main duty of warehouses is to keep items in their facilities to alter demand variability and decrease transportation lead times for customers. By the recent Industry 4.0 development, in warehouses, utilization of automation technologies has become a must. Automation technology development has presented a great advance and resulted with a high variety of warehouse automation options. Shuttle-based storage and retrieval system (SBS/RS) is one of those technologies that is developed to cope with high transaction rate ([1] – [11]). It is critical for companies to decide on the right technology with a right design of it for its business requirements. Therefore, development of analytical models producing performance analysis on those systems is critical to evaluate such systems' performance promptly. By this study, our aim is to develop an open queuing network (OQN) based tool, estimating several critical performance measures from a pre-defined physical SBS/RS warehouse design.

II. LITERATURE REVIEW

Since SBS/RS technology is relatively new in automated warehousing, there are only a few studies related to this system in the literature. We present some related studies here.

Marchet et al. [2] present an analytical model to estimate the average waiting time and cycle time for solely retrieval transactions. The model is based on an open queuing network approach. The model effectiveness in performance estimation is validated via simulation.

Marchet et al. [12] use simulation to highlight the main design trade-offs for SBS/RS for several warehouse design scenarios involving tier-captive shuttle carriers. Four performance measures observed from the system are: utilizations of lifts and shuttles, average flow time, waiting time, and total cost for limited number of pre-defined rack designs.

Ekren et al. [13] develop an analytical model based tool for mean travel time estimation of lift and shuttle per transaction and their variance, energy consumption and energy regeneration per transaction in a pre-defined SBS/RS design. The analytical results are validated by simulation.

Recent studies on SBS/RS by Lerher [3] and Lerher et al. [4] consider the concept of energy efficiency in the system design. The proposed models present several warehouse designs including velocity profiles of lifts and shuttles along with the amount of energy (electricity) consumption and CO_2 oscillation, and the throughput capacity in the system. These studies provide a significant contribution on environmentally friendly automated warehouse planning by emphasizing the importance of energy efficiency.

Different from the existing studies, we develop a queuing network tool, providing queuing performance measures as well as energy consumption estimations from a pre-defined SBS/RS design. We consider that there exist both storage and retrieval transactions in the system. To the best of our knowledge, in the literature there is no such an analytical model based tool providing numerous outputs (performance measures) for different SBS/RS designs also including energy consumption and energy regeneraiton. After developing the analytical models, their results are validated by the simulation models.

III. SBS/RS Description and Assumptions for Modelling

Figure 1 shows the top view of a tier of an SBS/RS aisle. There are two buffer areas in each tier where loads are dropped-off to be picked up by the lifts or shuttles. Namely, the lifts drop-off the load on the buffer location when the transaction is a storage; pick-up the load when the transaction is a retrieval. There are two types of transaction requests: storage and retrieval. The processes take place based on the transaction types that are summarized below:

***For a storage transaction*:**

If the processed transaction is storage, then the following operations take place: i) the lift moves from its dwell point to the ground-floor tier, i.e., the first tier – the I/O point of the system; ii) the lift picks up the storage transaction and travels to the designated tier; iii) when the lift reaches its destination tier, then it releases the load in the one of the two buffer locations (Fig. 2); iv) the shuttle in the designated tier moves from its dwell point to the buffer location; v) the shuttle picks-up the load; vi) the shuttle travels to the designated storage address with the load and discharges it in the storage location.

If the storage position is at the ground-floor (first) tier, the lift does not move. Hence, only the iv), v) and the vi) steps take place.

***For a retrieval transaction*:**

If the processed transaction is retrieval, then the following operations take place: i) the shuttle in the designated tier moves from its dwell point to the retrieval address to pick-up the load, and then travels to the buffer location; ii) the shuttle releases the load in one of the buffer locations; iii) the lift moves from its dwell point to the designated tier; iv) the lift picks up the load from the buffer location; v) the lift travels to the I/O point (first tier) with the load and discharges it.

If the retrieved load is at the first tier then, the lift does not move. Solely the i) and the ii) steps take place.

The assumptions that are used in the SBS/RS modelling (both in analytical and simulation models) are summarized below:

- There are two buffer areas that transactions can stay.
- The lift and shuttles follow the single command cycle (SC) scheduling rule.
- Loading and unloading delays are ignored in the models.
- The dwell point of lifts/shuttles are assumed to be the points where they complete their last process.
- A pure random storage policy is assumed in the models. Under this policy, the storage address is assigned randomly by selecting any tier and bay with the same probability.
- In travel time estimations, acceleration and deceleration delays are considered to be the same.
- If the transaction is at the first tier, then lift is not utilized.
- The storage and retrieval transaction arrivals to the system follow independent Poisson distribution whose mean rates are equal, $\lambda_S = \lambda_R$.
- The distance between two adjacent bays and tiers are assumed to be 0.5m. and 0.35m., respectively.

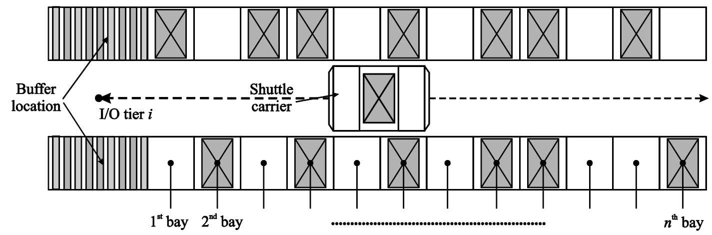

Fig. 2. Top view of an SBS/RS

IV. Queuing Network Modelling Approach

The SBS/RS queuing system can be modeled as an OQN. In the OQN model of an SBS/RS, storage and retrieval transactions are assumed to be arriving customers and, the lifts and the shuttles are two different types of servers. Fig. 2 shows an OQN model of the studied SBS/RS. An arriving transaction (storage or retrieval) enters the network of servers immediately. λ_S shows the mean arrival rate of the storage transactions and λ_R shows the mean arrival rate of the retrieval transactions in the system. Nodes represent the servers (i.e., lifts and shuttles). Note that the storage transactions enter the system from the lift node while the retrieval transactions enter the system from the shuttle node.

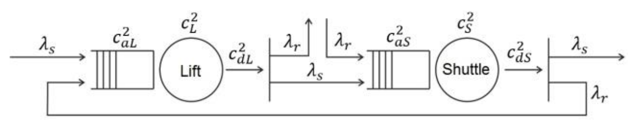

Fig. 2. Open queuing network of the studied SBS/RS

Based on the decomposition approach explained in the following sections, the first node can be modeled as an *G*/*G*/2 queuing system. In this case, the lift's capacity is doubled and the arrival and the service rates are assumed to be generally distributed. The second node can be modeled as an *G*/*G*/*m* queuing system where there is an *m* number of shuttles in an aisle. A generally distribution can be described by their first two moments – the mean and the squared coefficient of variation (scv - c^2) [14]. Scv is the ratio of variance (σ^2) to the mean square (μ^2) In Fig. 2, each node representing a service delay is defined by the values of μ and scv, c^2.

A. *Queuing Performance Calculations*

Based on Fig. 2, three basic network operations: departure, split and superposition on arrival rates take place. The first and the second moment calculations of these network operations are summarized in [13]. For instance, Figure 3, 4 and 5 show departure, split and superposition network operations and their two moment calculations, respectively. After calculating these first and second moments, we compute the queuing performance measures: the mean waiting time of a transaction in a lift queue - $E(W_L)$ - and in a shuttle queue - $E(W_S)$ - as well as the mean number of transactions waiting in those queues $E(L_L)$ and $E(L_S)$. The energy consumption and regeneration calculations are also given in [13].

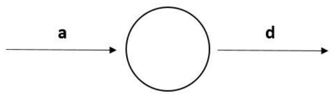

Fig. 3. Departure network operation

In Fig. 3, departure's rate and its scv are calculated by (1)-(2) [14]:

$$\lambda_d = \lambda_a \quad (1)$$

$$c_d^2 = 1 + (1 - \rho^2)(c_a^2 - 1) + \rho^2 / \sqrt{m}(c_s^2 - 1) \quad (2)$$

where m is the number of parallel servers in that node.

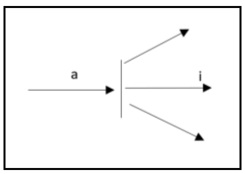

Fig. 4. Split network operation

Fig. 4 shows a split network operation. The regarding formulations are given by (3) and (4):

$$\lambda_i = p_i \lambda_a \quad (3)$$

$$c_i^2 = p_i c_a^2 + 1 - p_i \quad (4)$$

where p_i is the probability of splitting to the i^{th} route.

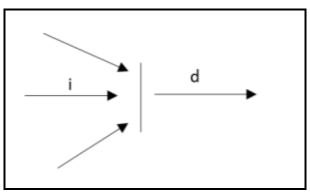

Fig. 5. Superposition network operation

Fig. 5 shows a superposition network operation. The regarding calculations are given by (5)-(6).

$$\lambda_d = \sum \lambda_i \quad (5)$$

$$c_d^2 = \omega \sum (\lambda_i / (\sum \lambda_k))\, c_i^2 + 1 - \omega \quad (6)$$

where ω is calculated by (7)-(8):

$$w = [1 + 2.1(1-\rho)^{1.8} v]^{-1} \quad (7)$$

$$v = \left[\sum_i \left({}^{\lambda_i}/_{\sum_k \lambda_k}\right)^2\right]^{-1} \quad (8)$$

Note that c^2 of a Poisson process is always 1. After calculating the two moments of the arrivals into the server, the performance measures can be calculated via $G/G/m$ queuing models (Whitt, 1983a). For the mean waiting time calculations for the lift and shuttle queues, we consider Whitt's $G/G/m$ QNA approach [14]. The details of this method is given below:

In $G/G/m$ of QNA approach [14] the mean waiting time, $E(WQ_L)$ or the $E(WQ_S)$, is approximated by (9).

$$E(WQ) \approx \left(\frac{c_a^2 + c_s^2}{2}\right) E(WQ)(M/M/m) \quad (9)$$

where (9) is decared to be a good approximation when c_a^2 and c_s^2 are larger than or equal to 0.9 or for an $M/G/m$ queue. In our case, the scv values for arrivals to and service times of the nodes are larger than or equal to 0.9. Specifically the scv of arrival rates to the nodes are close to one which treats the process as an $M/G/m$ queue. Hence, it would not be surprising that we would have good queuing performance results by the suggested method in (9). In (9) approximation, for waiting time in queue, $E(WQ)(M/M/m)$, has an exact solution that can be computed by Little's formula by (10)-(13).

$$E(WQ)(M/M/m) = \frac{E(LQ)}{\lambda} \quad (10)$$

$$E(LQ) = \frac{P(j \geq m)\rho}{1-\rho} \quad (11)$$

$$P(j \geq m) = \frac{(m\rho)^m \pi_0}{m!\,(1-\rho)} \quad (12)$$

$$\pi_0 = \frac{1}{\sum_{i=0}^{i=(m-1)} \frac{(m\rho)^i}{i!} + \frac{(m\rho)^m}{m!\,(1-\rho)}} \quad (13)$$

where λ is the arrival rate to the node (server), ρ is the mean utilization of the server, $E(LQ)$ is the mean number of jobs (i.e. transactions) waiting in queue of that server and π_0 is the long-run probability that there is no item in the queue and server. Here, $\rho = \lambda / m\mu$ where it is assumed that $\rho < 1$.

V. CONDUCTED EXPERIMENTS AND RESULTS

To test the accuracy of the above proposed analytical approach, first we create a warehouse design table showing based on which physical design of the SBS/RS, the analytical and simulation models are run (see Table I). In this table, the scenarios are defined based on two number of bays (B), 120 and 150, two number of tiers (N_T), 20 and 16, and a single number of aisles (A) scenario which is 20. The lift's and shuttle's maximum velocities are considered to be 2 m/sec. and 3 m/sec., respectively. The acceleration and deceleration values are assumed to be same for lift and vehicle which is 1 m/sec^2. The arrival rate of transactions to the system is assumed to have poisson distribution with mean rate $\lambda_S = \lambda_R$. In the experiments, we run the models for the arrival rate scenarios of, $\lambda_S + \lambda_R$ = 26,000, 25,000, 24,000, 23,000, 22,000, 21,000 transactions/hour.

TABLE I. WAREHOUSE DESIGN TABLE

B	N_T	A	V_L (m/sec)	V_S (m/sec)
150	16	20	2	3

The analytical results are validated by the simulation results. Table II-III summarize the analytical and simulation results. In Table 2, mean travel time per transaction for a lift, $E(T_L)$ and for a shuttle, $E(T_S)$; mean energy consumption per transaction for a lift, $E(W_L)$, and for a shuttle, $E(W_S)$ are summarized. Also, mean amount of energy regeneration per transaction for a lift, $E(RW_L)$, and for a shuttle, $E(RW_S)$, are presented in this table. In Table III, utilization of lifts, ρ_L, and some queuing performance measure results from lifts and shuttles are illustrated. For the comparison purpose, the simulation models are run for 10 replications hence, we provide these results at 95% confidence intervals. Note that in Table III, in the last columns, we also provide absolute percantage error (APE) results which show the deviations of analytical results from the simulation results in percentage unit. The APE value are calculation for WQ_L performance measure is shown by (14) as an example:

$$\frac{\left|E(WQ_L)_{\text{Analytical}} - E(WQ_L)_{\text{Simulation}}\right|}{E(WQ_L)_{\text{Simlation}}} \times 100 \qquad (14)$$

In Table II, since the APE values are very small (i.e., all are nearly zero), we do not provide them in this table. However, in queuing performance measures, the APE values are provided for the mean waiting time in lift queue, $E(WQ_L)$. Since the number of transactions waiting in lift queue, $E(LQ_L)$ is already computed from $E(WQ_L)$ by (11), we do not provide the APE results for $E(WQ_L)$ because it would produce the same APE results as in $E(WQ_L)$.

TABLE II. TRAVEL TIME, ENERGY CONSUMPTION AND ENERGY REGENERATION RESULTS

$E(T_L)$ (min.)	$E(T_S)$ (min.)	$E(W_L)$ (kWh)	$E(W_S)$ (kWh)	$E(RW_L)$ (kWh)	$E(RW_S)$ (kWh)
Analytical Results					
5.03	26.11	$2.07 \cdot 10^{-3}$	$6.16 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$	$1.11 \cdot 10^{-4}$
Simulation Results					
5.03 ±0.0206	26.11 ±0.02	$2.07 \cdot 10^{-3}$	$6.16 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$	$1.11 \cdot 10^{-4}$

Note that the travel time - $E(T_L)$ and $E(T_S)$, energy consumption - $E(W_L)$ and $E(W_S)$, and energy regeneration amount per transaction - $E(RW_L)$ and $E(RW_S)$, performance measures do not depend on the arrival rate of transaction to the system. However, they depend on the velocity profiles as well as the number of bays and tiers in the system. Hence, in Table II, we provide the output results just for the Table I design. From Table II, it can be seen that the analytical model results produce exactly the same results as in the simulation results. Hence, the APE values are all zero in Table II for the performance measures. Therefore, we do not provide the APE values in a separate column.

TABLE III. UTILIZATION AND QUEUING PERFORMANCE RESULTS

		Analytical Results			Simulation Results			APE (%)
Ex.	$\lambda_S + \lambda_R$	ρ_L	$E(WQ_L)$	$E(LQ_L)$	ρ_L	$E(WQ_L)$	$E(LQ_L)$	
1	26,000	0.907	14.32	5.17	0.906	13.73	4.95	4.26
2	25,000	0.873	9.80	3.40	0.872	9.5	3.30	3.05
3	24,000	0.838	7.23	2.41	0.837	7.04	2.34	2.72
4	23,000	0.803	5.58	1.78	0.802	5.48	1.75	1.70
5	22,000	0.768	4.42	1.35	0.767	4.37	1.33	1.25
6	21,000	0.733	3.58	1.04	0.732	3.54	1.03	0.89

Since lifts are usually bottlleneck in these systems, the queuing performances are given for different level of utilization of lifts. These values are obtained by the trial of different arrival rate scenarios of transactions in the system. The queuing performances are observed for average waiting time of a transaction and average number waiting in a lift queue. In the last column, the APE values are provided. Note that the APE values are always less than 5%. This shows that the developed analytical model could produce good estimates when the results are compared with the simulation results. Fig. 6 illustrates a screenshot figure from the developed tool. The toll is developed by using MatlabR2009b.

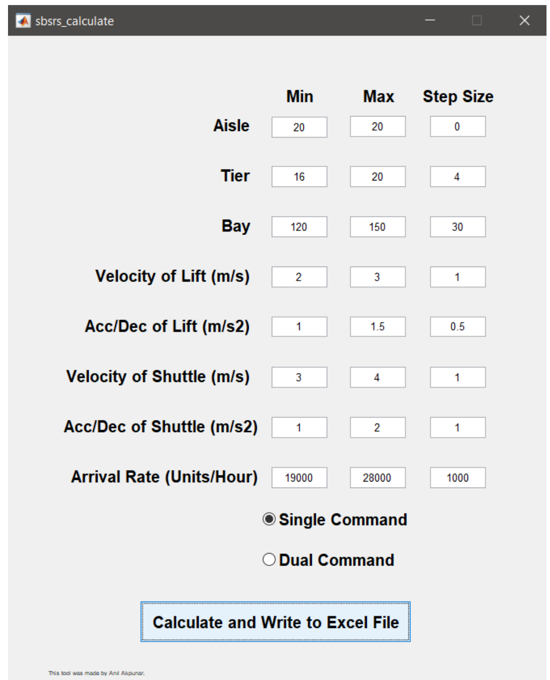

Fig. 6. A screenshot from the developed tool

As a future work, because it is already considered to include dual command scheduling rule in the system as well, we created a button in the tool for this case as well. Except that by the developed tool seen from Fig. 6, once the minimum and the maximum levels for the input design variables are defined, the tool implements a design of experiment by considering all the possible combinations of these input design parameters and calculates each design's performance measures: $E(T_L)$, $E(T_S)$, $E(W_L)$, $E(W_S)$, $E(RW_L)$, $E(RW_S)$, ρ_L, $E(WQ_L)$, $E(LQ_L)$. By that, the user can evaluate several designs of SBS/RS promptly and can decide on the right SBS/RS for his/her requirement.

VI. CONCLUSION

In this work, we develop a tool based on an OQN analytical model, estimating some critical performance measures from a pre-defined SBS/RS design. After validating the tool by using simulation results, we can suggest the utilization of this tool for the practitioners for deciding the right design of an SBS/RS. Specifically, by the developed tool, one can evaluate numerous SBS/RS designs promptly and decide on the right SBS/RS design for his/her requirements.

As a future study, this work can be extended by also considering dual command scheduling rule in the system as well as more experimentation to trace how the APE values change based on the different warehouse designs.

ACKNOWLEDGMENT

This work was supported by The Scientific and Technological Research Council of Turkey and Slovenian Research Agency: ARRS [grant number: 214M613].

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