2014

An Experimental Study of the Impact of Warehouse Parameters on the Design of a Case-picking Warehouse

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SIMULATION-BASED ENERGY AND CYCLE TIME ANALYSIS OF SHUTTLE-BASED STORAGE AND RETRIEVAL SYSTEM

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Abstract

This study explores the best warehouse design for shuttle-based storage and retrieval system (SBS/RS) minimizing average energy consumption per transaction and average cycle time per transaction, simultaneously. For that we provided average energy consumption per transaction versus average cycle time per transaction graphs, for different design scenarios of the studied SBS/RS warehouse. In the design concept, we considered, rack design in terms of number of bays, number of tiers, number of aisles, as well as velocity profiles of lifts in the system. We completed 144 number of experiments by simulation to see the trade-offs based on the design scenarios and provided them by two separate graphs. The results show that while the SBS/RS warehouse has low number of tiers, it has low energy consumption per transaction as well as low average cycle time per transaction in the two lift velocity scenarios.

1. Introduction

Due to the willingness of companies to be highly responsive to varying customer demands, flexibility of supply chain gains significance. Warehouses and the material handling technology used in warehouses play a critical role in the flexibility of a supply. Fast and efficient storage and retrieval of items to/from storage locations is important for obtaining a high throughput transaction rate. Since the 1950s, Automated Storage and Retrieval Systems (AS/RSs) have been widely used in warehouses. Compared to what it was, to meet customer demand, nowadays they have more flexibility. With advances in automation technology, new automated material handling technologies providing greater responsiveness and additional flexibility in fulfilling orders have been developed. A recent technology is a Shuttle-based Storage and Retrieval System (SBS/RS) developed for high transaction throughput rates. This new design is created due to increasing trends towards more product variety and short response time. An SBS/RS is also developed as an alternative system to mini-load Crane-based Storage and Retrieval System (CBAS/RS) where CBAS/RS cannot handle the desired throughput rate (Carlo and Vis, 2012; Marchet et al., 2012; Marchet et al., 2013; Lerher, 2013; Lerher et al., 2013). A typical SBS/RS is a tier-captive automated warehouse design where shuttles can only travel within a tier and each aisle has a lift mechanism (Figure 1). The main advantage of this system is that it is light-weight (energy efficient) and it has high transaction throughput capacity due to having a dedicated shuttle in each tier of an aisle. Shuttles carry loads in totes so this system is also known as automated warehouse with product totes (Marchet et al., 2014).

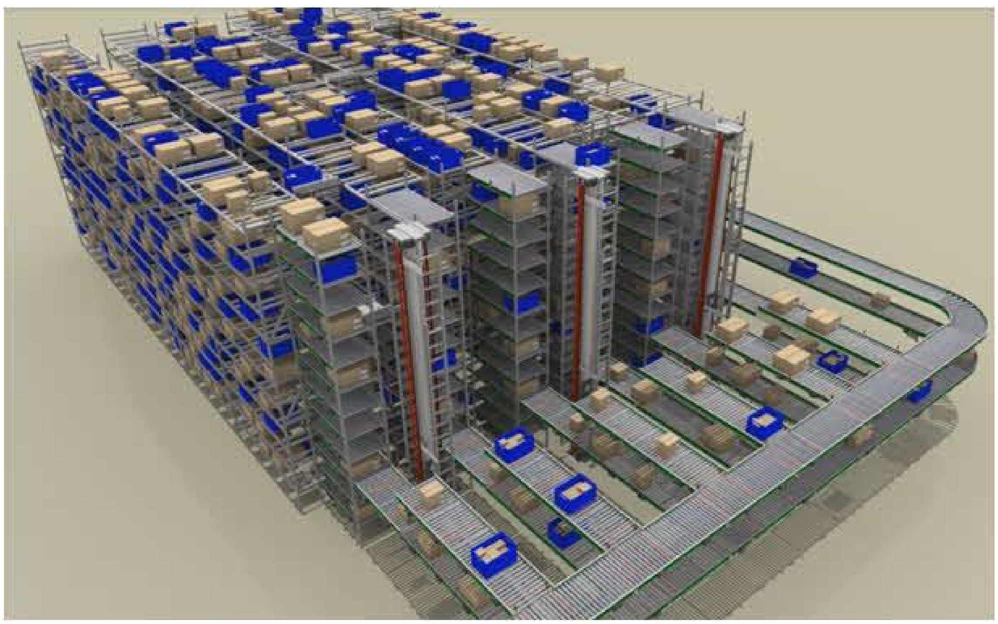

Figure 1: SBS/RS warehouse (Dematic Multishuttle 2 White Paper, 2013)

In the literature, SBS/RS seems to have been disregarded despite its higher adoption in a number of industrial applications. There are very few studies on SBS/RS (Marchet et al., 2012; Carlo and Vis, 2012; Marcet et al., 2013) which present analytical and simulation models to estimate SBS/RS performance measures (typically the transaction cycle time and waiting times). Lerher et al. (2015a) presented analytical travel time model for the computation of travel (cycle) time for SBS/RS by considering several operating characteristics of elevator's lifting table and the shuttle carrier, such as acceleration and deceleration and the maximum velocity. Lerher et al. (2015b) also presented a simulation-based performance evaluation of SBS/RS. The objective of this study was to exploit the benefits of SBS/RS. In this study, our aim is to fill this gap in the literature by adding a new design concept for the system considering energy consumption minimization in the system.

As seen in Fig. 1, an SBS/RS works with aisle and tier captive shuttles. This new technology is mostly used for mini-load warehouses where the maximum weight of a tote does not exceed 50 kg. on average The vertical movement of totes is facilitated by lifts mounted along the periphery of the storage racks.

In this study, we explore the best warehouse design of SBS/RS providing minimum energy consumption per transaction and average cycle time per transaction performance measures. For this aim, we simulated an SBS/RS and experimented 144 different design scenarios. The results are summarized in two separate graphs provided in the following sections. In the next section, we detail the simulation modeling of the system by also providing the assumptions that are considered in the model. In that section, we also present the conducted experiments and their simulation results illustrated via two separate graphs.

2. Simulation Model of the SBS/RS and Energy Consumption Calculations

In an SBS/RS, two types of transactions arrive into the system - storage and retrieval. In a storage transaction, the transaction arrives at the I/O point which is at the first level of the tier. If the destination storage location is not at the first tier, the transaction requests a lift to travel to the destination tier. The lift drops off the load at the buffer location of the destination tier and then a shuttle picks up the load to store it at the destination storage compartement. In a retrieval transaction, the shuttle retrieves the load from the storage rack and transfers it to the buffer location at its tier. If the transaction is not located at the first tier then, the load requests lift and travels to the first level of the tier – i.e. I/O location – to be dropped off. Hence, all storage transactions are assumed to arrive at the I/O point and all retrieval transactions end at the I/O point.

The simulation flowchart is given in Figure 2 to provide more details on the simulation model. To facilitate the simulation modeling, we modeled a single aisle.

The assumptions that are used in the simulation model are:

- Each aisle has one lift mechanism that can carry two loads independently.
- Each tier has two buffer locations, each is in front of its lifting table. Hence, each lifting table has its own buffer location which has one tote capacity.
- Lifts operate by dual-command (DC) scheduling rule, where a storage transaction follows a retrieval transaction or vice versa. If there is no required transaction type waiting in the queue, then lift processes the waiting first transaction without considering DC scheduling policy.
- Lifts and shuttles travel simultaneously when a request takes place for both.

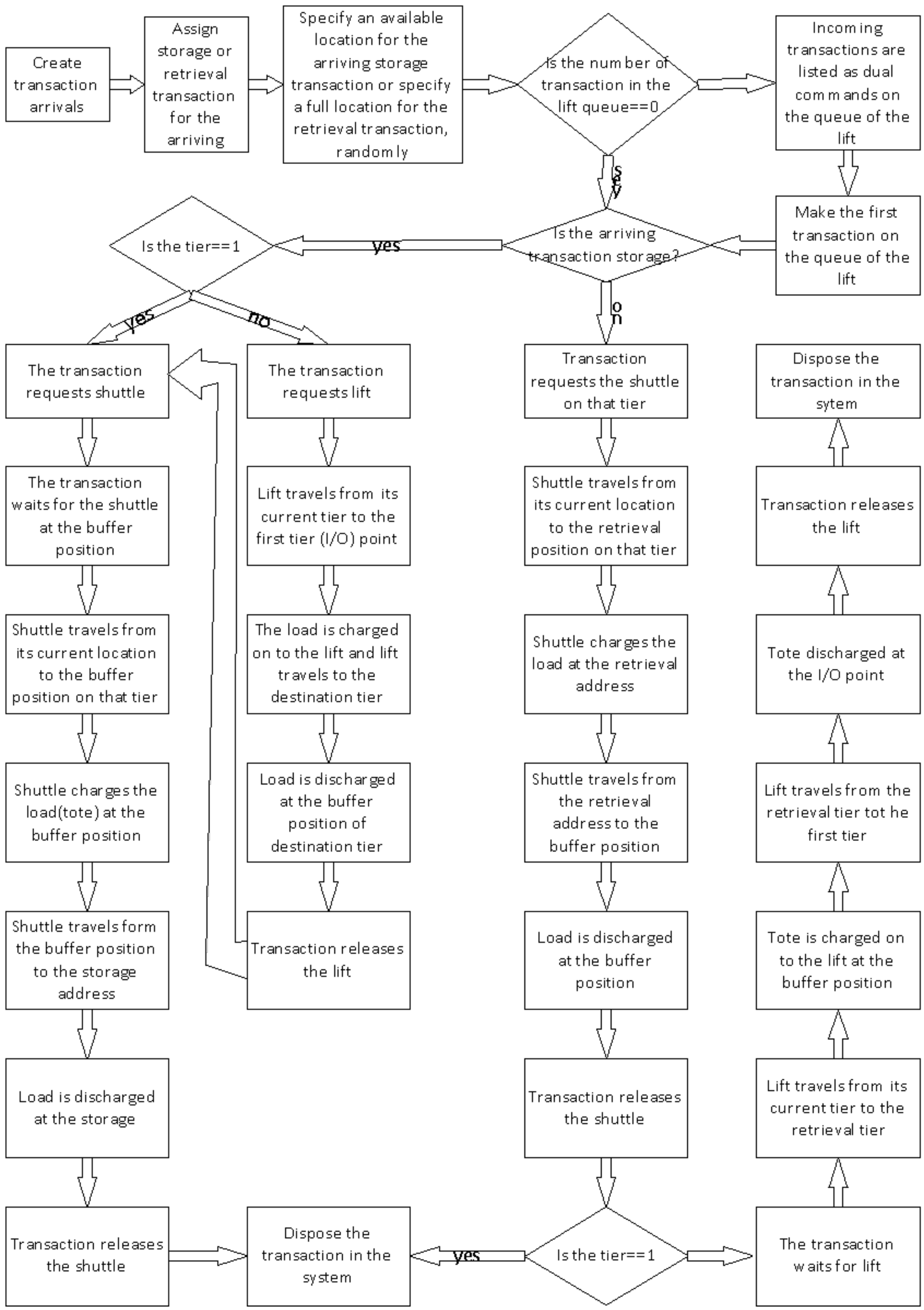

Figure 2: Flowchart of the SBS/RS simulation model

- The dwell point of a shuttle is the place where the last storage or retrieval transaction is completed.
- The dwell point of the lift is where the last vertical movement is completed.
- The system uses pure random storage policy.
- The single-deep racks on either side of an aisle consist of bays, and each bay can hold one tote.
- Unit loads are transferred by the conveyors and arrive to the I/O locations.
- The simulation is run for one year with one month warm-up period and one replication.
- In the simulation model, the "common random variables" (CRN) variance reduction technique is used.
- Arrivals follow a Poisson process and the mean arrival rates for S/R transactions are equal ($\lambda\_S = \lambda\_R$) totes/hour

The notations that are used in the modelling are summarized below.

T	: number of tiers	H	: the height of one tier
A	: number of aisles	L	: the number of lifts
B	: number of bays per aisle	V_S	: the maximum velocity of a shuttle
W	: width of one storage bay	m_{lift}	: the mass of the lift
λ_r	: the arrival rate of retrieval transactions	λ_s	: the arrival rate of storage transactions
V_L	: the maximum velocity of lift	$T_{L/U}$	: load/unload time of tote in any case
$m_{shuttle}$	: the mass of the shuttle	m_{tote}	: the mass of the tote
T_T	: the load/unload transfer time to the lift buffer/conveyor from the conveyor/lift buffer		

Specific values for some variables are set as in below.

W	: 0.5 m.	H	: 0.3 m.
m_{lift}	: 40 kg	$T_{L/U}$	: 3 sec.
m_{tote}	: 20 kg	$m_{shuttle}$	: 20 kg

2.1 Velocity versus Time Graphs for Travel Time Calculations

In the simulation model, the energy (electricity) consumption calculations are completed for shuttles and lifts, separately by considering the conditions that they are accelerating, decelerating or traveling at the maximum velocity. Since the amount of electricity consumption depend on acceleration, deceleration conditions as well as travelling with constant speed (at the maximum speed) condition of the shuttles and lifts, we need to define velocity versus time relations. For that, we define two cases where shuttle/lift reaches to its maximum speed (Case I) or not (Case II). Before presenting details on the energy consumption calculations, we provide the required notations that are used in this section.

V_{max} : the maximum velocity that a shuttle or a lift that can reach (m / sec)

V_{last} : the last velocity that a shuttle or lift reaches (due to short distance $V_{last} < V_{max}$)

a_V : accelaration value of shuttle (m / sec^2)

d_V : deceleration value of shuttle (m / sec^2)

a_L : accelaration value of lift (m / sec^2)

d_L : deceleration value of lift (m / sec^2)

G : force of gravity ($G = m \cdot g$ - $kg \cdot$ m / sec^2 =Newton)

g : standard gravity ($\approx$10 m / sec^2)

c_r : resistance coefficient

f_r : factor for resistance of rotating masses with variable speed

F_T : traction force in the acceleration (Newton)

F_B : traction force in braking (Newton)

F_C : traction force in travel with constant velocity (Newton)

P_T : engine power to overcome F_T (kW)

P_B : engine power to overcome F_B (kW)

P_C : engine power to overcome F_C (kW)

F_L : lifting force (Newton)

P_L : engine power to overcome F_L (kW)

W_A : amount of energy (electricity) consumption in acceleration case (kWh)

W_D : amount of energy (electricity) consumption in decceleration case (kWh)

W_C : amount of energy (electricity) consumption in travel with constant velocity case (kWh)

Figure 3-4 represent travel distance versus time graphs of lifts/shuttles. By these graphs how long a shuttle or lift accelerates/decelerates and travels with constant velocity can be calculated. For instance, in Case I, lift/shuttle cannot reach its maximum velocity due to relatively shorter travel distance. It accelerates/decelerates t_1 amount of time and can reach up to a speed V_{last} which is smaller than its maximum velocity. In Figures 3-4, since it is assumed that acceleration value is equal to deceleration value, the time spent in acceleration and deceleration will be equal in two cases. It should be noted that the area under these Figures 3-4 graphs will provide us with the distance travelled (D) by lifts/shuttles. For instance, in Figure 3, D is calculated by (1):

$$D = V_{last} \cdot t_1 \quad (1)$$

where V_{last} is calculated by (2) and t_1 is calculated by (3):

$$V_{last} = a \cdot t_1 \quad (2)$$

$$t_1 = \sqrt{(D/a)} \quad (3)$$

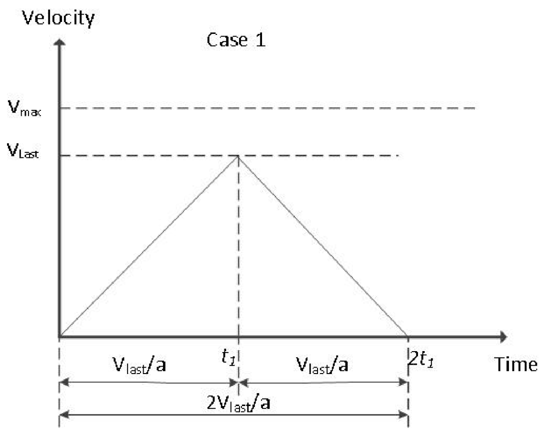

Figure 3: Case I

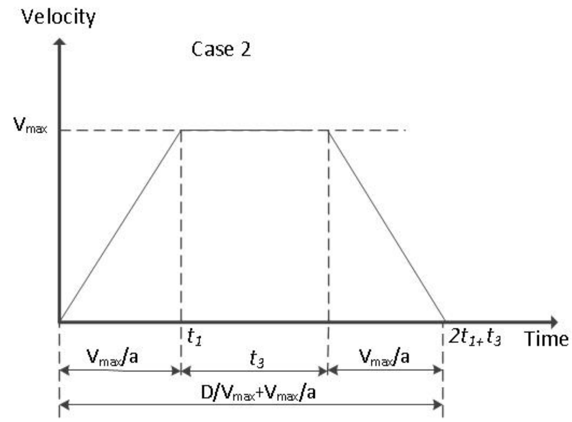

Figure 4: Case II

In Figure 4, lift/shuttle is able to reach to its maximum velocity due to longer travel distance. It accelerates/decelerates t_1 amount of time and travels with constant velocity (i.e., with its maximum velocity) for t_3 amount of time. By assuming that acceleration and deceleration values are equal, V_{max} is calculated by (4):

$$V_{max} = a \cdot t_1 \quad (4)$$

Hence, the total travel time in Case II becomes as in (5):

$$2 \cdot t_1 + t_3 = D/V\_max \ + V\_max/a \quad (5)$$

2.2 Energy Consumption Calculations for Shuttles

Based on Case I and II, a shuttle can realize two types of travels based on whether it reaches to its maximum velocity or not as presented in Figures 3-4. Note that in Case I-II, it is assumed that vehicle accelerates/decelerates t_1 amount of time.

In the acceleration case, the traction force is calculated by (6):

$$F_T = G \cdot c_r + G/g \cdot a\_s \cdot f_r \text{ (Newton – kg m / sec}^2\text{)} \quad (6)$$

The required engine power to overcome F_T as kW is calculated by (7):

$$P\_T = (F\_T \cdot V\_last)/(1000 \cdot \eta) \quad (7)$$

In the deceleration case, the braking force is calculated by (8):

$$F_B = G/g \cdot d\_S \cdot f_r - G \cdot c_r \text{ (Newton – kg m / sec}^2\text{)} \quad (8)$$

The required engine power to overcome F_B as kW is calculated by (9).

$$P\_B = (F\_B \cdot V\_last)/(1000 \cdot \eta) \quad (9)$$

In the travel case with constant velocity, the traction force is calculated by (10):

$$F_C = G \cdot c_r \text{ (Newton – kg m / sec}^2) \quad (10)$$

The required engine power, P_C, to overcome F_C as kW is calculated by (11).

$$P\_C = (F\_C \cdot V\_max)/(1000 \cdot \eta) \text{ (kW)} \quad (11)$$

Hence, the energy (electricity) consumption in acceleration 〖(W〗 _A) deceleration 〖(W〗 _D) and constant velocity travel case 〖(W〗 _C) for vehicle can be calculated by (12)-(14) respectively:

$$W\_A = P\_T.t\_1 \text{ (kWh)} \quad (12)$$

$$W\_D = P\_B.t\_1 \text{ (kWh)} \quad (13)$$

$$W\_C = P\_C.t\_2 \text{ (kWh)} \quad (14)$$

2.3 Energy Consumption Calculations for Lifts

In the lift case, although travel time calculations do not change, namely are same as in the shuttle case, the energy consumption calculations change due to travel of lift in the vertical direction.

In the acceleration case, the lifting force is calculated by (15):

$$F_L = G + G/g \cdot a\_L \cdot f_r \text{ (Newton – kg m / sec}^2) \quad (15)$$

The required engine power to overcome F_L as kW is calculated by (16):

$$P\_L = (F\_L \cdot V\_last)/(1000 \cdot \eta) \quad (16)$$

In the deceleration case, the braking force is calculated by (17):

$$F_B = G + G/g \cdot d\_L \cdot f_r \text{ (Newton – kg m / sec}^2) \quad (17)$$

The required engine power to overcome F_B as kW is calculated by (18).

$$P\_B = (F\_B \cdot V\_last)/(1000 \cdot \eta) \quad (18)$$

In the travel case with constant velocity, the traction force is calculated by (19):

$$F_C = \text{G (Newton – kg m / sec}^2\text{)} \quad (19)$$

The required engine power, P_C, to overcome F_C as kW is calculated by (20).

$$P\_C = (F\_C \cdot V\_max)/(1000 \cdot \eta) \text{ (kW)} \quad (20)$$

Hence, the energy (electricity) consumption in acceleration $〖(W〗 \_A)$ deceleration $〖(W〗 \_D)$ and constant velocity travel case $〖(W〗 \_C)$ of lift can be calculated by (21)-(23) respectively:

$$W\_A = P\_L.t\_1 \text{ (kWh)} \quad (21)$$

$$W\_D = P\_B.t\_1 \text{ (kWh)} \quad (22)$$

$$W\_C = P\_C.t\_2 \text{ (kWh)} \quad (23)$$

3 Scenarios and Results for Conducted Experiments

The simulation runs are completed based on three *T* and four *B* scenarios and, six arrival rate - *AR* - scenarios. There is a strong relationship between *AR* and the number of aisles in the system. This is because *AR* would be defined by dividing the total arrival rate to the number of aisles in the system. As a note, in the simulation model of the SBS/RS, a singe aisle is modelled. For the *T* and *B*, the levels we considered these values: 14, 15, 16 and 30, 40, 50, 60, respectively. In SBS/RS, lifts are mostly bottleneck and affect the system's throghput rate, significantly. Therefore, the *AR* levels are selected so that the utilization of lifts (U_L) are obtained to be around 95%, 90%, 85%, 80%, 75%, 70%. The completed experiments and their results for $T = 14$ are provided in Table 2 as an example. For instance, in that table, the *AR* levels are considered to be 410, 385, 360, 340, 315 and 290 totes/hour to obtain the U_L values around 95%, 90%, 85%, 81%, 75%, 69%, respectively. It should be noted that we observe average cycle time per transaction - C_T – and average energy consumption per transaction - E_C - as performance measures from the system that are provided in the last columns of Table 2.

Table 1: Design scenarios cunducted in simulation experiments

***AR* (*UL*)**	***B***	***T***	**Lift speed profile**		**Shuttle speed profile**	
			a_V **(m/sec^2)**	V_{max} **(m/sec)**	a_L **(m/sec^2)**	V_{max} **(m/sec)**
95%	30	14	2	2	2	2
90%	40	15		3		
85%	50	16				
80%	60					
75%						

70%

Note that in Table 1 there are 144 possible combinations to experiment. Hence, we completed 144 experiments in simulation and observed their results. Figure 5-6 show energy consumption per transaction (E_C) versus average cycle time per transaction (C_T) graphes when lift $V_{\max}$ = 2 m/sec. and lift $V_{\max}$ = 3 m/sec., obtained from the simulation results, respectively.

Table 2: Design scenarios for $T = 14$, lift $V_{max} = 2$ and their simulation results

T	***B***	***AR***	U_L	C_T **(min.)**	E_C **(kWh)**
14	30	410	0.95	1.80	0.000649 ±0,0000009
14	40	410	0.95	1.88	0.000653 ±0,0000010
14	50	410	0.95	1.95	0.000656 ±0,0000009
14	60	410	0.95	2.05	0.000659 ±0,0000010
14	30	385	0.90	1.02	0.000667 ±0,0000013
14	40	385	0.90	1.07	0.000670 ±0,0000013
14	50	385	0.90	1.13	0.000673 ±0,0000013
14	60	385	0.90	1.19	0.000676 ±0,0000013
14	30	360	0.85	0.79	0.000679 ±0,0000011
14	40	360	0.85	0.83	0.000682 ±0,0000020
14	50	360	0.85	0.89	0.000686 ±0,0000013
14	60	360	0.85	0.94	0.000688 ±0,0000011
14	30	340	0.81	0.69	0.000687 ±0,0000012
14	40	340	0.81	0.74	0.000690 ±0,0000020
14	50	340	0.81	0.78	0.000693 ±0,0000013
14	60	340	0.81	0.84	0.000696 ±0,0000015
14	30	315	0.75	0.61	0.000694 ±0,0000014
14	40	315	0.75	0.66	0.000698 ±0,0000014
14	50	315	0.75	0.70	0.000701 ±0,0000014
14	60	315	0,75	0.75	0.000703 ±0,0000015
14	30	290	0.69	0.56	0.000700 ±0,0000015
14	40	290	0.69	0.60	0.000704 ±0,0000016
14	50	290	0.69	0.65	0.000706 ±0,0000017
14	60	290	0.69	0.70	0.000709 ±0,0000016

We summarize our findings from the simulation results and Tables 5-6 as in below:

- We observe that when utilization of lifts - U_L - decreases energy consumption per transaction - E_C – increases and average cycle time per transaction – C_T - decreases. E_C decrease is most probably due to having reduced number of dual command cycles in the lower utilized lift condition.

- When the number of tiers – T - increases energy consumption per transaction - E_C - also increases. This is probably due that large portion of energy consumption belongs to lift travel.
- In the fixed value of U_L (i.e., fixed level of arrival rate and tier) when the number of bays increases, E_C and C_T also increase.
- When the velocity of lift increases to 3 m/sec., the energy consumption per transaction increases.

In Figures 5-6, the blue dots present the design scenarios provided in Table 1 where their details are also labeled above them.

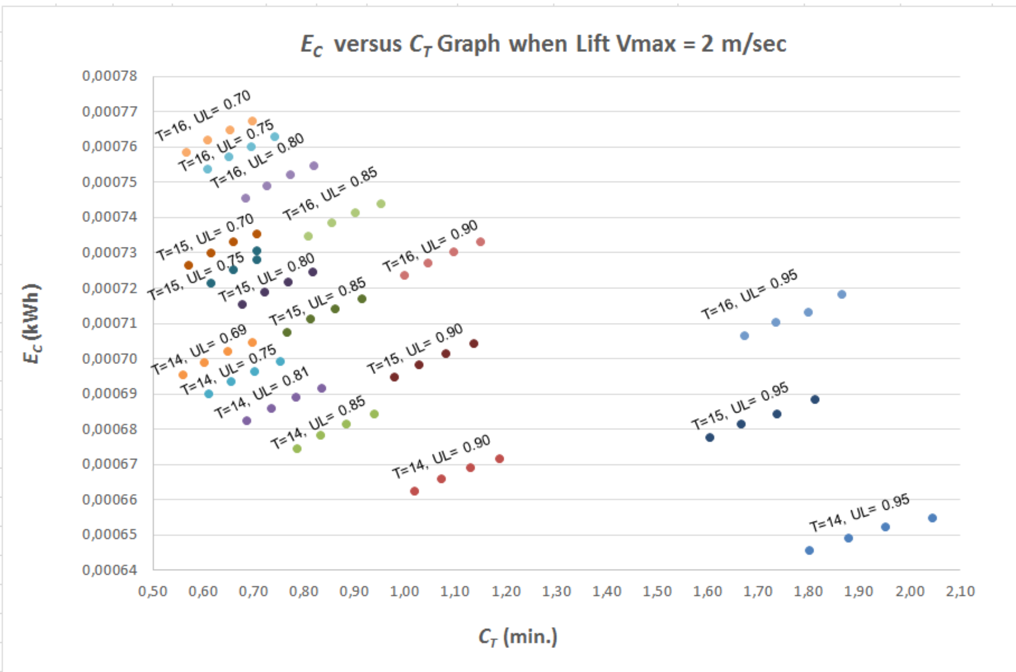

Figure 5: E_c versus C_T graph when lift $V_{\max}$ = 2 m/sec

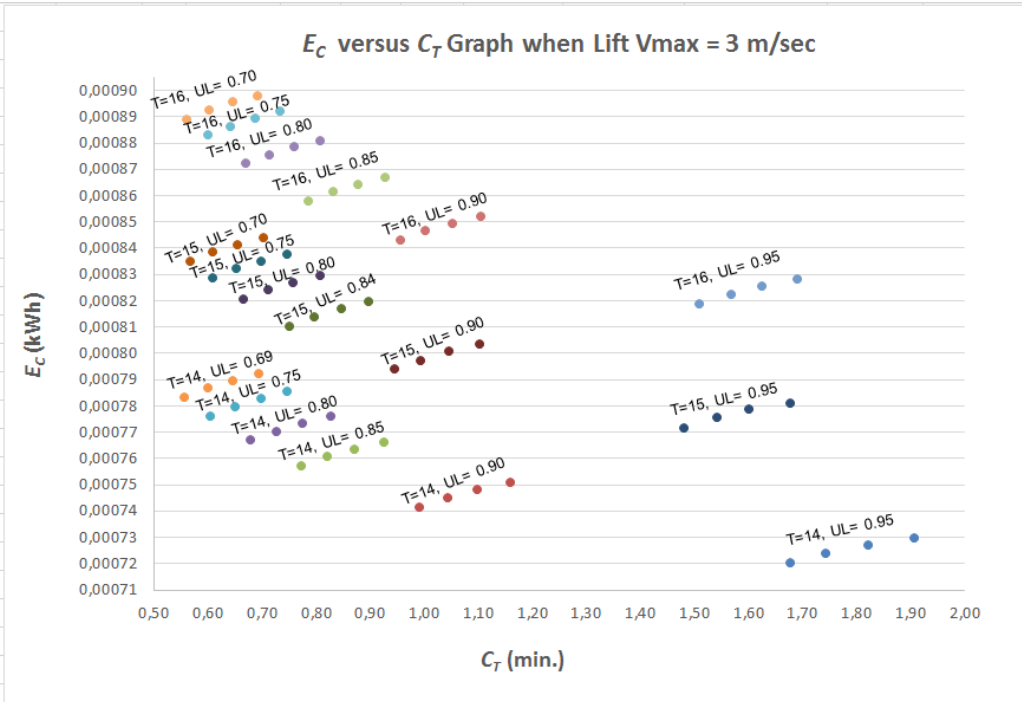

Figure 6: E_c versus C_T graph when lift $V_{\max}$ = 3 m/sec

From both Tables 5-6, it is also observed that the minimum E_c and C_T are always obtained in the design scenarios having low number of tiers (i.e., T = 14). As a heuristic solution, one may consider the best warehouse design minimizing E_c and C_T as the design having T = 14, U_L = 0.85, B = 30. It should be noted that in those designs, C_T and the E_C values are moderately low in both lift $V_{\max}$ scenarios.

4 Conclusion

In this study, we explore the best warehouse design for shuttle-based storage and retrieval system (SBS/RS) minimizing average energy consumption per transaction (E_C) and average cycle time per transaction (C_T), simultaneously. To see the trade-offs of these two responses, we provided two separate graphs showing E_C versus C_T values for two velocity scenarios of lifts - $V_{\max}$ = 2 and 3 m/sec. To obtain these graphs, we completed 144 simulation experiments for different design scenarios of the SBS/RS including number of tiers, number of bays, average arrival rate to a single aisle, and velocity of lift. As a result, since they have moderately low responses, one may consider the optimum design to be the design having 14 number of tiers and 30 number of bays in the warehouse to minimize the E_C and C_T in both velocity scenarios of lift.

Acknowledgement

This study is produced from a bilateral research project funded by the domestic research councils of Turkey (TUBITAK) and Slovenia (ARRS) – Project No: 214M613.

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