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Throughput Analysis of S/r Shuttle Systems

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ENERGY AND CYCLE TIME EFFICIENT WAREHOUSE DESIGN FOR AUTONOMOUS VEHICLE-BASED STORAGE AND RETRIEVAL SYSTEM

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Abstract

This study explores the best warehouse design for an autonomous vehicle based storage and retrieval system (AVS/RS) minimizing average energy consumption per transaction and average cycle time per transaction, simultaneously. In the design concept, we consider, rack design in terms of number of bays, number of tiers, number of aisles; number of resources, namely number of autonomous vehicles and lifts and; velocity profiles of lifts and autonomous vehicles in the AVS/RS. We completed 1,296 number of experiments in simulation to obtain Pareto solutions representing the "average energy consumption per transaction" and "average cycle time per transaction" trade-offs based on designs which is a very useful visual tool in decision making. Different from the existing studies, we approach to the warehouse design problem of AVS/RSs from a multi-objective view as well as energy efficient view minimizing both electricity consumption and cycle time per transaction in the system.

1. Introduction

Automated Storage and Retrieval Systems (AS/RSs) are widely used in modern distribution centres which typically have a high-bay storage design and can provide continuously fast, accurate and efficient service. An AS/RS consists of storage racks and storage and retrieval (S/R) devices where products are stored and retrieved automatically. Typically, there are two types of AS/RSs: traditional crane-based AS/RS (CBAS/RS) and autonomous vehicle (AV) based AS/RS (AVS/RS). This study deals with a relatively new technology, AVS/RS, which is an alternative, material handling technology for unit load storage and retrieval.

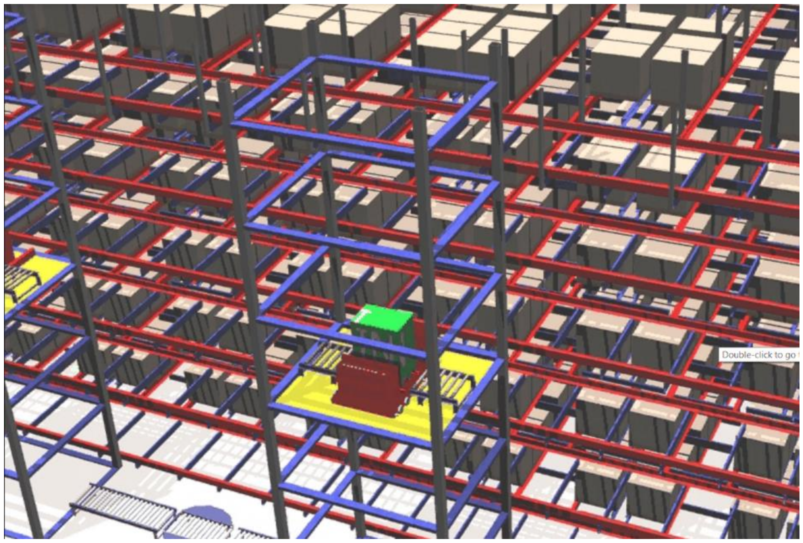

Figure 1: An AVS/RS warehouse

In the 2000 International Material Handling Research Colloquium event, AVS/RS was introduced by a Systems Product Manager for a major supplier of automated material flow systems as a relatively new alternative technology to unit load AS/RSs (Zizzi, 2000). This new technology has been implemented at several European facilities during the late 1990s and exploits the capabilities of `autonomous vehicles' within high- density storage systems. AVS/RSs utilize a rail system running in two horizontal dimensions within a storage rack. Figure 1 presents an AVS/RS with an AV carrying a unit load. An AVS/RS is composed of AVs, lift mechanism and storage racks. Vehicles travel along rails within storage aisles, vehicle movement within aisles is along one dimension at a time, and vehicles travel along end-of-aisle rails when transferring between aisles. Lifts are mounted at fixed locations along the periphery of the storage racks. The number of lifts installed and AVs in a system can vary depending on the desired throughput.

The existing studies in literature about AVS/RS, mostly focus on warehouse design minimizing performance values of *average cycle time of transactions* as well as *queue lengths and utilization of* lifts and AVs (Malmborg, 2002,2003; Fukunari and Malmborg, 2008, 2009; Kuo et al., 2007, 2008; Zhang et al., 2009; Ekren et al., 2010; Ekren, 2011; Ekren and Heragu, 2011; Ekren and Heragu, 2010a; Ekren and Heragu, 2010b; Ekren et al., 2010; Roy et al., 2012). However, due to recent trends on ecological concerns, an automated warehouse design should also consider minimization of energy (i.e., electricity) consumption and hence CO_2 oscillation caused by these systems. By considering minimization of energy consumption, operational cost of these systems and more importantly, negative environmental effects due to releasing CO_2 gas to the atmosphere will also be decreased. The novelty and contribution of this study can be summarized as in below:

- Different from the existing studies, we approach to an AVS/RS warehouse design problem from also an energy efficiency view by minimizing electricity consumption in the system.
- A multi-objective approach is developed to minimize both average electricity consumption per transaction and average cyle time per transaction in the system.
- Several design inputs (decision variables) such as: rack design in terms of number of bays, aisles and tiers; number of resources (lifts and AVs); velocity profiles of AVs and lifts; and acceleration and deceleration of AVs and lifts are considered as decision variables.
- By also considering energy consumption minimization in the system, we aim to contribute to EU's future decreased CO_2 emission target.
- In the modeling purpose, we utilized real data obtained from a company in France.

In the modelling approach, we utilize simulation to complete a very detailed model of the system. The simulation model details, assumptions and the energy consumption calculations are provided in the following section.

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

In an AVS/RS, two types of transactions arrive into the system - storage and retrieval. In a storage transaction, the AV picks up the unit load from the input/output (I/O) location at the first tier and stores it in its pre-assigned storage rack location. In a retrieval transaction, the AV retrieves the load from the storage rack and transfers it to the I/O location at the first tier. Hence, all storage transactions are assumed to arrive at the I/O point and all retrieval transactions end at the I/O point.

A transaction arriving to the system first enters the AV queue, after matching with an available AV, the AV enters the lift queue. If the arriving transaction is a storage and the seized vehicle is on a tier other than the first tier, then the vehicle first travels to the lift location and then enters the lift queue. After seizing the lift, lift travels to the vehicle's tier and vehicle travels to the first tier (I/O) in the lift to pick up the load. If the destination storage location is not on the first tier, then after picking up the load, the vehicle seizes the lift again to travel to the destination tier. After vehicle arrives at the destination tier, it travels to the storage location to discharge the load. The vehicle seizes the lift twice in this scenario. In the current AVS/RS, the warehouse has as many lifts as there are zones in the system.

A specific number of vehicles is assigned to each zone. Therefore, a vehicle always uses the same lift for its vertical movement. The simulation flowchart is given in Figure 2 to provide more details on the simulation model.

The assumptions that are used in the simulation model are:

- The warehouse in divided into homogen zones having same number of bays, aisles, tiers, AVs with the other zones.
- Each zone has one lift system.

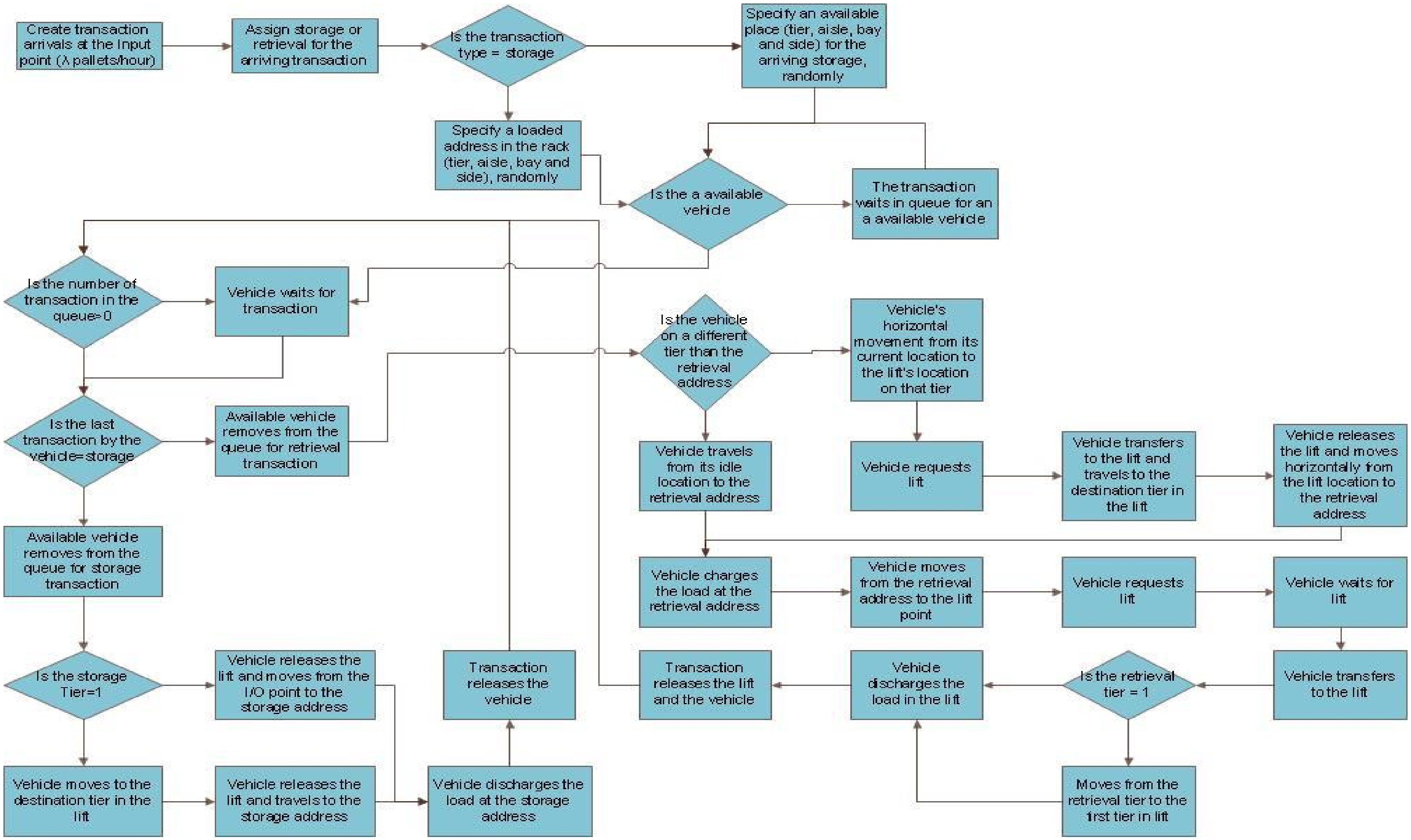

Figure 2: Flowchart of the AVS/RS simulation model

- The dwell point of an AV 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 transactions are served by the vehicles on a dual command rule.
- The vehicles requiring lifts for vertical movement are served by FCFS order.
- The single-deep racks on either side of an aisle consist of bays, and each bay can hold three unit loads.
- 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.

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

Z	: number of zones	H	: the height of one tier
A	: number of aisles	L	: the number of lifts
B	: number of bays per aisle	V_{AV}	: the maximum velocity of the AV
T	: number of tiers	N_V	: the number of AVs/zone
W	: width of one storage bay	m_{lift}	: the mass of the lift
V_L	: the maximum velocity of the lift	λ_s	: the arrival rate of storage transactions to the warehouse
λ_r	: the arrival rate of retrieval transactions to the warehouse	$T_{L/U}$	: load/unload time to or from the storage rack
$m_{vehicle}$	: the mass of the vehicle	m_{pallet}	: the mass of the pallet
D	: the distance between two aisles		
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. Note that these values are obtained from the France company.

D	: 4.25 m.	H	: 2.35 m.
W	: 3.02 m.	$T_{L/U}$	: 0.233 min.
T_T	: 0.167 min	$m_{vehicle}$	: 150 kg
m_{lift}	: 350 kg	m_{pallet}	: 100 kg
λ_s	: 225 pallets/hour	λ_r	: 225 pallets/hour

2.1 Velocity versus Time Graphs for Travel Time Calculations

In the simulation model, the energy (electricity) consumption calculations are completed for AVs and lifts, separately by considering the conditions that they are accelerating, decelerating or traveling at the maximum velocity. Since the amount of electricity consumptions depend on the acceleration, deceleration and the steady state (at the maximum speed) traveling conditions of the AVs and lifts, we need to define velocity versus time relation graphs. For that we define two cases where AV/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 an AV or a lift can reach
V_{last} : the last velocity that an AV or lift reaches (due to short distance $V_{\text{last}} < V_{\max}$)
a_{V} : accelaration ~~value~~ of AV
d_{V} : deceleration ~~value~~ of AV
a_{L} : accelaration ~~value~~ of lift
d_{L} : deceleration ~~value~~ of lift
G : force of gravity ($G = m \cdot g$ - $kg \cdot \text{m} / \text{sec}^2$ - N)
g : standard gravity (≈ 10 m / sec^2)
c_r : resistant 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/AVs. By these graphs how long an AV or lift accelerates/decelerates and travels with constant velocity can be calculated. For instance, in Case I, lift/AV cannot reach to 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 the distance travelled (D) by lifts/AVs. For instance, in Figure 3, D is calculated by (1):

$$D = V_{\text{last}} \cdot t_1 \tag{1}$$

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

$$V_{\text{last}} = \text{a} \cdot t_1 \tag{2}$$

$$t_1 = \sqrt{D/a} \tag{3}$$

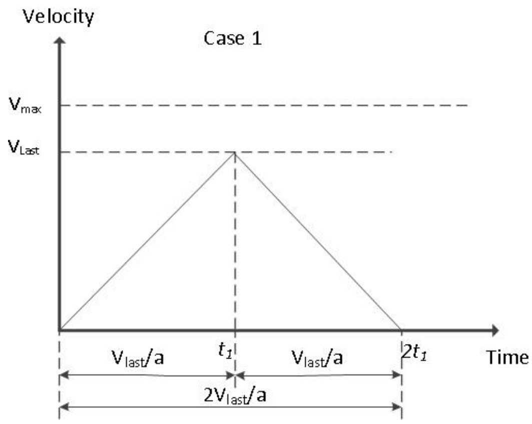

Figure 3: Case I

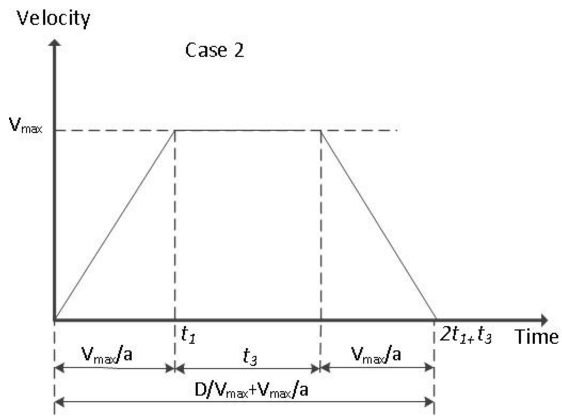

Figure 4: Case II

In Figure 4, lift/AV is able to reach to its maximum velocity due to the 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):

$$V_{\max} = \mathrm{a} \cdot t_1 \tag{4}$$

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

$$2 \cdot t_1 + t_3 = \frac{D}{V_{max}} + \frac{V_{max}}{a} \tag{5}$$

2.2 Energy Consumption Calculations for AVs

Based on Case I and II, an AV 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):

$$F_T = \mathrm{G} \cdot c_{\mathrm{r}} + \frac{G}{g} \cdot a_s \cdot f_r \,(\text{Newton} - \text{kg m / sec}^2) \tag{6}$$

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

$$P_T = \frac{F_T \cdot V_{last}}{1000 \cdot \eta} \tag{7}$$

Where η is the efficiency of the motor engine and considered to be 0.9. In the deceleration case, the braking force is calculated by (8):

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

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

$$P_B = \frac{F_B \cdot V_{last}}{1000 \cdot \eta} \tag{9}$$

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

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

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

$$P_C = \frac{F_C \cdot V_{max}}{1000 \cdot \eta} \text{ (kW)} \tag{11}$$

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:

$$W_A = P_T . t_1 \text{ (kWh)} \tag{12}$$

$$W_D = P_B . t_1 \text{ (kWh)} \tag{13}$$

$$W_C = P_C . t_2 \text{ (kWh)} \tag{14}$$

2.3 Energy Consumption Calculations for Lifts

In the lift case, although travel time calculations do not change, namely are same as in the AV 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):

$$F_L = G + \frac{G}{g} \cdot a_L \cdot f_r \text{ (Newton – kg m / sec}^2\text{)} \tag{15}$$

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

$$P_L = \frac{F_L \cdot V_{last}}{1000 \cdot \eta} \tag{16}$$

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

$$F_B = G + \frac{G}{g} \cdot d_L \cdot f_r \text{ (Newton – kg m / sec}^2\text{)} \tag{17}$$

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

$$P_B = \frac{F_B \cdot V_{last}}{1000 \cdot \eta} \tag{18}$$

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).

$$P_C = \frac{F_C \cdot V_{max}}{1000 \cdot \eta} \text{ (kW)} \quad (20)$$

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:

$$W_A = P_L . t_1 \text{ (kWh)} \quad (21)$$

$$W_D = P_B . t_1 \text{ (kWh)} \quad (22)$$

$$W_C = P_C . t_2 \text{ (kWh)} \quad (23)$$

2.3 Scenarios Based on Design Inputs for Conducted Experiments

To obtain the pareto solutions, we conducted experiments based on input scenarios, number aisles – A -, number of bays – B -, number of tiers – T -, such that they provide the total number of storage capacity as 55,000 pallets ($A \times B \times T \times 2$ sides $\times$ 3 pallets/bay). Table 1 summarizes the scenarios that are run in the simulation models. It should be noted that after running the Table 1 experiments, we obtained four performance measures from the system. These are: average energy consumption per transaction (E_C), average cycle time per transaction (C_T), average utlization for lifts (U_L) and average utilization for vehicles (U_V).

Table 1: Scenarios cunducted in simulation experiments

L	**N_V**	**T**	**Lift speed profile**		**AV speed profile**		**A**
			a_V (m/sec^2)	**V_{max} (m/sec)**	**a_L (m/sec^2)**	**V_{max} (m/sec)**	
6	2	5	0.5	1	0.5	2	Low (40, 42 54)
7	3	7	-	-	-	-	Medium (48, 56, 60)
8	4	9	1.5	2	1	4	High (64, 63, 66)

Note that in Table 1 there are 1,296 possible combinations to experiment. Hence, we completed 1,290 experiments in simulation and observed their results. To be able to provide 55,000 storage capacity, based on the chosen A value, B is rounded up to the closest integer after it is calculated by: $B = 55{,}000 / (A \times T \times 2$ sides $\times$ 3 pallets/bay). Hence, in the dsign B does not become a design parameter, when A is a design parameter in the experiments. The value of A is defined by considering a divisible and practical value based on the L value (i.e., number of zones – Z).

Figure 5 shows Pareto solutions based on the conducted experiments. Since we consider practical performance values for average utilization values of lifts/vehicles (i.e., high utilization values for lifts/AVs), we filtered these 1,296 designs so that we there is no design providing low utlization values for lifts and AVs, namely lower than 70%. After filtering, the number of designs considered in the Pareto solutions is decreased to 244 designs. These 244 designs and their performance values - E_C and C_T - are illustrated in Figure 5.

3 Results and Interpretations

In Figure 5, average energy consumption per transaction (E_C) versus average cycle time per transaction (C_T) graph based on 244 designs is shown. The red line in Figure 5 shows pareto frontier which are the potential optimal solutions for this multi-objective problem.

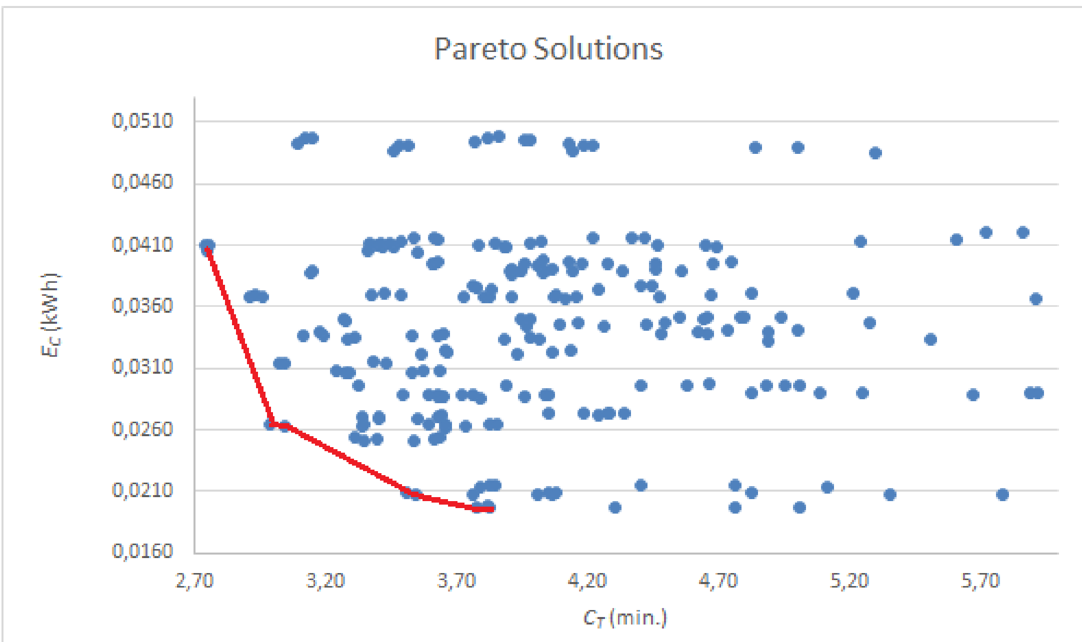

Figure 5: Pareto solutions diagram

By Figure 5, through the Pareto frontier, the point having the least C_T value is found to be 2.75 min. with 0.0406 kWh/transaction E_C value. This design is the design with $L = 6$, $T = 7$, $A = 54$, $B = 21$, $N_V = 3$, $a_L = 0.5$ m/sec^2, $V_L = 1$ m/sec, $V_{AV} = 4$ m/sec, $a_V = 1.5$ m/sec^2. The point having the least Ec value is found to be 0.0197 kWh where its C_T value is 3.78 min. This design has $L = 6$, $T = 5$, $A = 54$, $B = 30$, $N_V = 4$, $a_L = 1$ m/sec^2, $V_L = 2$ m/sec, $V_{AV} = 2$ m/sec, $a_V = 0.5$ m/sec^2. Note that, these designs are the edge points on Pareto frontier line.

As a heuristic solution, one may consider euclidean distances of points from those edge points on the Pareto frontier line. To make a common numerical value the distances are considered to be percentage differences from those edge values. As a result of these distances, the closest design to those edge points are obtained to be the design having $L = 6$, $T = 5$, $A =$

66, B = 24, N_V = 4, a_L = 1 m/sec^2, V_L = 2 m/sec, V_{AV} = 2 m/sec, a_V = 0.5 m/sec^2. In this design, C_T= 3.51 min. and E_C = 0.0208 kWh. One may assume this design to be the optimum solution providing the least distanced design to the edge values on the Pareto frontier line.

Conclusion

In this study, we provide a multi-objective optimization approach on design of an AVS/RS. In the best warehouse design, we consider minimizing of average energy consumption per transaction and average cycle time per transaction, simultaneously. We complete 1,296 simulation experiments to obtain the Pareto solutions showing trade-offs on responses. In the design concept, we vary the values of velocity profiles and acceleration/deceleration of lifts/AVs, number of aisles, number of bays, number of tiers and number of lifts/AVs in the system. Since it would not be practical, we ignored the designs resulting with low utilization values of lifts/AVs (i.e., 70%). As a result, we obtain the Pareto solutions graph for 244 designs. As a heuristic based solution, we find the optimum design, by finding the closest distanced point to the edge points on the Pareto frontier line which is the design with L = 6, T = 5, A = 66, B = 24, N_V = 4, a_L = 1 m/sec^2, V_L = 2 m/sec, V_{AV} = 2 m/sec, a_V = 0.5 m/sec^2 and, C_T= 3.51 min. and E_C = 0.0208 kWh/transaction.

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