

# Additional reference material for the paper titled “Optimal Stack Layout in a Sea Container Terminal with Automated Lifting Vehicles”

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## 1 Vehicle Travel Time Expressions for Overlapping Operations (Roy and De Koster, 2015)

For overlapping operations, the ALVs may need to process an unload transaction after processing a load transaction or vice versa. In such situations, the ALVs have to move from one QC location to another QC location or from one SC location to another SC location. In this section, we adopt the analytical model from Roy and De Koster, 2015 to develop travel time expressions for such movements.

### 1.1 Movement of ALVs from one QC Location to Another QC Location

We consider the movement of an ALV from  $QC_i$  (buffer lane  $Nb_i$ ) to  $QC_j$  (buffer lane  $Nb_j$ ). The terms  $i$  and  $j$  correspond to the QC numbers. Note that the QCs are numbered from left to right and buffer lanes are numbered from top to bottom. The expressions are described for  $i, j \in \{1, 2, \dots, N_{qc}\}$  and  $Nb_i, Nb_j \in \{1, 2, \dots, N_{bq}\}$ . We do not consider the case when  $i = j$ .

**Case 1:** When  $i < j$

$$T_1^{qq} = \sum_{i=1}^{N_{qc}} \sum_{j=i+1}^{N_{qc}} \sum_{Nb_i=1}^{N_{bq}} \sum_{Nb_j=1}^{N_{bq}} \left( (j-i)(D_{ex} + D_{in}) + |Nb_i - Nb_j|W_{bq} \right) \frac{1}{h_v} \quad (1)$$

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Table 1: Notations used in the travel time expressions

Scenarios	Cases	Subcases	Terminology for time expressions	Number of possible routes (refer to Figure ??)
From QC to QC	Case 1	-	$T_1^{qq}$	240
	Case 2	-	$T_2^{qq}$	240
From SC to SC	Case 1	<i>Subcases 1</i>	$T_{1_1}^{ss}$	448
		<i>Subcases 2</i>	$T_{1_2}^{ss}$	448
	Case 2	-	$T_2^{ss}$	9216
	Case 3	-	$T_3^{ss}$	6144

For instance, we discuss the movement of an ALV from the second buffer lane ( $Nb_i = 2$ ) of  $QC_3$  ( $i = 3$ ) to the fourth buffer lane ( $Nb_j = 4$ ) of  $QC_6$  ( $j = 6$ ). Since the layout allows left to right movement of the ALV in quayside, the ALV directly reaches  $QC_6$  after travelling  $(3(D_{ex} + D_{in}) + 2W_{bq})$  units along the X-axis.

**Case 2:** When  $i > j$

$$\begin{aligned}
 T_2^{qq} = & \sum_{i=1}^{N_{qc}} \sum_{j=1}^{i-1} \sum_{Nb_i=1}^{N_{bq}} \sum_{Nb_j=1}^{N_{bq}} \left( \frac{D_{ex}}{2} + (Nb_i - 1)W_{bq} + W_l + (N_{lbs}[i] - 1)S + X_e + D_{dl} \right. \\
 & + (N_{smx} - N_{srmx}[i] - 1)(W_{sb} + 2D_{dl} + D_d) + L'_l + W_l + L_l + \frac{D_{ex}}{2} + (j - 1) \\
 & \left. (D_{ex} + D_{in}) + (Nb_j - 1)W_{bq} \right) \frac{1}{h_v} \quad (2)
 \end{aligned}$$

For instance, we consider the movement of an ALV from second buffer lane ( $Nb_i = 2$ ) of  $QC_5$  to third buffer lane ( $Nb_j = 3$ ) of  $QC_2$ . For the given layout shown in Figure ??,  $N_{smx}$  is 4 and  $N_{srmx}[5]$ , the number of stack module to the right of fifth short-cut is 1. Therefore, the value of term  $(N_{smx} - N_{srmx}[5] - 1)$  is 2. Since the layout has only uni-directional paths, the ALV travels using the inner loop to reach the destination. The ALV moves  $(\frac{D_{ex}}{2} + W_{bq}(Nb_j - 1) + W_l)$  units and reaches the stackside inner loop. Now, the ALV travels  $(N_{lbs}[5]S + X_e + D_{dl} + 2(W_{sb} + 2D_{dl} + D_d) + L'_l)$  units to reach the left end of the loop. It turns left and moves  $(W_l - W_{bl} + L_l)$  to reach the quayside. Again, the ALV travels  $(\frac{D_{ex}}{2} + (D_{ex} + D_{in}) + W_{bl} + W_{bq})$  units to reach the destination.

The average time spent by an ALV to move from one QC to another is given by Equation 3.

$$T^{qq} = \frac{T_1^{qq} + T_2^{qq}}{N_{qc}(N_{qc} - 1)N_{bq}^2} \quad (3)$$

## 1.2 Movement of ALVs from one SC Location to Another SC Location

Similar to ALV motion in the quayside, we consider movement of an ALV from one SC location) to another in the stackside. The origin and the destination points are described as  $(X_a, Y_a, B_a)$  and  $(X_b, Y_b, B_b)$ , respectively. Here  $X_a, X_b \in \{1, 2, 3, \dots, N_{smx}\}$ ,  $Y_a, Y_b \in \{1, 2, 3, \dots, N_{smy}\}$  and  $B_a, B_b \in \{1, 2, 3, \dots, N_{bs}\}$ .

**Case 1:** When  $X_a = X_b$  and  $Y_a = Y_b$

*Subcase 1:*  $B_a < B_b$

$$T_{1_1}^{ss} = \sum_{B_a=1}^{N_{bs}} \sum_{B_b=B_a+1}^{N_{bs}} \frac{(B_b - B_a)S}{h_v} \quad (4)$$

For instance, we consider the movement of an ALV from fifth buffer lane ( $B_a = 5$ ) to eighth buffer lane ( $B_b = 8$ ) in same stack crane  $SC_{10}$ . The ALV only needs to travel  $3S$  units to reach the destination as the layout permits clockwise movement.

*Subcase 2:*  $B_a > B_b$

$$T_{1_2}^{ss} = \sum_{Y_a=1|Y_b=Y_a}^{N_{smy}} \sum_{B_a=1}^{N_{bs}} \sum_{B_b=1}^{B_a-1} \left( (N_{bs} - B_a)S + X_e + D_{dl} + 2(Y_a - 1)(2W_{sr} + W_s + 2D_t) + (W_{sb} + 2D_{dl}) + X_e + D_{dl} + (B_b - 1)S \right) \frac{1}{h_v} \quad (5)$$

For instance, we consider the movement of an ALV from seventh buffer lane ( $B_a = 7$ ) to fifth buffer lane ( $B_b = 5$ ) in the same stack block ( $SC_{10}$ ). Since layout has only unidirectional path, the ALV has to travel in the loop. The ALV moves  $(S + X_e + D_{dl})$  units to reach uni-directional driving lane. Now, the ALV travels  $2(2W_{sr} + W_s + 2D_t)$  units to reach outer loop. Now, ALV moves  $(W_{sb} + 2D_{dl})$  units to the left of uni-directional driving lane to reach another driving lane that leads to  $SC_{10}$ . Now, the ALV again travels  $2(W_{sr} + W_s + 2D_t)$  to reach  $SC_{10}$ . Now, it moves  $(X_e + D_{dl} + 4S)$  to reach the destination buffer lane.

**Case 2:** When  $X_a \geq X_b$

$$T_2^{ss} = \sum_{X_a=1}^{N_{smx}} \sum_{X_b=1}^{X_a-1} \sum_{Y_a=1}^{N_{smy}} \sum_{Y_b=1}^{N_{smy}} \sum_{B_a=1}^{N_{bs}} \sum_{B_b=1}^{N_{bs}} \left( (N_{bs} - B_a)S + X_e + D_{dl} + (Y_a - 1)(2W_{sr} + W_s + 2D_t) + (X_a - X_b + 1)(W_{sb} + 2D_{dl}) + (X_a - X_b)D_d + (Y_b - 1)(2W_{sr} + W_s + 2D_t) + (D_{dl} + X_e) + (B_b - 1)S \right) \frac{1}{h_v} \quad (6)$$

For instance, we consider that an ALV moves from fourth buffer lane ( $B_a = 4$ ) of  $SC_{16}$  to sixth buffer lane ( $B_b = 6$ ) of  $SC_4$ . We are considering  $SC_{16}$  that corresponds to  $X_a = 3$ ,  $Y_a = 3$  and  $SC_4$  that corresponds to  $X_b = 1$  and  $Y_b = 3$  ( $X_a \geq X_b$ ). Now, the ALV travels  $(4S + X_e + D_{dl})$  units to reach the uni-directional driving lane. Similar to Subcase 2 of Case 1, the ALV travels  $2(2W_{sr} + W_s + 2D_t)$  units and reaches the main guide path. Now, the ALV travels  $3(W_{sb} + 2D_{dl} + D_d)$  units to reach the unidirectional driving lane to the left of  $SC_4$ . Further, the ALV moves  $2(W_{sr} + W_s + 2D_t)$  to reach the destination block. Now, the ALV travels  $(D_{dl} + X_e + 5S)$  to reach the destination buffer lane.

**Case 3:** When  $X_a < X_b$

$$T_3^{ss} = \sum_{X_a=1}^{N_{smx}} \sum_{X_b=X_a+1}^{N_{smx}} \sum_{Y_a=1}^{N_{smy}} \sum_{Y_b=1}^{N_{smy}} \sum_{B_a=1}^{N_{bs}} \sum_{B_b=1}^{N_{bs}} \left( (N_{bs} - B_a)S + X_e + D_{dl} + |Y_a - Y_b|(2W_{sr} + W_s + 2D_t) + (B_b - 1)S + X_e + D_{dl} + (X_b - X_a - 1)(W_{sb} + 2D_{dl}) + (X_b - X_a)D_d \right) \frac{1}{h_v} \quad (7)$$

For instance, we consider the movement of an ALV from the sixth buffer lane ( $B_a = 6$ ) of  $SC_4$  to the fourth buffer lane ( $B_b = 4$ ) of  $SC_{16}$ . The value of  $X_a$ ,  $Y_a$ ,  $X_b$  and  $Y_b$  can be defined similar to Case 2 from the layout shown in Figure ???. The ALV moves  $(2S + X_e + D_{dl})$  to reach the uni-directional driving line. Depending on the position of destination stack block, the ALV takes either upward or downward motion path. Since both stack blocks have same position along the Y-direction ( $Y_a = Y_b = 3$ ), the ALV doesn't move in the Y-direction. Now, the ALV takes the transfer lane that leads to  $SC_{16}$  and travels  $(W_{sb} + 2D_{dl} + 2D_d)$  units to reach the  $SC_{16}$ . Further, ALV travels  $3S + X_e + D_{dl}$  to reach the destination buffer lane.

The average time spent by an ALV to move from one SC to another SC is given by Equation 8

$$T^{ss} = \frac{T_{1_1}^{ss} + T_{1_2}^{ss} + T_2^{ss} + T_3^{ss}}{N_{smx}N_{smy}N_{bs}(N_{smx}N_{smy}N_{bs} - 1)} \quad (8)$$

## 2 AutoMod<sup>TM</sup> Simulation Model Details

**Quayside Process:** Containers arrive at quay and are being served based on a First-in First-out basis. Each QC is modeled in Arena using the “Process” module available in “Basic Process” template. There are six identical “Process” modules which represent the six quay cranes. Each “Process” module has one resource that seizes the container, delays the movement with a mean of 120 seconds and CV of 0.3 to unload the container from the vessel to the quayside buffer lane, and then releases the container to a buffer lane.

**Transaction Matching:** Containers at the quayside buffer lanes wait in the queue for an ALV to be served. Similarly, if there is no container available at the quayside buffer lanes, all idle ALVs wait in a virtual common queue for the containers to arrive. This process in ARENA is presented with a “Match” module in the “Advance Process” panel.

**Transportation of the ALV from quayside to stackside:** An ALV picks the container and is assigned to a new storage location by the “Assign” module using the “Basic Process” panel. This assignment to a stack block is uniformly distributed. The transportation time of an ALV is presented with a “Process” module. In the “Process” module, “Action” is set as Delay and the “Delay type” is set as an Expression. This “Process” block provides delay to the ALV depending on value obtained from the expression. This delay time depends on the source and destination location. Once the ALV transfers the container to its destination stack block, the vehicle becomes idle and joins a common queue of idle vehicles.

**Arrival of containers at the stackside:** Containers that were unloaded at the stack block wait for their respective stack cranes to become idle, upon which they are stowed away in the stacks. The waiting containers queue before their respective stack cranes. Similar to the quayside, the stack cranes are also modeled with the “Process” module. All stack cranes are positioned in a layout as indicated in Figure 1. There are 24 identical “Process” modules which represent 24 SCs. The service time of an SC depends on the container’s position in buffer and its storage location in stack block. Note that container’s position in the stack block and in the buffer lane is uniformly distributed. The SC picks the container from the stack buffer lane and drops it into its storage location in a delay expressed by  $\max\left(\frac{|x_{n_i}-x_{n_j}|}{v_{sx}}, \frac{|y_{m_i}-y_{m_j}|}{v_{sy}}\right)$ . Then the vertical motion by the spreader is executed as a part of the drop-off time.

### **3 Model Validation Results**

In Tables 2-5, we compare the results obtained from the analytical model with the results obtained from the discrete-event simulation model.

Table 2: Comparison of analytical and simulation results for a layout with 24 stack blocks and 20 vehicles

Parameters $\lambda(\text{containers/hr})$	Analytical Results												Simulation Results												Error																																										
	Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside																																		
	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$																															
126	4.90	70%	260.0	0.08	72%	412.6	0.12	11%	76.4	749.0	4.92	70%	257.7	0.01	73%	412.5	0.12	10%	76.9	747.0	0.41%	0.00%	0.91%	0.96%	0.02%	0.41%	0.00%	0.91%	0.96%	0.02%	7.03%	6.23%	0.64%	0.26%																																	
129	5.38	72%	270.5	0.10	73%	413.1	0.13	11%	76.4	760.0	5.20	71%	268.6	0.02	74%	412.5	0.12	11%	76.8	757.8	3.49%	0.70%	0.72%	0.34%	0.14%	7.26%	0.47%	0.40%	0.52%	7.24%	0.71%	0.53%	0.29%																																		
131	5.92	73%	282.2	0.12	75%	413.6	0.13	11%	76.5	772.3	6.06	73%	286.3	0.03	76%	413.1	0.15	11%	76.9	776.3	2.29%	0.00%	1.41%	0.81%	0.11%	7.21%	0.71%	0.53%	0.29%	3.65%	0.68%	2.85%	0.22%																																		
134	6.53	75%	295.3	0.14	76%	414.2	0.14	11%	76.6	786.1	6.30	74%	287.1	0.04	76%	413.3	0.15	11%	77.1	777.5	1.37%	0.66%	0.41%	0.68%	0.37%	7.27%	3.91%	0.55%	0.30%	7.95%	0.65%	1.91%	0.31%																																		
137	7.22	76%	310.0	0.17	78%	414.9	0.15	12%	76.7	801.6	7.32	76%	308.7	0.05	79%	413.4	0.16	11%	77.1	799.2	7.95%	0.66%	0.41%	0.62%	0.31%	6.41%	3.33%	0.67%	0.68%	8.01	78%	326.7	0.21	80%	415.6	0.15	12%	76.8	819.1	8.70	77%	333.0	0.07	80%	414.2	0.16	12%	77.3	824.7	7.39	77%	334.8	0.09	82%	414.2	0.18	12%	77.4	836.5	9.04%	0.00%	0.26%	0.56%	9.07%	0.92%	0.73%	0.31%
142	8.92	79%	345.7	0.25	81%	416.5	0.16	12%	76.9	839.1	9.00	79%	344.8	0.09	82%	414.2	0.18	12%	77.6	836.5	6.51%	0.68%	2.91%	0.03%	0.65%	6.39%	0.14%	0.79%	1.47%	9.97	81%	367.7	0.29	83%	417.6	0.17	12%	77.0	889.1	10.80	82%	397.7	0.17	85%	416.4	0.18	12%	77.6	891.7	3.77%	0.00%	1.10%	0.57%	5.49%	3.36%	0.75%	0.29%										
148	11.21	82%	393.3	0.34	84%	418.7	0.17	12%	77.0	889.1	10.80	82%	397.7	0.17	85%	416.4	0.18	12%	77.6	891.7	0.61%	0.00%	0.19%	0.75%	0.46%	5.45%	0.22%	0.70%	0.60%	12.68	84%	423.6	0.41	86%	420.1	0.18	13%	77.1	920.8	12.60	84%	424.4	0.26	86%	418.2	0.19	13%	77.7	920.3	0.61%	0.00%	0.19%	0.75%	0.46%	5.45%	0.22%	0.70%	0.60%									
150	12.68	84%	423.6	0.41	86%	420.1	0.18	13%	77.1	920.8	12.60	84%	424.4	0.26	86%	418.2	0.19	13%	77.7	920.3	0.35%	0.00%	3.48%	0.92%	0.39%	5.33%	0.00%	0.58%	1.58%	14.45	85%	460.0	0.48	87%	421.6	0.19	13%	77.2	958.9	14.40	85%	476.6	0.32	88%	420.0	0.20	13%	77.7	974.3	0.35%	0.00%	3.48%	0.92%	0.39%	5.33%	0.00%	0.58%	1.58%									

Table 3: Comparison of analytical and simulation results for a layout with 24 stack blocks and 18 vehicles

Parameters $\lambda(\text{containers/hr})$	Analytical Results												Simulation Results												Error																																	
	Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside																									
	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[CT_q]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[CT_v]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[CT_s]$																						
108	2.70	60%	210.0	0.07	68%	412.6	0.09	9%	75.8	698.4	2.64	60%	209.5	0.03	69%	413.9	0.10	9%	76.2	699.1	2.22%	0.00%	0.24%	0.87%	0.33%	6.56%	0.49%	0.51%	0.10%	3.03	62%	217.9	0.09	71%	413.3	0.10	9%	76.3	705.8	3.12%	0.00%	0.87%	0.85%	0.06%	6.84%	0.10%	0.50%	0.18%										
112	3.41	64%	226.7	0.13	73%	414.2	0.10	10%	76.0	716.9	2.94	62%	216.0	0.03	71%	413.5	0.10	10%	76.4	717.8	3.99%	0.00%	0.18%	1.17%	0.01%	6.83%	0.90%	0.48%	0.11%	3.84	66%	236.5	0.17	75%	415.4	0.11	10%	76.1	728.0	3.78	66%	237.4	0.08	75%	414.8	0.12	10%	76.6	728.8	1.65%	0.00%	0.38%	0.94%	0.14%	8.04%	0.84%	0.56%	0.10%
119	4.34	68%	247.5	0.22	78%	416.9	0.12	10%	76.3	740.6	4.47	68%	251.9	0.11	78%	415.5	0.12	10%	76.7	742.1	3.11%	0.00%	1.76%	0.92%	0.32%	6.97%	1.16%	0.55%	0.10%	4.90	70%	260.0	0.29	80%	418.7	0.12	11%	76.4	755.1	4.80	70%	258.9	0.17	80%	417.0	0.14	11%	76.8	762.8	2.04%	0.71%	0.41%	0.27%	0.41%	9.54%	0.22%	0.61%	0.31%
126	5.55	72%	274.3	0.39	82%	421.1	0.13	11%	76.5	771.9	5.55	72%	273.6	0.29	83%	420.0	0.14	11%	76.9	770.5	0.08%	0.00%	0.25%	0.65%	0.26%	3.19%	0.24%	0.56%	0.18%	6.32	74%	290.8	0.51	84%	424.1	0.14	11%	76.6	782.2	1.24%	0.68%	2.54%	0.17%	0.55%	6.72%	0.27%	0.61%	1.17%										
133	7.22	76%	310.0	0.68	87%	428.1	0.15	12%	76.7	814.8	6.90	75%	307.4	0.58	87%	427.4	0.15	11%	77.2	812.0	4.43%	0.79%	0.83%	0.03%	0.16%	3.53%	2.03%	0.58%	0.34%	8.30	78%	332.7	0.91	89%	433.6	0.16	12%	76.8	843.1	8.22	78%	332.3	0.95	89%	438.9	0.17	12%	77.3	848.4	0.92%	0.64%	0.13%	0.11%	1.23%	6.25%	2.00%	0.57%	0.63%
140	9.60	80%	360.0	1.25	91%	441.6	0.16	12%	76.8	878.5	9.00	79%	342.1	1.32	91%	445.3	0.17	12%	77.3	864.7	6.25%	1.23%	4.98%	0.20%	0.84%	5.40%	0.48%	0.58%	1.58%																													

Table 4: Comparison of analytical and simulation results for a layout with 16 stack blocks and 20 vehicles

Parameters $\lambda(\text{containers/hr})$	Analytical Results												Simulation Results												Error											
	Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside			
	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}](\text{sec})$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}](\text{sec})$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}](\text{sec})$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}](\text{sec})$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}](\text{sec})$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}](\text{sec})$
126	4.90	70%	260.0	0.06	70%	400.1	0.19	16%	78.4	738.5	4.50	69%	253.3	0.01	69%	399.4	0.19	16%	79.0	731.7	8.89%	1.45%	2.63%	1.05%	0.17%	1.25%	2.47%	0.75%	0.92%							
130	5.55	72%	274.3	0.07	72%	400.5	0.21	16%	78.6	753.4	5.52	73%	276.2	0.02	73%	400.2	0.22	17%	79.4	705.8	0.62%	0.69%	0.69%	1.08%	0.07%	2.14%	0.55%	0.96%	6.74%							
133	6.32	74%	290.8	0.10	74%	401.0	0.22	17%	78.8	770.6	6.36	74%	291.2	0.02	74%	400.3	0.22	17%	79.5	773.5	0.65%	0.60%	1.15%	0.39%	0.19%	0.80%	0.27%	0.91%	0.38%							
137	7.22	76%	310.0	0.12	76%	401.7	0.23	17%	79.0	790.6	6.90	75%	304.6	0.02	76%	400.6	0.25	17%	79.6	784.0	4.61%	1.33%	1.76%	0.27%	0.28%	5.57%	0.58%	0.83%	0.85%							
140	8.30	78%	332.7	0.16	78%	402.4	0.25	18%	79.2	814.3	8.28	78%	322.3	0.04	78%	400.9	0.26	18%	80.0	802.7	0.20%	0.65%	3.24%	0.03%	0.39%	6.66%	0.32%	1.06%	1.45%							
144	9.60	80%	360.0	0.19	80%	403.3	0.26	18%	79.4	842.6	8.90	80%	339.3	0.04	79%	400.9	0.28	18%	80.1	819.7	7.87%	0.63%	6.09%	0.36%	0.59%	5.83%	0.61%	0.95%	2.79%							
148	11.21	82%	393.3	0.24	82%	404.3	0.28	19%	79.6	877.2	11.16	82%	393.5	0.07	82%	401.0	0.29	19%	80.3	874.7	4.01%	0.61%	0.03%	0.04%	0.82%	4.36%	0.36%	0.86%	0.28%							
151	13.23	84%	435.0	0.29	84%	405.5	0.29	19%	79.8	920.2	12.72	84%	421.2	0.02	84%	401.7	0.30	19%	80.5	903.5	4.01%	0.48%	3.27%	0.09%	0.93%	4.35%	0.41%	0.89%	1.85%							
155	15.85	86%	488.6	0.36	86%	406.8	0.31	20%	80.0	975.3	15.30	86%	487.5	0.16	86%	404.1	0.34	20%	80.8	971.5	3.69%	0.60%	0.21%	0.56%	0.67%	8.72%	0.12%	1.07%	0.39%							
158	19.36	88%	560.0	0.44	88%	408.4	0.32	20%	80.2	1048.5	18.66	88%	526.6	0.12	87%	404.7	0.35	20%	81.2	1014.8	3.75%	0.57%	5.75%	0.41%	0.90%	8.18%	1.17%	1.20%	3.32%							
162	24.30	90%	660.0	0.53	90%	410.2	0.34	20%	80.4	1150.6	24.06	90%	664.0	0.35	90%	407.3	0.37	20%	81.1	1152.5	1.00%	0.00%	0.61%	0.61%	0.70%	7.52%	2.44%	0.85%	0.16%							

Table 5: Comparison of analytical and simulation results for a layout with 16 stack blocks and 18 vehicles

Parameters $\lambda(\text{containers/hr})$	Analytical Results												Simulation Results												Error											
	Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside				Quayside				Vehicle Transfer				Stackside			
	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}]$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}]$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}]$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}](\text{sec})$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}](\text{sec})$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}](\text{sec})$	$L_q$	$U_q$	$\mathbb{E}[T_q]$	$\mathbb{E}[C_{T,q}](\text{sec})$	$L_v$	$U_v$	$\mathbb{E}[T_v]$	$\mathbb{E}[C_{T,v}](\text{sec})$	$L_s$	$U_s$	$\mathbb{E}[T_s]$	$\mathbb{E}[C_{T,s}](\text{sec})$
112	3.03	62%	217.9	0.07	69%	400.6	0.15	14%	77.7	696.2	2.94	62%	214.4	0.16	68%	399.5	0.16	14%	78.3	692.2	3.22%	0.81%	1.63%	0.91%	0.27%	4.46%	0.81%	0.82%	0.57%							
115	3.41	64%	226.7	0.09	71%	401.3	0.16	15%	77.9	705.8	3.22	63%	222.3	0.03	70%	400.1	0.18	14%	78.5	700.5	6.00%	1.59%	1.92%	1.19%	0.29%	8.88%	1.17%	0.81%	0.76%							
119	3.84	66%	236.5	0.12	73%	402.1	0.17	15%	78.0	716.6	3.78	65%	233.6	0.05	73%	400.5	0.18	15%	78.8	712.9	1.68%	1.54%	1.22%	0.23%	0.40%	5.83%	0.83%	0.92%	0.53%							
122	4.34	68%	247.5	0.16	75%	403.2	0.18	15%	78.2	728.9	4.08	68%	240.9	0.07	75%	401.1	0.20	15%	79.0	721.0	6.25%	0.60%	2.73%	0.43%	0.51%	6.72%	0.52%	0.96%	1.09%							
126	4.90	70%	260.0	0.21	77%	404.5	0.19	16%	78.4	742.9	4.98	70%	261.1	0.10	78%	402.5	0.21	16%	79.3	746.0	1.61%	0.43%	1.57%	0.29%	0.48%	6.37%	0.32%	1.06%	0.41%							
130	5.55	72%	274.3	0.28	80%	406.1	0.21	16%	78.6	759.0	5.52	72%	273.8	0.17	80%	404.6	0.22	17%	79.4	756.8	0.62%	0.60%	0.35%	0.32%	0.38%	7.53%	0.67%	0.95%	0.30%							
133	6.32	74%	290.8	0.36	82%	408.1	0.22	17%	78.8	777.7	6.31	73%	291.0	0.17	82%	404.6	0.24	17%	79.5	792.8	0.10%	1.09%	0.09%	0.12%	0.87%	6.46%	0.27%	0.89%	1.91%							
137	7.22	76%	310.0	0.47	84%	410.7	0.23	17%	79.0	799.7	7.08	76%	305.5	0.29	84%	407.7	0.24	17%	79.7	792.8	1.98%	0.66%	1.49%	0.61%	0.73%	2.76%	0.58%	0.83%	0.86%							
140	8.30	78%	332.7	0.61	86%	414.0	0.25	18%	79.2	825.9	8.40	78%	345.0	0.46	87%	411.8	0.28	18%	79.8	836.7	1.23%	0.60%	3.56%	0.43%	0.52%	5.61%	0.25%	0.80%	1.29%							
144	9.60	80%	360.0	0.80	89%	418.3	0.26	18%	79.4	857.7	9.60	80%	350.0	0.64	88%	416.0	0.28	18%	80.3	855.3	0.00%	0.60%	0.00%	0.28%	0.51%	0.56%	7.19%	1.11%	0.28%	0.28%						
148	11.21	82%	393.3	1.07	91%	424.5	0.28	19%	79.6	897.4	10.60	81%	379.5	1.13	90%	428.0	0.30	18%	80.4	887.9	5.72%	0.86%	3.65%	0.61%	0.82%	6.50%	1.45%	1.00%	1.07%							



## 4 Additional Performance Results for Stack Layouts

In Tables 6-9, we show the good and poor terminal layout with 36000 and 48000 storage locations. Further, we show the top 3 stack configuration groups for 36000 and 48000 storage locations in Tables 10 and 11 respectively.

Table 6: Good Terminal Layout Design Choices when the total number of storage locations is 36000 (container arrival rate: 126 containers/hr; 15 ALVs )

$N_{smx}$	$N_{smy}$	$N_r$	$N_b$	$N_t$	$N_s$	$L_q$	$U_q$	$\mathbb{E}[T_q]$ (sec)	$L_v$	$U_v$	$\mathbb{E}[T_v]$ (sec)	$L_s$	$U_s$	$\mathbb{E}[T_s]$ (sec)	$\mathbb{E}[CT_u]$ (sec)
2	9	10	23	5	32	4.9	70%	260	0.09	70%	303.1	0.06	6%	60.9	624.0
2	8	10	26	5	28	4.9	70%	260	0.09	70%	301.6	0.08	8%	63.9	625.5
2	9	9	25	5	32	4.9	70%	260	0.10	70%	304.2	0.06	7%	61.6	625.8
2	7	10	30	5	24	4.9	70%	260	0.10	70%	304.2	0.10	10%	68.2	632.4
2	8	9	29	5	28	4.9	70%	260	0.11	71%	308.1	0.08	8%	65.8	633.9

Table 7: Poor Terminal Layout Design Choices when the total number of storage locations is 36000 (container arrival rate: 126 containers/hr; 15 ALVs )

$N_{smx}$	$N_{smy}$	$N_r$	$N_b$	$N_t$	$N_s$	$L_q$	$U_q$	$\mathbb{E}[T_q]$ (sec)	$L_v$	$U_v$	$\mathbb{E}[T_v]$ (sec)	$L_s$	$U_s$	$\mathbb{E}[T_s]$ (sec)	$\mathbb{E}[CT_u]$ (sec)
2	6	10	60	3	20	4.9	70%	260	6.1	96%	587.2	0.2	15%	89.8	937.1
2	7	6	63	4	24	4.9	70%	260	9.7	98%	694.8	0.2	13%	96.3	1051.1
4	5	10	38	3	32	4.9	70%	260	11.6	98%	750.3	0.1	7%	64.6	1074.9
2	6	7	65	4	20	4.9	70%	260	11.6	98%	751.4	0.2	16%	100.2	1111.5
2	8	4	65	5	28	4.9	70%	260	26.3	99%	1174.6	0.2	12%	103.2	1537.8

Table 8: Good Terminal Layout Design Choices when the total number of storage locations is 48000 (container arrival rate: 126 containers/hr; 15 ALVs )

$N_{smx}$	$N_{smy}$	$N_r$	$N_b$	$N_t$	$N_s$	$L_q$	$U_q$	$\mathbb{E}[T_q]$ (sec)	$L_v$	$U_v$	$\mathbb{E}[T_v]$ (sec)	$L_s$	$U_s$	$\mathbb{E}[T_s]$ (sec)	$\mathbb{E}[CT_u]$ (sec)
2	9	10	30	5	32	4.9	70%	260	0.24	77%	337.0	0.07	7%	67.5	664.4
2	8	10	35	5	28	4.9	70%	260	0.29	79%	345.2	0.10	9%	72.8	678.0
2	9	9	34	5	32	4.9	70%	260	0.32	79%	348.5	0.08	7%	70.5	679.0
2	7	10	40	5	24	4.9	70%	260	0.37	80%	354.6	0.13	11%	78.5	693.1
2	8	9	39	5	28	4.9	70%	260	0.41	81%	359.6	0.10	9%	76.1	695.7

Table 9: Poor Terminal Layout Design Choices when the total number of storage locations is 48000 (container arrival rate: 126 containers/hr; 15 ALVs )

$N_{smx}$	$N_{smy}$	$N_r$	$N_b$	$N_t$	$N_s$	$L_q$	$U_q$	$\mathbb{E}[T_q]$ (sec)	$L_v$	$U_v$	$\mathbb{E}[T_v]$ (sec)	$L_s$	$U_s$	$\mathbb{E}[T_s]$ (sec)	$\mathbb{E}[CT_u]$ (sec)
2	9	10	50	3	32	4.9	70%	260	7.5	97%	630.2	0.01	8%	77.1	967.3
4	4	10	40	5	24	4.9	70%	260	8.7	97%	666.8	0.13	11%	78.5	1005.3
4	5	10	38	4	32	4.9	70%	260	11.6	98%	750.3	0.08	7%	70.0	1080.3
2	9	5	60	5	32	4.9	70%	260	11.9	98%	761.1	0.14	10%	97.0	1118.1
2	5	9	67	5	16	4.9	70%	260	17.2	99%	914.5	0.37	22%	112.0	1286.5

Table 10: Top 3 stack configuration groups (for 36000 storage locations) based on Tukey's range test

Configuration	Subset 1	Subset 2	Subset 3
Pl_28_10_26_5	596.5		
Pl_28_9_29_5	604.4	604.4	
Pl_28_8_33_5	618.2	618.2	618.2
Pl_20_10_36_5	620.6	620.6	620.6
Pl_28_10_33_4	628.4	628.4	628.4
Pl_28_7_37_5	632.5	632.5	632.5
Pl_28_9_36_4	636.9	636.9	636.9
Pl_20_9_40_5	637.3	637.3	637.3
Pr_20_10_36_5	647.6	647.6	647.6
Pr_30_8_30_5	648.0	648.0	648.0
Pr_30_7_35_5		653.0	653.0
Pr_30_9_27_5		653.6	653.6
Pl_28_8_41_4		658.1	658.1
Pl_28_6_43_5		659.4	659.4
Pl_20_8_45_5		659.4	659.4
Pr_30_6_40_5		659.7	659.7
Pr_30_10_24_5			660.4
Pr_20_9_40_5			662.4
Pl_20_10_45_4			665.5
Pr_30_9_34_4			671.9
Pr_30_8_38_4			672.0
Pr_40_5_36_5			672.3
Pr_40_6_30_5			673.2
Pr_30_10_30_4			673.3

Table 11: Top 3 stack configuration groups (for 48000 storage locations) based on Tukey's range test

Configuration	Subset 1	Subset 2	Subset 3
Pl_28_10_35_5	644.8		
Pl_28_9_39_5	660.1	660.1	
Pl_28_8_43_5	675.2	675.2	675.2
Pl_28_10_43_4	686.7	686.7	686.7
Pl_20_10_48_5	688.8	688.8	688.8
Pr_30_9_36_5	695.8	695.8	695.8
Pr_30_10_32_5	696.3	696.3	696.3
Pr_30_8_40_5	696.8	696.8	696.8
Pl_28_7_49_5	703.6	703.6	703.6
Pl_28_9_48_4		710.0	710.0
Pr_30_7_46_5		710.1	710.1
Pr_40_6_40_5		716.3	716.3
Pl_20_9_54_5		720.1	720.1
Pr_30_10_40_4		720.8	720.8
Pr_40_7_35_5			722.5
Pr_30_9_45_4			726.9
Pr_40_5_48_5			727.0
Pr_20_10_48_5			733.8
Pr_40_8_30_5			734.0
Pr_30_8_50_4			735.1

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