

Appendix A: Service time expressions in the SOQN

The mean value of the movement time $T_{d,r}$ (under both dedicated and shared storage policies) can be calculated by the following equation.

$$\bar{T}_{d,r} = \sum_{x_d=1}^W \sum_{y_d=1}^L \sum_{x_r=1}^W \sum_{y_r=1}^L \left[\frac{|x_d - x_r| \cdot w + |y_d - y_r| \cdot l}{v_r} + g \cdot t_t \right] \cdot P(x_d)P(y_d)P(x_r)P(y_r)$$

We can obtain the mean values of both movement times T_{r,w_i} and $T_{w_i,s}$ by the same logic. The resulting first two moments of service times of the service nodes in the SOQN are presented in Table 1

Table 1 The first two moments of service times of service nodes in the SOQN

Service node	Storage policy	Mean value of service time	scv of service time
$\mu_{d,r}$	random stacks	$\frac{Ww+Ll}{3v_r} + \frac{(LW-W-L-3)t_t}{LW-1}$	$cv_{d,r}^2 = \frac{E[T_{d,r}^2] - \bar{T}_{d,r}^2}{\bar{T}_{d,r}^2}$
	zoned stacks	$\left[\frac{P_A^2 w_A}{3} + P_B^2 \left(\frac{w_B}{3} + \frac{w_A}{2} \right) + P_C^2 \left(\frac{w_C}{3} + \frac{w_B}{2} + \frac{w_A}{2} \right) + 2P_A P_B (w_A + \frac{w_B}{2}) + 2P_A P_C (w_A + w_B + \frac{w_C}{2}) + P_B P_C (w_A + w_B + \frac{w_C}{2}) \right] \frac{w}{v_r} + \frac{Ll}{3} + \frac{(LW-W-L-3)t_t}{LW-1}$	
μ_{r,w_i}	random stacks	$\frac{Ww}{2v_r} + \frac{1}{L} \sum_{j=1}^L \frac{ j-yw_i l}{v_r} + \frac{t_t}{L}$	$cv_{r,w_i}^2 = \frac{E[T_{r,w_i}^2] - \bar{T}_{r,w_i}^2}{\bar{T}_{r,w_i}^2}$
	zoned stacks	$\frac{Ww}{2v_r} + \frac{1}{L} \sum_{j=1}^L \frac{ j-yw_i l}{v_r} + \frac{t_t}{L}$	
$\mu_{w_i,s}$	random stacks	$\frac{Ww}{2v_r} + \frac{1}{L} \sum_{j=1}^L \frac{ j-yw_i l}{v_r} + \frac{t_t}{L}$	$cv_{w_i,s}^2 = \frac{E[T_{w_i,s}^2] - \bar{T}_{w_i,s}^2}{\bar{T}_{w_i,s}^2}$
	zoned, dedicated	$\frac{Ww}{2v_r} + \frac{1}{L} \sum_{j=1}^L \frac{ j-yw_i l}{v_r} + \frac{t_t}{L}$	
	zoned, shared	$\left[P_A \left(\frac{w_A}{4} + \frac{w_B}{2} + \frac{w_C}{2} \right) + P_B \left(\frac{w_B}{4} + \frac{w_C}{2} \right) + \frac{P_C w_C}{4} \right] \frac{w}{v_r} + \sum_{j=1}^L \frac{ j-yw_i l}{v_r} + \frac{t_t}{L}$	
μ_w	-	$\frac{1}{\frac{2Hh_b}{v_l} + 2t_{lu} + t_p - \frac{\lambda t_p^2}{n_w}}$	$\frac{(t_p - \frac{\lambda t_p^2}{n_w})^2}{[\frac{2Hh_b}{v_l} + 2t_{lu} + t_p - \frac{\lambda t_p^2}{n_w}]^2}$
μ_{re1}	shared	$\left[\left(\frac{w\tau^2}{9v_r} - \frac{2h_b\tau^2}{9v_l} + \frac{h_b\tau}{2v_l} \right) H^2 + \left(\frac{w\tau}{6v_r} - \frac{h_b}{2v_l} + \frac{h_b\tau}{6v_l} \right) H + \frac{h_b}{6v_l} - \frac{w}{3v_r} \right] (1 + \gamma) + \frac{t_{lu}\tau H}{2} - \frac{t_{lu}}{2}$	$cv_{re1}^2 = \frac{E[T_{re1}^2] - \bar{T}_{re1}^2}{\bar{T}_{re1}^2}$
μ_{re2}	shared	$\left[\left(\frac{w\tau^2}{9v_r} - \frac{2h_b\tau^2}{9v_l} + \frac{h_b\tau}{2v_l} \right) H^2 + \left(\frac{w\tau}{6v_r} - \frac{h_b}{2v_l} + \frac{2h_b\tau}{3v_l} \right) H + \frac{h_b}{6v_l} - \frac{w}{3v_r} \right] (1 + \gamma) + \frac{t_{lu}\tau H}{2} - \frac{t_{lu}}{2}$	$cv_{re2}^2 = \frac{E[T_{re2}^2] - \bar{T}_{re2}^2}{\bar{T}_{re2}^2}$
μ_{lu}^D	dedicated	$\sum_{i=1}^N \frac{p_i}{I_i} \sum_{h=1}^{I_i} \frac{2(H-h)h_b}{v_l} + t_{lu}$	$cv_{lu}^2 = \frac{E[T_{lu}^2] - \bar{T}_{lu}^2}{\bar{T}_{lu}^2}$
μ_{lu}^S	shared	$\left[\frac{(2-\tau)h_b H}{v_l} - \frac{h_b}{v_l} \right] (1 + \gamma) + t_{lu}$	
μ_{lu}^{SI}	shared, immediate	$\left[\frac{(2-\tau)h_b H}{v_l} - \frac{h_b}{v_l} \right] (1 + \gamma) + 3t_{lu} + \frac{3l}{v_r}$	
μ_{lu}^{SD}	shared, delayed	$\left[\frac{(2-\tau)h_b H}{v_l} - \frac{h_b}{v_l} \right] (1 + \gamma) + t_{lu}$	

Notes: The parameter γ models the honeycombing effect, which allows inflating the travel time in the storage stack.

Based on above equation, we can obtain \mathbf{R} by the following iterative method (Cai, Heragu, and Liu (2014), Tappia et al. (2017))

```

 $\mathbf{R}_0 = \mathbf{0}, \mathbf{R}_1 = -(\mathbf{A} + \mathbf{R}_0^2 \mathbf{C})\mathbf{B}^{-1}, k = 0$ 
while  $\|\mathbf{R}_{k+1} - \mathbf{R}_k\| > \varepsilon$ 
   $k++$ ;
   $\mathbf{R}_{k+1} = -(\mathbf{A} + \mathbf{R}_k^2 \mathbf{C})\mathbf{B}^{-1}$ ;
end
 $\mathbf{R} = \mathbf{R}_k$ 

```

Appendix C: Proof of optimal width to length ratio in the case of random storage stacks

The objective of optimizing the width to length ratio (in traveling time) is to minimize the expected movement time of robots on the grid in a dual command cycle, i.e., $T = \bar{T}_{d,r} + \bar{T}_{r,w} + \bar{T}_{w,s}$. In the case of random storage stacks, both storage and retrieval positions could be in any cell with the same probability. Moreover, any workstation will be equally likely assigned to the robot. So, we can write T as Eq.(C.1)

$$T = \frac{1}{v_r} \left[\frac{W \cdot w}{3} + \frac{L \cdot l}{3} + 2 \left(\frac{W \cdot w}{2} + \frac{1}{n} \sum_{i=1}^n \frac{1}{L} \sum_{j=1}^L |j - y_{w_i}| \cdot l \right) \right], \quad (\text{C.1})$$

where $n = \frac{n_w}{2}$, y_{w_i} is the y-axis coordinate of the i th workstation and $y_{w_i} = \frac{iL}{n+1}$.

After some simplification, we get

$$T = \frac{1}{v_r} \left[\frac{4Ww}{3} + \frac{(3n+2)Ll}{3n+3} \right] \geq \frac{2}{v_r} \sqrt{\frac{4Ww}{3} \cdot \frac{(3n+2)Ll}{3n+3}} = \frac{2}{v_r} \sqrt{\frac{4(3n_w+2)wl \frac{C}{H}}{3(3n+3)}}.$$

Therefore, T takes the minimum value when $\frac{4Ww}{3} = \frac{(3n+2)Ll}{3n+3}$. So, the optimal width to length ratio (in traveling time) is $r_t^* = \frac{W \cdot w}{L \cdot l} = \frac{(3n_w+4)}{(4n_w+8)}$. In a RCSRS with 4 workstations, $r_t^* = \frac{2}{3}$ and $r^* = \frac{1}{2}$.

Appendix D: SOQN for multiple-line order

After the completion of a retrieval transaction, the robot goes back to Q_R with probability p , while it continues picking up another item with probability $1-p$. For orders with N_O items, $p = \frac{1}{N_O}$ (Lamballais, Roy, and De Koster (2017)).

Appendix E: Simulation model

The simulation model contains the following processes (see Fig.2 for a flow diagram):

1. The orders arrive at the system, following a Poisson process with mean arrival rate λ per hour.
2. The system randomly assigns a robot to the order. If all robots are busy, the order waits in the order queue.
3. The assigned robot moves from its dwell point to the retrieval point according to a shortest path. In the case of random storage stacks, both the robot dwell point and the retrieval point are uniformly distributed over the stacks. In the case of zoned storage stacks, they are in each zone with a probability proportional to the percentage of products turnover in that zone.

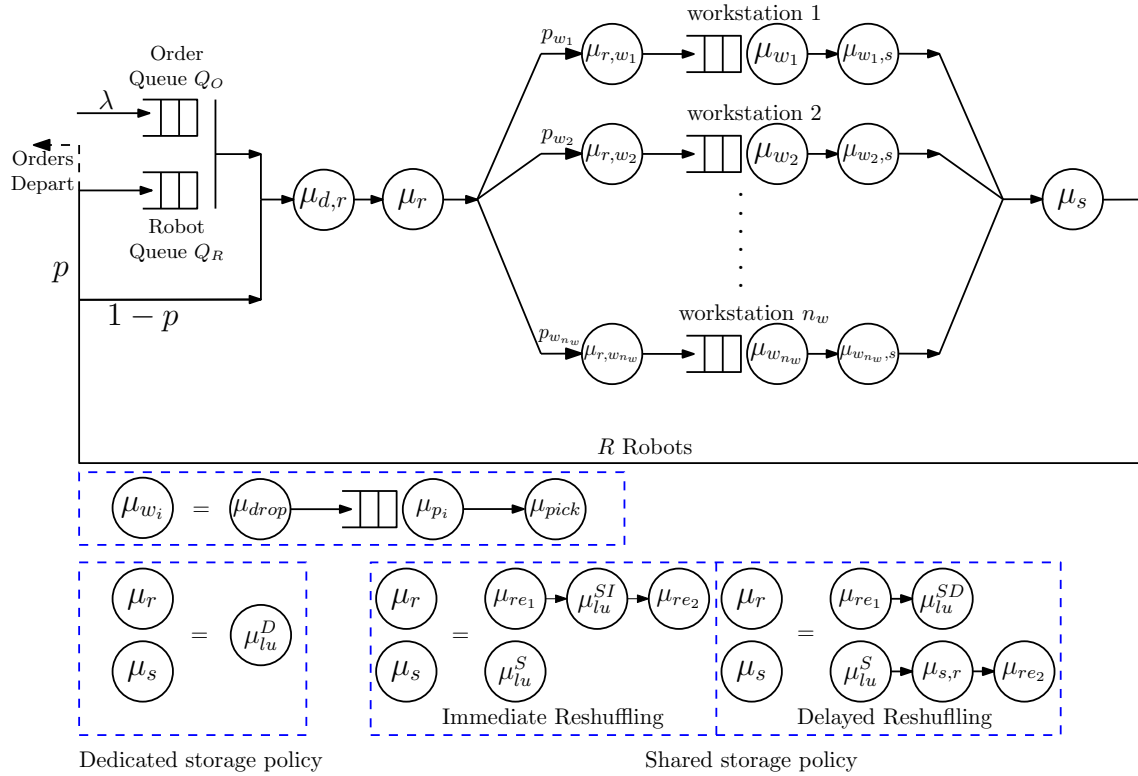


Figure 1 SOQN for multiple-line order in robotic-compact storage and retrieval system

4. The robot fetches the retrieval bin, which may include reshuffling of blocking bins. Under the dedicated storage policy, the robot directly picks up the top bin. Under the shared storage policy, the system will first identify whether the retrieval bin is on the top of the storage stack. If not, the robot will first reshuffle the blocking bins on the grid and then fetch the retrieval bin. The blocking bins will be returned following the original stack sequence. If immediate reshuffling is used, the robot will put the retrieval bin on the grid temporarily, and then return the blocking bins into the stack. If delayed reshuffling is used, returning of the blocking bins will be done afterwards.

5. The robot transports the retrieval bin to the designated workstation according to a shortest path. There, the robot drops off the retrieval bin and picks up a storage bin.

6. The robot transports the storage bin to the storage point. In the case of random stacks, the stack that will hold the storage bin will be located equally likely at any position. In the case of zoned stacks, the probability that the robot will go to one zone is determined by the turnover of products in it.

7. The robot drops off the bin on the top of the storage stack.

8. If the previous retrieval operation includes reshuffling of blocking bins and the delayed reshuffling rule is used, the robot will move back to the retrieval point and returns the blocking bins into the storage stack.

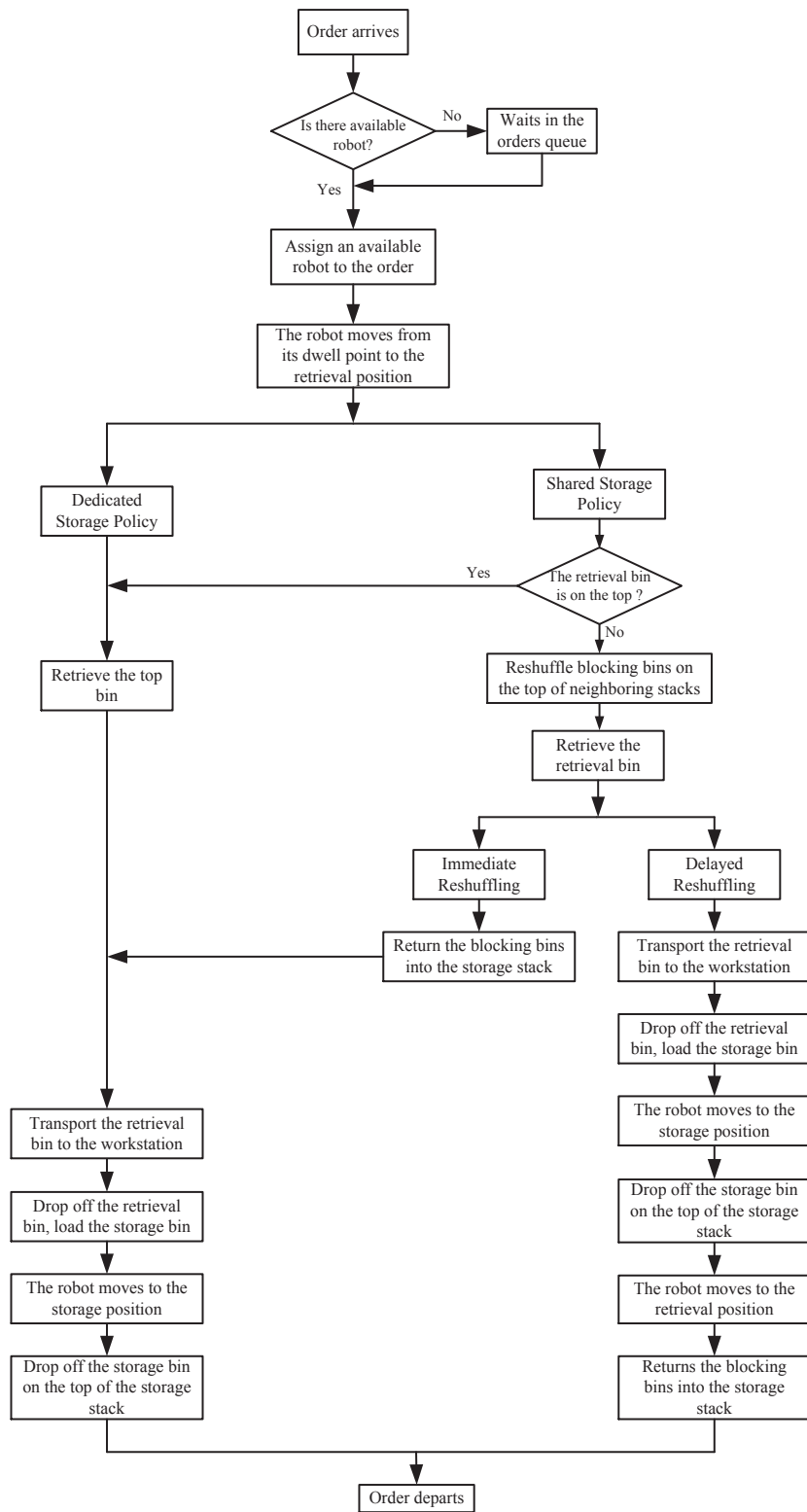


Figure 2 Flowchart of simulation models

Appendix F: Simulation validation results

Table 2 Average analytical and simulation results of system scenarios with $r = 1$ or 1.5

SP	Zoning	Resh	R	H, W, L	λ	THT_{DC}^A	THT_{DC}^S	W_w^A	W_w^S	W_R^A	W_R^S	ρ_R^A	ρ_R^S	ρ_D^A	ρ_D^S	FD^A	FD^S	
Ded	Rand	-	25	10,134,134	750	93.85	96.45	0.96	1.19	1.95	1.92	76.59	73.72	61.11	61.14	84.57	85.63	
		-	25	10,134,134	850	103.83	104.01	2.02	2.07	10.86	10.35	87.80	85.66	73.36	73.39	84.57	85.42	
		-	25	10,134,134	900	125.19	119.05	3.16	2.73	31.55	33.13	93.55	92.21	79.84	79.86	84.57	85.42	
		-	25	15,113,113	750	86.97	88.74	1.83	2.11	0.90	0.84	71.72	68.16	71.85	71.87	79.28	80.07	
		-	25	15,113,113	850	92.28	96.72	5.06	4.75	4.84	4.54	82.58	81.20	85.53	85.45	79.28	79.68	
		-	25	15,113,113	900	99.85	105.47	11.84	11.77	11.63	12.92	88.22	89.73	92.73	92.68	79.28	78.69	
		-	25	10,164,109	650	97.91	100.54	0.49	0.59	0.73	0.64	70.18	66.91	49.83	49.74	84.95	84.31	
		-	25	10,164,109	750	102.61	104.36	0.96	1.10	4.50	4.42	81.76	78.92	61.11	61.19	84.95	86.01	
		-	25	10,164,109	850	133.07	125.89	2.02	2.10	33.92	34.18	93.64	91.45	73.36	73.20	84.95	84.31	
		-	25	15,140,93	750	94.16	95.67	1.83	2.22	2.07	1.90	76.74	73.11	71.85	71.87	77.75	76.97	
		-	25	15,140,93	850	105.45	106.80	5.06	4.44	12.03	11.70	88.23	86.63	85.53	85.59	77.75	78.72	
		-	25	15,140,93	900	131.72	140.59	11.84	10.93	37.56	40.20	94.16	94.87	92.73	92.79	77.75	78.33	
	Zoned	Rand	-	25	10,134,134	750	89.55	86.35	0.96	1.00	1.20	1.26	73.62	71.34	61.11	61.08	84.57	84.15
			-	25	10,134,134	850	95.75	91.58	2.02	1.72	6.33	6.53	84.46	82.91	73.36	73.40	84.57	84.78
			-	25	10,134,134	900	105.59	99.19	3.16	2.77	15.57	14.08	90.02	89.08	79.84	79.80	84.57	83.94
			-	25	15,113,113	750	83.55	80.17	1.83	1.86	0.58	0.51	69.14	66.57	71.85	71.90	79.28	80.27
			-	25	15,113,113	850	87.49	87.24	5.06	4.65	3.12	3.00	75.68	79.39	85.53	85.35	79.28	78.69
			-	25	15,113,113	900	92.34	98.38	10.39	11.20	7.17	6.51	85.17	88.44	92.73	92.77	79.28	78.29
			-	25	10,164,109	750	96.30	91.38	0.96	1.08	2.55	2.60	78.13	75.23	61.11	61.24	84.95	84.74
			-	25	10,164,109	850	109.85	103.78	2.02	1.80	15.03	15.10	89.55	87.10	73.36	73.35	84.95	85.80
			-	25	10,164,109	900	147.19	135.70	3.16	2.71	51.79	50.86	95.39	93.42	79.84	79.71	84.95	84.31
			-	25	15,140,93	750	89.49	84.84	3.95	3.82	1.24	1.30	73.55	70.22	71.85	71.92	77.75	77.94
			-	25	15,140,93	850	96.40	93.09	5.06	4.42	6.78	6.37	84.64	83.34	85.53	85.59	77.75	78.53
			-	25	15,140,93	900	107.69	109.05	11.84	10.82	17.31	17.77	90.39	91.28	92.73	92.72	77.75	78.14
Sha		Imm	-	30	10,94,94	800	101.77	102.60	1.37	1.39	1.00	0.98	74.64	75.45	67.11	67.27	98.05	97.31
			-	30	10,94,94	900	107.49	110.27	3.16	2.73	5.52	6.06	84.97	86.91	79.84	79.09	98.05	96.82
			-	30	10,94,94	950	116.42	125.00	5.58	5.99	13.78	14.69	90.28	93.19	86.57	86.60	98.05	96.82
			-	30	15,76,76	650	122.15	121.82	0.86	0.91	0.89	0.75	72.98	72.85	59.14	59.12	99.97	99.72
			-	30	15,76,76	750	128.99	128.49	1.83	1.57	6.62	6.42	84.98	85.48	71.85	71.81	99.97	99.72
			-	30	15,76,76	800	142.26	146.13	2.88	2.61	19.26	21.03	91.11	92.87	78.57	80.58	99.97	99.97
			-	30	10,114,76	750	104.82	105.45	0.96	1.12	0.68	0.65	72.32	72.67	61.11	61.10	99.97	99.97
			-	30	10,114,76	850	109.24	111.34	2.02	1.90	4.00	4.22	82.83	84.29	73.36	73.34	99.97	99.72
			-	30	10,114,76	920	120.52	129.56	3.89	3.54	14.41	16.61	90.39	93.18	82.51	83.65	99.97	99.97
			-	30	15,95,63	650	127.16	127.06	0.86	0.99	1.22	1.46	75.65	75.66	59.14	59.08	96.50	96.26
			-	30	15,95,63	750	138.16	137.70	1.83	1.69	11.35	10.81	88.06	88.94	71.85	71.96	96.50	95.54
			-	30	15,95,63	800	167.72	170.65	2.88	2.36	40.30	41.53	94.38	95.67	78.57	78.59	96.50	95.29
	Rand	-	30	10,94,94	700	113.20	117.07	0.69	0.77	0.79	0.82	72.86	75.05	55.35	55.24	98.05	96.82	
		-	30	10,94,94	800	118.56	125.22	1.37	1.36	5.14	5.62	84.01	87.09	67.11	66.91	98.05	98.30	
		-	30	10,94,94	880	141.05	144.02	2.62	2.10	26.73	28.29	93.15	94.28	77.22	77.20	98.05	99.03	
		-	30	15,76,76	650	133.71	132.00	0.86	0.93	2.63	2.73	78.89	78.42	59.14	59.25	99.97	98.97	
		-	30	15,76,76	700	139.08	136.28	1.23	1.22	7.48	7.38	85.30	84.85	65.38	65.33	99.97	99.22	
		-	30	15,76,76	750	155.81	148.23	1.83	1.58	23.65	22.67	91.78	91.63	71.85	71.80	99.97	99.97	
		-	30	10,114,76	700	118.26	117.88	0.69	0.86	1.36	1.18	75.77	75.67	55.35	55.37	99.97	98.64	
		-	30	10,114,76	750	120.92	120.57	0.95	1.14	3.53	3.01	81.52	81.65	61.11	61.12	99.97	98.19	
		-	30	10,114,76	850	146.41	148.18	2.02	1.97	27.97	28.25	93.22	94.31	73.36	73.29	99.97	98.22	
		-	30	15,95,63	650	140.88	139.07	0.86	1.02	4.55	4.43	82.06	81.74	59.14	59.20	96.50	96.26	
		-	30	15,95,63	700	150.57	146.31	1.23	1.33	13.71	14.58	88.71	88.44	65.38	65.31	96.50	96.26	
		-	30	15,95,63	730	166.85	160.86	1.56	1.63	29.66	28.00	92.73	93.07	69.23	70.02	96.50	95.78	
Imm	-	25	10,95,95	700	94.83	90.65	0.69	0.67	1.08	1.08	72.92	70.05	55.35	55.32	99.87	98.62		
	-	25	10,95,95	800	100.81	95.05	1.37	1.16	6.07	6.48	84.22	81.64	67.11	67.14	99.87	98.37		
	-	25	10,95,95	900	151.53	146.59	3.16	3.60	55.67	52.56	95.86	93.66	79.84	79.77	99.87	99.62		
	-	25	15,78,78	600	119.27	113.94	0.60	0.57	2.82	2.84	77.64	75.06	53.14	53.18	98.77	99.26		
	-	25	15,78,78	650	124.77	116.92	0.86	0.76	7.84	7.38	84.45	81.88	59.14	59.21	98.77	98.03		
	-	25	15,78,78	700	141.83	135.25	1.23	0.99	24.38	22.44	91.35	88.78	65.38	65.44	98.77	98.52		
	-	25	10,117,78	700	98.71	93.76	0.69	0.75	1.67	1.66	75.48	72.28	55.35	55.35	98.77	98.03		
	-	25	10,117,78	800	107.81	99.25	1.37	1.23	9.78	9.26	87.14	84.08	67.11	67.09	98.77	97.54		
	-	25	10,117,78	850	126.99	116.70	2.02	2.04	28.42	25.62	93.09	90.07	73.36	73.21	98.77	99.76		
	-	25	15,96,64	600	122.89	116.67	0.60	0.62	3.75	3.72	79.42	76.64	51.67	53.21	97.80	97.31		
	-	25	15,96,64	650	130.35	123.48	0.86	0.82	10.73	9.90	86.39	83.39	59.14	59.11	97.80	97.31		
	-	25	15,96,64	700	157.91	148.11	1.23	1.06	37.78	33.05	93.43	90.59	65.38	65.32	97.80	98.78		
	Zoned	-	25	10,95,95	650	105.58	101.03	0.49	0.49	1.66	1.82	75.05	72.30	49.83	49.82	99.87	99.87	
		-	25	10,95,95	750	115.65	106.82	0.96	0.86	10.82	10.48	87.36	84.48	61.11	60.98	99.87	98.87	
		-	25	10,95,95	800	139.45	128.41	1.37	1.14	34.12	31.84	93.63	91.21	67.11	67.20	99.87	99.12	
		-	25	15,78,78	580	129.09	123.12	0.52	0.52	4.50	4.68	80.29	77.87	50.81	50.83	98.77	98.52	
		-	25	15,78,78	630	138.64	127.96	0.74	0.68	13.58	13.04	87.54	85.03	56.71	56.72	98.77	99.26	
		-	25	15,78,78	680	181.71	168.95	1.06	0.90	56.16	51.93	94.86	92.17	62.85	62.76	98.77	99.51	
		-	25	10,117,78	650	110.07	104.72	0.49	0.54	2.55	2.62	77.65	74.76	49.83	49.88	98.77	97.54	
		-	25	10,117,78	750	126.82	118.11	0.96	0.93	18.38	16.54	90.36	87.29	61.11	61.05	98.77	98.77	
		-	25	10,117,78	800	195.59	183.28	1.37	1.21	86.66	79.40	96.82	93.97	67.11	67.11	98.77	99.02	
		-	25	15,96,64	550	130.39	124.71	0.43	0.47	3.13	3.40	77.77	75.29	47.39	47.46	97.80	96.82	
		-	25	15,96,64	600	137.19	128.00	0.60	0.62	9.49	8.82	85.14	82.27	53.14	53.06	97.80	97.56	
		-	25	15,96,64	650	162.01	159.00	0.86	0.83	33.83	32.03	92.57	90.02	59.14	59.23	97.80	98.78	

Appendix G: Optimal system scenarios to minimize the total system cost

Table 3 The optimal system scenarios to minimize the total costs

		THT_{DCmax}																			
SP	s	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250			
SP	0.065	W^*	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112		
		L^*	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	
		H^*	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
		R^*	13	10	10	9	9	9	9	9	9	9	8	8	8	8	8	8	8	8	8
		P_A^*	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		P_B^*	0.7	0.6	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.8	0.7	0.6	0.6	0.5	0.4	0.4	0.4
		P_C^*	0.1	0.3	0.8	0.5	0.8	0.8	0.8	0.8	0.8	0.8	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.5	0.5
		W^*	NaN	153	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140
		L^*	NaN	153	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
		H^*	NaN	18	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
		R^*	NaN	9	14	12	11	11	11	10	10	10	10	10	10	10	10	10	10	10	10
		Ded	0.222	P_A^*	NaN	0.2	0.1	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
P_B^*	NaN			0.6	0.5	0.1	0.3	0.1	0.1	0.5	0.5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
P_C^*	NaN			0.2	0.4	0.8	0.6	0.8	0.8	0.1	0.4	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
W^*	NaN			NaN	121	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	
L^*	NaN			NaN	200	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155	
H^*	NaN			NaN	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	
R^*	NaN			NaN	16	13	12	12	11	11	11	11	11	11	11	11	11	11	10	10	
P_A^*	NaN			NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
P_B^*	NaN			NaN	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.2	
P_C^*	NaN			NaN	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.5	0.7	
SP	0.065			W^*	NaN	87	67	68	82	58	55	63	63	64	64	64	64	64	64	64	64
				L^*	NaN	124	134	113	82	116	109	90	90	80	80	80	80	80	80	80	80
		H^*	NaN	10	12	14	16	16	18	19	19	21	21	21	21	21	21	21	21		
		R^*	NaN	15	13	14	15	13	15	16	15	17	16	16	15	15	15	15	15		
		P_A^*	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1		
		P_B^*	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1		
		P_C^*	NaN	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8		
		W^*	NaN	NaN	98	85	79	104	101	98	62	93	93	93	93	93	93	93	93		
		L^*	NaN	NaN	196	170	158	104	101	98	155	93	93	93	93	93	93	93	93		
		H^*	NaN	NaN	9	12	14	16	17	18	18	20	20	20	20	20	20	20	20		
		R^*	NaN	NaN	16	14	16	16	16	16	15	18	17	16	16	16	16	16	16		
		Shared	0.222	P_A^*	NaN	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
P_B^*	NaN			NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1			
P_C^*	NaN			NaN	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8			
W^*	NaN			NaN	NaN	118	116	88	80	110	107	72	89	89	89	89	89	89			
L^*	NaN			NaN	NaN	168	145	176	160	110	107	144	111	111	111	111	111	111			
H^*	NaN			NaN	NaN	11	13	14	17	18	19	21	22	22	22	22	22				
R^*	NaN			NaN	NaN	17	16	15	18	18	18	20	20	19	18	18	18				
P_A^*	NaN			NaN	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1				
P_B^*	NaN			NaN	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1					
P_C^*	NaN			NaN	NaN	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8					
Shared	0.576			W^*	NaN	NaN	NaN	118	116	88	80	110	107	72	89	89	89	89	89		
				L^*	NaN	NaN	NaN	168	145	176	160	110	107	144	111	111	111	111			
		H^*	NaN	NaN	NaN	11	13	14	17	18	19	21	22	22	22						
		R^*	NaN	NaN	NaN	17	16	15	18	18	18	20	20	19	18						
		P_A^*	NaN	NaN	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1						
		P_B^*	NaN	NaN	NaN	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1						
		P_C^*	NaN	NaN	NaN	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8						

References

Cai X, Heragu SS, Liu Y, 2014 *Modeling and evaluating the avs/rs with tier-to-tier vehicles using a semi-open queueing network. IIE Transactions* 46(9):905–927.

Lamballais T, Roy D, De Koster R, 2017 *Estimating performance in a robotic mobile fulfillment system. European Journal of Operational Research* 256(3):976–990.

Neuts MF, 1980 *The probabilistic significance of the rate matrix in matrix-geometric invariant vectors. Journal of Applied Probability* 17(01):291–296.

Tappia E, Roy D, De Koster R, Melacini M, 2017 *Modeling, analysis, and design insights for shuttle-based compact storage systems. Transportation Science* 51(1):269–295.