Queuing-Based Operational Indicators For Explaining and Predicting Port Operations

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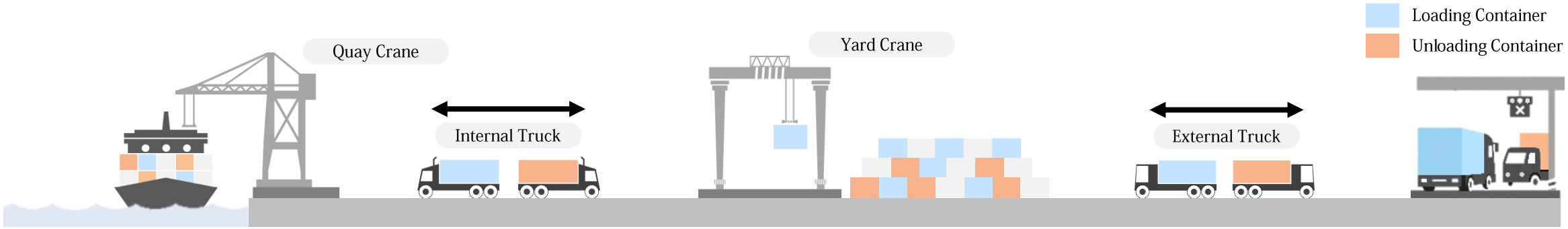
02. Literature Reviews

➢ Existing Operational Indicators in Ports



Berth	Yard	Gate
Number of Arrived Vessels	Container Dwell Time	ET Arrival Rate
Number of Berthed Vessels	ET Turnaround Time	ET Waiting Time
Berth Utilization Rate	Yard Utilization Rate	Container Throughput
QC Cycle Time	Rehandling Frequency	
	YC Cycle Time	

Fragmented, observation-based OIs lacking cross-area interdependency awareness, limiting holistic understanding of port system dynamics

02. Literature Reviews

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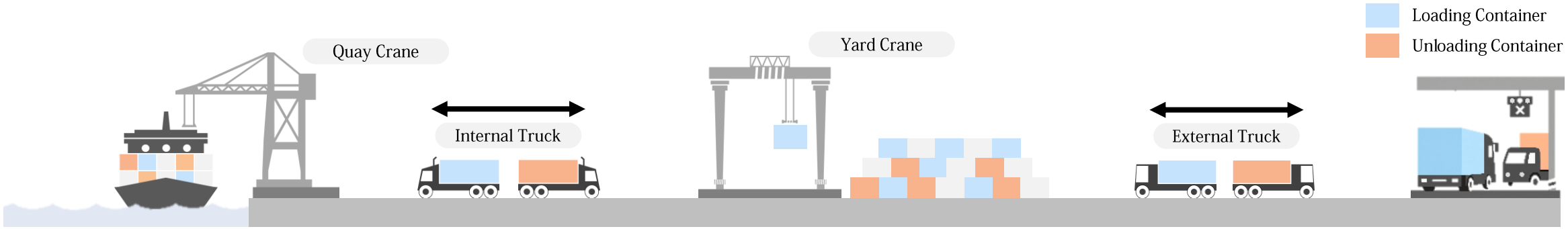
➢ Applications and Limitations of Queuing Models in Port Operations



Berth	Yard	Gate
Canonaco et al., M/M/s		
Roy and De Koster, G/G/s		
Zhang et al., M/M/1		

Limited representation of operational variability and interdependencies.

- Systemwide two-stage (berth–yard–gate) modeling
- Variability-aware G/G/1 and G/G/s formulation by Kingman's formula

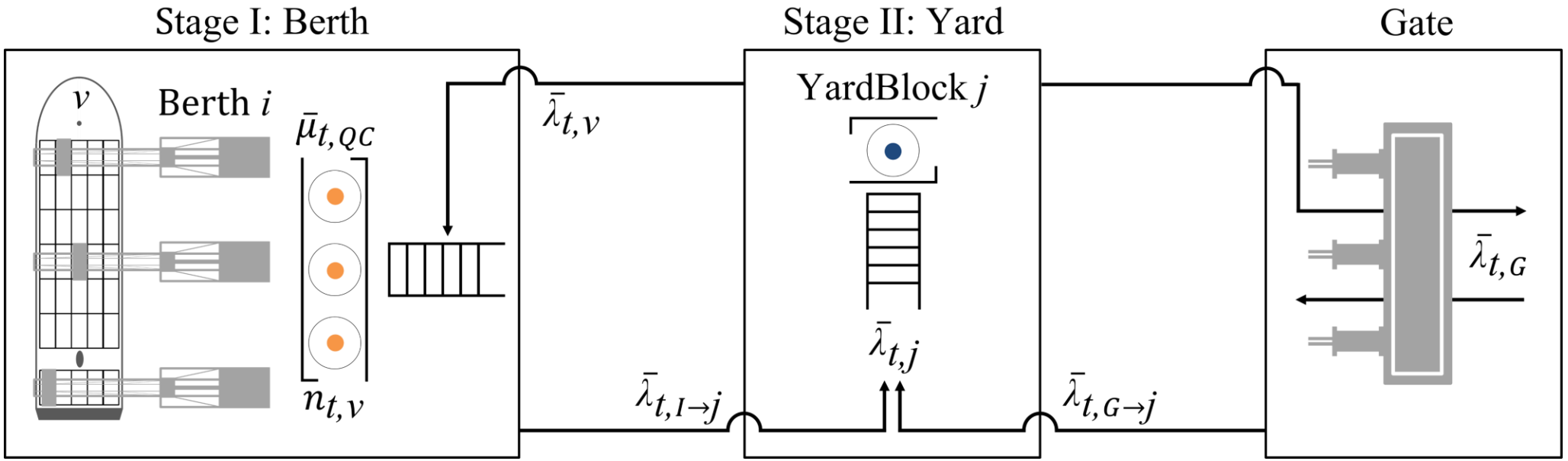
03. Methodology

➢ Two-Stage Queuing Model

QC and YC play critical roles in port operations, and their cycle times effectively **describe the overall operational state of the port.**

- Lee and Kim [11] and Zhang et al. [34]

QC cycle time, YC cycle time → Queuing-based cycle time indicator (QCI)



04. Validation and Analytical Evaluation of QCI

- Assumption I: Distribution-free variability (Kolmogorov-Smirnov test)

Table 4.1 K-S test results for distributional goodness-of-fit

Variable	Exponential	Gamma	Weibull	Beta	Lognormal
QC inter-arrival	0.07**	0.99**	0.10**	0.06**	0.57**
YC inter-arrival	0.08**	0.99**	0.06**	0.06**	0.57**
QC service	0.16**	1.00**	0.23**	0.17**	0.10**
YC service	0.17**	1.00**	0.14**	0.18**	0.08**

Note: Reported values represent the K-S D-statistics.
Significance levels: ** $p < 0.01$, * $p < 0.05$.

- Assumption II: Arrival-rate segmentation
- Assumption III: Time-invariant service rates(Cliff's delta and Levene's test)
  - Appendix 참고

04. Validation and Analytical Evaluation of QCI

➢ Evaluation of QCI Forecasting Performance

Table 4.6 Distribution Equivalence Tests Between Training and Test Sets

Variable	Cliff's delta		Levene's test
	δ	Effect size	p-value
QC inter-arrival	-9.63e-08	Negligible	0.11
YC inter-arrival	5.30e-04	Negligible	0.48
QC service	9.30e-03	Negligible	0.12
YC service	3.28e-04	Negligible	0.68

Table 4.7 Description of QCI

Name	Average	Median	Standard deviation	RMSE	RSR
QC-QCI	197.63	180.65	85.08	28.97	0.34
YC-QCI	325.07	322.94	56.40	20.88	0.37

Note: Average, Median, Standard deviation and RMSE are reported in seconds; RSR is unitless

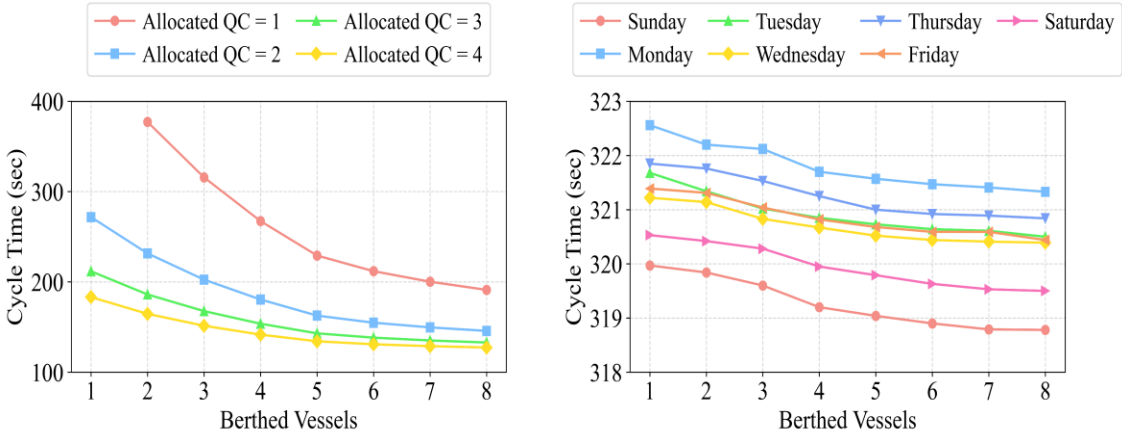


Figure 4.1 Visualization of QC-QCI (left) and YC-QCI (right) at Terminal A

➢ Comparison with Existing OIs

Table 4.11 Cross-area mutual information among observed OIs and predicted QCIs

Area	Berth_OI	Yard_OI	Gate_OI	**QC-QCI**	**YC-YCI**
Berth	0.616	0.022	0.017	**0.777**	**0.926**
Yard	0.022	0.069	0.212	**0.001**	**0.063**
Gate	0.017	0.212	1.339	**0.015**	**0.216**

05. Operational Applications of QCI

➢ Vessel Turnaround Time Prediction

Table 2.2 Overview of VTT Prediction Approaches and Input Configurations

Studies	Model	Input Configurations					
		Berth Plan	Resource Allocation	Vessel Specificatio	Cargo Informatio	Weather Informatio	Operation Informatio
Mokhtar and shal[5]	Linear Regression		✓		✓		
Štepec et al. [35]	CatBoost	✓			✓		
Balamwar et al.[36]	ANN	✓		✓	✓		
Yoon et al.[37]	CatBoost	✓		✓	✓		
Chu et al.[6]	XGBoost	✓		✓		✓	
Yan et al.[7]	Stacking	✓		✓			
Abreu et al.[38]	RandomForest Class	✓		✓	✓		

Note: Chu et al. [6] used observed weather conditions at ATB.

Table 5.5 Performance comparison across OI configurations for VTT prediction

Variables	MAPE	MAE	RMSE	R^2_{adj}
Baseline	21.64	3.06	5.59	0.57
ET Arrival Rate	21.75	3.07	5.61	0.56
Container Throughput	20.96	2.99	5.57	0.57
ET Turnaround Time (ETT)	20.20	2.92	5.56	0.57
YC Cycle Time	21.36	3.04	5.59	0.57
Number of Berthed Vessels	19.06	2.88	5.57	0.57
Berth Utilization Rate	19.07	2.87	5.55	0.57
QC Cycle Time	18.62	2.75	5.43	0.59
QCI (Proposed Method)	**17.81**	**2.65**	**4.44**	**0.73**

Note: MAPE is expressed as a percentage (%); MAE and RMSE in hours, and R^2_{adj} is unitless.

Bold values denote which setting performs better for each metric.

Table 5.3 VTT prediction performance before and after QCI integration

Studies	With QCI				Without QCI				Wilcoxon P-value
	MAPE	MAE	RMSE	R^2_{adj}	MAPE	MAE	RMSE	R^2_{adj}	
Mokhtar et al.[5]	**17.81**	**2.65**	**4.44**	**0.73**	21.64	3.06	5.59	0.57	< 0.01
Štepec et al.[35]	**19.70**	**3.21**	**5.55**	**0.57**	24.89	4.16	6.92	0.34	< 0.01
Balamwar et al.[36]	**39.52**	**5.02**	**7.69**	**0.23**	43.49	5.59	8.40	0.08	< 0.01
Yoon et al.[37]	**24.99**	**3.70**	**6.30**	**0.45**	27.89	4.21	6.89	0.34	< 0.01
Chu et al.[6]	**37.34**	**5.08**	**7.50**	**0.26**	40.06	5.41	8.32	0.11	< 0.01
Yan et al.[7]	**38.39**	**5.13**	**7.69**	**0.23**	41.00	5.33	8.14	0.12	< 0.01

Note: MAPE is expressed as a percentage (%); MAE and RMSE in hours, and R^2_{adj} is unitless.

Bold values denote which setting performs better for each metric.

Table 5.4 Feature importance in VTT prediction with QCI integration

Type	Studies	Ranking				
		1st	2nd	3rd	4th	5th
Linear Regressi	Mokhtar et al.[5]	LOD_CNT (32.25)	UNL_CNT (27.44)	Allocated_QC (25.96)	**QC-QCI** (11.81)	**YC-QCI** (2.54)
ANN	Balamwar et al.[36]	Berth_No (69.80)	Gross_Ton (11.10)	Net_Ton (7.32)	**QC-QCI** (6.17)	**YC-QCI** (3.45)
Tree Based Models	Štepec et al.[35]	LOD_CNT (38.04)	UNL_CNT (36.09)	**QC-QCI** (14.66)	**YC-QCI** (5.88)	Berth_No (3.56)
	Yoon et al.[37]	LOD_CNT (37.45)	UNL_CNT (35.08)	**QC-QCI** (4.81)	Vessel_Width (4.63)	Net_Ton (4.34)
	Chu et al.[6]	Vessel_Width (26.40)	**QC-QCI** (15.26)	Vessel_Length (15.06)	Gross_Ton (10.39)	**YC-QCI** (7.59)
Stacking Mod	Yan et al.[7]	Vessel_Width (24.79)	VTT_Delay (17.56)	Gross_Ton (15.68)	Vessel_Length (12.44)	**QC-QCI** (8.44)

Thank you

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Appendix

➢ Assumption II: Arrival-rate segmentation

Table 4.2 Cliff's delta & Levene's test results for $\bar{\lambda}_{t,v}$ by number of berthed vessels

	1	2	3	4	5	6	7	8
1		0.15	0.20	0.21	0.19	0.26	0.30	0.33
2	0.04		0.18	0.24	0.21	0.29	0.34	0.38
3	<0.01	0.04		0.21	0.18	0.26	0.31	0.35
4	<0.01	<0.01	<0.01		0.14	0.20	0.26	0.31
5	<0.01	<0.01	<0.01	<0.01		0.35	0.23	0.15
6	<0.01	<0.01	<0.01	<0.01	<0.01		0.19	0.15
7	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		0.15
8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	

Note: The upper triangle presents Cliff's delta, the lower triangle shows Levene's test p -values.

Table 4.3 Cliff's delta & Levene's test results for $\bar{\lambda}_{t,G}$ by day of the week

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun		0.57	0.83	0.84	0.86	0.87	0.63
Mon	<0.01		-0.15	-0.15	-0.24	-0.22	0.19
Tue	<0.01	<0.01		0.15	-0.15	-0.18	0.41
Wed	<0.01	<0.01	0.02		-0.17	-0.19	0.40
Thu	<0.01	<0.01	<0.01	<0.01		0.17	0.49
Fri	<0.01	<0.01	0.03	0.02	<0.01		0.48
Sat	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	

Note: The upper triangle presents Cliff's delta, the lower triangle shows Levene's test p -values.

➢ Assumption III: Time-invariant service rates

Table 4.4 Cliff's delta & Levene's test results for $\bar{\mu}_{t,QC}$ by number of berthed vessels

	1	2	3	4	5	6	7	8
1		-0.04	-0.06	-0.07	-0.09	-0.10	-0.10	-0.10
2	0.82		-0.02	-0.04	-0.05	-0.07	-0.06	-0.06
3	0.72	0.77		-0.02	-0.04	-0.05	-0.05	-0.05
4	0.65	0.59	0.70		-0.02	-0.03	-0.03	-0.03
5	0.52	0.13	0.08	0.14		-0.01	-0.01	-0.01
6	0.67	0.09	0.09	0.12	0.14		0.00	0.00
7	0.72	0.09	0.07	0.06	0.11	0.08		0.00
8	0.84	0.10	0.07	0.05	0.08	0.09	0.06	

Note: The upper triangle presents Cliff's delta, the lower triangle shows Levene's test p -values.

Table 4.5 Cliff's delta & Levene's test results for $\bar{\mu}_{t,YC}$ by day of the week

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sun		0.06	0.08	0.07	0.06	0.06	0.06
Mon	0.07		-0.02	-0.02	3.96e-04	4.56e-03	5.16e-03
Tue	0.12	0.09		2.95e-03	0.02	0.01	0.02
Wed	0.06	0.08	0.66		0.02	0.01	0.02
Thu	0.09	0.07	0.18	0.09		4.99e-03	4.65e-03
Fri	0.15	0.45	0.35	0.13	0.19		9.71e-03
Sat	0.14	0.24	0.12	0.06	0.12	0.10	

Note: The upper triangle presents Cliff's delta, the lower triangle shows Levene's test p -values.