Original scientific paper
https://doi.org/10.31784/zvr.14.1.32
Received: 14. 2. 2026.
Accepted: 8. 5. 2026.

ELECTRIFICATION OF QUAYS AND GREEN PORT DESIGN: METHODS AND UNCERTAINTIES IN THE ESTIMATION OF EMMISSION

Cristiano Marinacci
PhD, Researcher, Sapienza University of Roma, Via Eudossiana 18, 00184 Rome, Italy;
email: cristiano.marinacci@uniroma1.it

Stefano Ricci
PhD, Full Professor, Sapienza University of Roma, Via Eudossiana 18, 00184 Rome, Italy;
email: stefano.ricci@uniroma1.it

ABSTRACT

The progressive decarbonization of maritime terminal design and operation includes a series of strategic decisions involving the engagement of relevant resources. The research in the field is focused on supporting these key decisions and selecting the most suitable parameters to describe the terminals' environmental performance. Starting from an extensive data collection, the research presented in this paper involves: I) selection of environmental parameters available from public and reliable sources; II) consistency and reliability analysis of data concerning these parameters; III) search of correlation among these factors and parameters related to port terminal dimensions, equipment, and traffic; IV) selection of consolidated reliable correlations; V) use of correlations to derive priority in the implementation of the electrification of quays and other green port design criteria (e.g., dimension and equipment compatible with a certain level of emissions) or operational performances (e.g., traffic manageable with a level of tolerable emissions). The focus is on the uncertainties detected in global and local gaseous emissions estimation, with reference to container, cruise, and Ro-Ro terminals, and the identification of the potential effects of these uncertainties in the following methodological steps for appropriate modeling of the emission generation mechanisms and forecasting them depending on the composition of the fleets calling the ports. In this study, these uncertainties in emission factors are presented, interpreted, and correlated with various parameters in view of their systematic use in the definition of green design of ports, starting from the prioritization of the quays to be electrified.

Keywords: *port, design, emissions, electrification, uncertainties*

1. INTRODUCTION

The present research has been developed within the ongoing collaborative international research project DEMASTER-Design of Maritime Sustainable Terminals, involving Sapienza University of Rome, University of Catania, and University of Ljubljana. It moved from the emerging environmental sustainability priorities, such as the reduction of global and local gaseous emissions, to strategic decision-making priorities at the port level, such as the electrification of quays and, more generally, the operational optimization of energy use, e.g., owing to the rationalization and automation of ports' processes (Twrdy *et al.*, 2025). Therefore, the specific objective becomes the development of sustainable port design and operation methodologies integrating DET with LGE. Section 2 describes the methodological approach. Section 3 is dedicated to the data collection of local LGE, Section 4 to the data collection of DTE, Section 5 to the correlations of LGE and DTE data, Section 6 to the results and discussion, and finally Section 7 to the conclusions.

2. METHODOLOGICAL APPROACH

According to the general objectives, the operational context of the study focuses on container, cruise, and Ro-Ro/Ro-Pax terminals. The initial state-of-the-art included public studies and databases, both included in scientific sources and gray literature, providing relevant inputs in terms of methods and data concerning DET and LGE in a purely bottom-up approach, including the following: 1) collection of data on DET and LGE on a worldwide sampling, 2) search of relevant reliable correlations among DET and LGE datasets, 3) validation test on a selection of Adriatic and Ionian ports, 4) forecasting framework of expected LGE according to defined DET, 5) assessment framework of DET compatible with fixed LGE values.

3. DATA COLLECTION OF LOCAL AND GLOBAL EMISSIONS (LGE)

The first data collection focused on available public data on gaseous emissions generated by port operations. The sources of concern include scientific literature, studies, archives, and assessments issued by port authorities, shipping companies, and terminal operators, normally under the request and pressure of local administrations and communities. The available data on concentrations of local pollutants in specific areas have not been considered for this research due to the complexity of gaseous dispersions processes depending on local geographical and meteorological conditions, which their systematic attributions to ports' operation activities. Therefore, the focus has been posed on the generation potential from ships, which is affected by numerous factors, such as ship typologies, motorization and propulsion systems, various fuels employed, time spent docking and maneuvering, and onboard equipment for the reduction of emissions. The following list species these parameters and (in bold) those that have been considered relevant for the focus of the study on emission in ports:

- Ship activities: navigation, maneuver, **docking**,
- Types of engines: principal, **auxiliary**,
- Engine speed: **low, medium, high**,

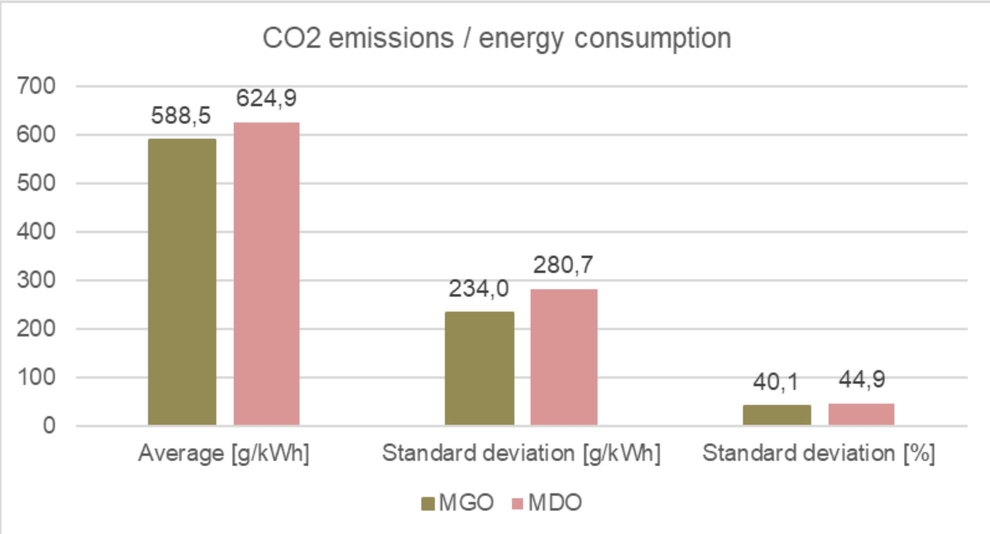
- Generation of engines: **Tier 0** (before 2000), **Tier 1** (2000-2010), **Tier 2** (2011-2015), and **Tier 3** (from 2016).
- Load factors of engines: 12–17% (auxiliary during docking phases),
- Emission factor units: **energy** [kWh], **mass** [t],
- Heavy fuel oil (HFO), residual oil (RO), **marine diesel** oil (MDO), **marine gas oil** (MGO), and low sulfur fuel oil (LSFO),
- Global and local gaseous emissions: **CO_2**, **NO_x**, **SO_x**, **$PM_{2.5}$**, and **PM_{10}**.

The elaboration of the data selected from the scientific sources (Albo López *et al.* 2023), (Canepa *et al.*, 2023), (Díaz Vázquez *et al.*, 2024), (Grigoriadis *et al.*, 2021), (Knezević *et al.*, 2018), (Knezević *et al.*, 2021), (Pastorčić *et al.*, 2020), (Radonja *et al.*, 2020), (Stazić *et al.*, 2020), (Tzannatos, 2010), (Zekić *et al.*, 2022), have been synthetically exemplified with reference to CO_2 emissions in Figure 1.

In parallel, the investigation on the gaseous emissions collected from studies, archives, and assessments issued by port authorities, shipping companies, and terminal operators involved the following sources:

- 15 Container terminals: Ancona, Constanta, Gavle, Genova, Goteborg, Long Beach, Los Angeles, Marseille, Osaka, Oslo, Piraeus, Santander, Sydney, Taranto, and Venezia;
- 25 Cruise terminals: Aarhus, Ancona, Barcelona, Chioggia, Civitavecchia, Copenhagen, Dubrovnik, Goteborg, Heraklion, Kotor, Long Beach, Los Angeles, Marseille, Napoli, Oslo, Piraeus, Santander, Sibenik, Souda Chania, Split, Sydney, Toulon, Trondheim, Venezia, Zadar;
- 17 Ro-Ro/Ro-Pax terminals: Aberdeen, Ancona, Barcelona, Civitavecchia, Goteborg, Heraklion, Klaipeda, Long Beach, Los Angeles, Marseille, Osaka, Oslo, Piraeus, Santander, Souda Chania, Venezia, and Vigo.

Figure 1. Average CO_2 emission factors in ports for ships using MGO and MDO collected from scientific sources



Source: Authors

4. CALCULATION MODELS AND RECOGNIZED INVENTORIES

Various references exist in this field that can be used for a cross-check analysis between the data emerging from our investigation and the recommended data from calculation models and largely recognized inventories. The references that have been considered, among many, are listed in Table 1):

- UK Ship Emissions Inventory (Defra, 2010) for all considered pollutants,
- EMEP/EEA air pollutant emission inventory guidebook 2023 European Environment Agency, 2023) for NO_x and PM.

Table 1. variability of emission factors based on selected literature references for the docking phase of ships

Average values for the docking phase	Emission factors (g/kWh)			
	CO_2	NO_x	SO_x	PM
From the selected references (ships using MGO)	588.500	13.014	0.556	0.286
Defra. 2010 (ships using MGO)	690.000	13.000	0.900	0.300
From the selected references (ships using MDO)	624.875	13.500	3.491	0.353
Defra. 2010 (ships using MDO)	690.000	13.000	6.500	0.400
European Environment Agency. 2023 (high speed)	-	8.530	-	0.221
European Environment Agency. 2023 (medium speed)	-	10.800	-	0.215

Source: Authors

The emerging differences confirm the uncertainties affecting large sets of data referring to ships with different motorization and fuel typologies. They typically change according to technological developments, though the evolutions are moderated by the vessels' long technical life. In particular:

- The moderate differences in CO_2 emissions (10–17% less), mainly depend on the temporal differences between the selected references (2018-2024) and the UK inventory (2010).
- The differences in NOx emissions are negligible in comparison with the UK inventory but more important (25–58% more) in comparison with the EMEP/EEA guidebook and would need further investigations beyond the present study's objective.
- The relevant differences in SO_x emissions (62–86% less) clearly depend on the temporal differences between the selected references (2018–2024) and the UK inventory (2010) and the important evolution of normative and fuel quality in the concerned period.
- The moderate differences in PM emissions with respect to the UK inventory (5–13% less) also depend on the temporal differences between the selected references and the UK inventory. Meanwhile, the more important differences (29–54% more) respect to the EMEP/EEA guidebook would also require further investigation.

5. DATA COLLECTION OF DIMENSIONS, TRAFFIC, AND EQUIPMENT

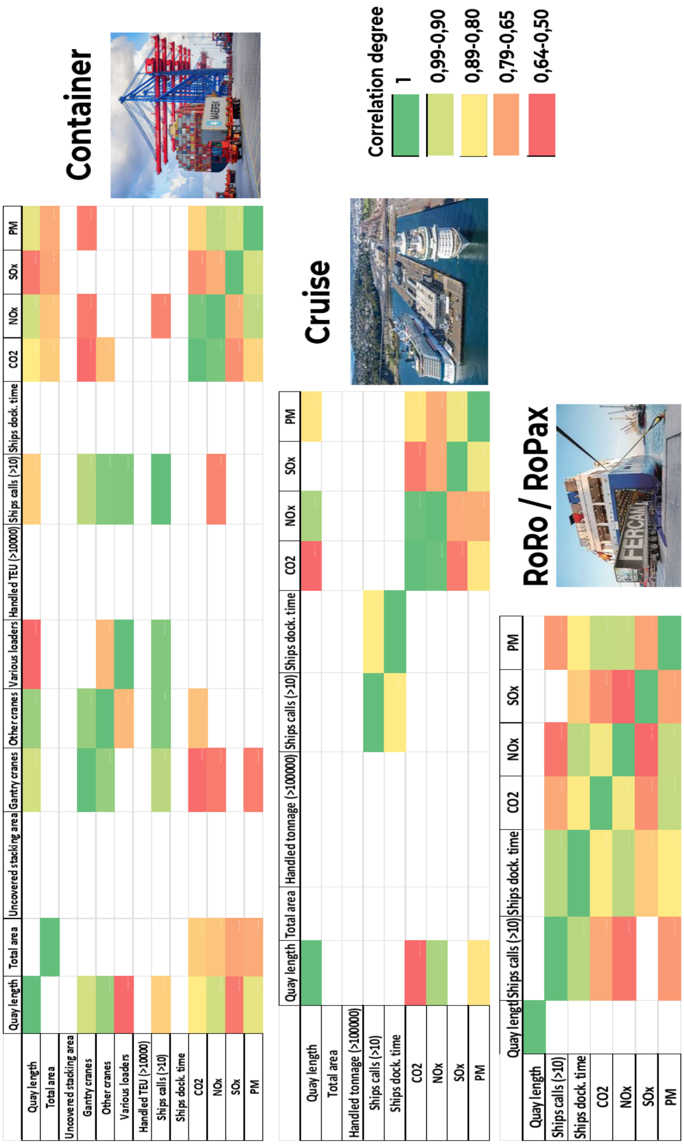
The data collection of dimensions, equipment, and traffic parameters, traditionally approached by the research group (Das Chagas *et al.*, 2021) (Ricci and Marinacci, 2009), considered the following extremely rich and varied panorama:

- Countries: 33 (30 in Europe, one in America, 1 in Asia, and 1 in Oceania)
- Ports: 241 (237 in Europe, 2 in America, one in Asia, and 1 in Oceania)
- Terminals 535 (238 Container, 181 Cruise, 187 R-Ro/R-Pax, and 18 aggregated
- Years: 2010–2025,
- Quay length (m): from 50 to 4,986
- Total area [m2]: from 5,667 to 5,000,000
- Uncovered stacking area [m2]: from 1,080 to 2,200,000
- Covered stacking area [m2]: from 572 to 500,000,
- Number of gantry cranes: 1–90,
- Number of other cranes: 1–80,
- Number of various loaders: 1–341
- TEU handled annually: from 10,516 to 138, 2000,
- Yearly handled tonnage: 101,000–148,900,000
- Yearly ship calls: from 10 to 105,596
- Ships' docking time (h): 90–200,000.

6. CORRELATIONS OF THE LGE AND DTE DATA

The cross-check of DTE and LGE collected data allowed us to investigate their correlations (Barbagallo *et al.*, 2026). In Figure 2, the existing reliable (R2 > 0.50) linear correlations are highlighted. The average CO_2, NO_x, SO_x, and PM emissions referred to the number of calls and total time spent in ports (docking phase) for Container, Cruise, and R-Ro/R-Pax ships are reported in Tables 2 and 3, respectively.

Figure 2. Reliable correlations between DTE and LGE parameters for the container, cruise, and R-Ro/R-Pax terminals.



Source: Authors

Table 2. CO_2, NO_x, SO_x, and PM emissions per port call for container, cruise, and Ro-Ro/Ro-Pax ships

Container ships	**Emissions [t/call]**			
Data records available: 18	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	57.859	0.634	0.106	0.038
Standard deviation	69.761	0.787	0.204	0.047
Percentage standard deviation	120.6%	124.2%	191.5%	122.9%
Cruise ships	**Emissions [t/call]**			
Data records available: 33	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	71.094	1.528	0.121	0.054
Standard deviation	51.200	1.338	0.118	0.048
Percentage standard deviation	72.0%	87.6%	98.3%	88.9%
Ro-Ro ships	**Emissions [t/call]**			
Data records available: 24	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	16.762	0.516	0.074	0.019
Standard deviation	11.775	0.569	0.089	0.014
Percentage standard deviation	70.2%	110.4%	120.9%	75.5%

Source: Authors

7. RESULTS AND DISCUSSION

The first emerging remark is the high level of uncertainty: the standard deviations are close to or beyond 100% of the average values for Container and Ro-Ro ships. Higher stability emerges for cruise ships, particularly for time-dependent values (standard deviations in the range 18–32%) mainly due to more homogeneous fleets (Marinacci *et al.*, 2022) and berth times.

In comparative terms, the emissions referring to the time spent at the berth are generally much more stable than those referring to the number of calls, which include variable durations of the calls themselves. The emissions of PM and CO_2 are normally more stable (max deviation of 92.4%) than those of NO_x and SO_x (max deviation of 143.9%), which are more sensible to used fuels and local regulations.

Table 3. CO_2, NO_x, SO_x and PM emissions per hour spent in port for Container, Cruise and Ro-Ro/Ro-Pax ships

Container ships	**Emissions [t/call]**			
Data records available: 4	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	1.663	0.030	0.002	0.001
Standard deviation	1.331	0.032	0.002	0.001
Percentage standard deviation	80.0%	107.6%	91.9%	63.1%
Cruise ships	**Emissions [t/call]**			
Data records available: 9	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	3.676	0.069	0.003	0.003
Standard deviation	0.646	0.020	0.000	0.001
Percentage standard deviation	17.6%	29.7%	16.8%	32.0%
Ro-Ro ships	**Emissions [t/call]**			
Data records available: 8	**CO_2**	**NO_x**	**SO_x**	**PM**
Average value	2.016	0.089	0.008	0.003
Standard deviation	1.862	0.083	0.012	0.002
Percentage standard deviation	92.4%	93.5%	143.9%	63.5%

Source: Authors

Finally, in absolute terms, the most relevant global and local emissions from cruise ships, both per call (71.1 t of CO_2 and 0.054 t of PM) and per hour (3.7 t of CO_2 and 0.003 t of PM), are generally higher than those from container and Ro-Ro ships. Meanwhile, the trend is different for SO_x, which is positively affected by technological updates that result in the generally shorter technical life of this type of vessel.

8. CONCLUSIONS

From the analysis of the scientific literature data on EFs, the standard deviations are near or beyond 50% of the average values. Meanwhile, more stable values (standard deviation under 40%) are emerging for CO_2 only, which is less sensible to used fuels and local regulations.

From the analysis of operated terminals data, the highest reliability emerges for local and global emissions referred to berthing time instead of the number of calls, mainly depending on the variability of the calls' duration, for cruise ships and for CO_2 and PM emissions. Meanwhile, the highest emission values for all pollutants are from cruise ships, both per call and per hour, due to higher power needs.

The values of the expected emissions, depending on dimensions, traffic, and equipment, are potentially very useful for prioritizing the electrification of quays and green port design in general.

The accurate assessment of uncertainties is indeed a key parameter to prevent possible under- or overestimation of pollution, which plays a key role in selecting the most appropriate measures to mitigate the environmental impacts of ships during berthing and for green port design and operation in general (Gharehgozli, 2019), such as the most appropriate quays to be electrified (Peddi *et al.*, 2024), the most effective fuels restrictions, and the most appropriate traffic limitation and management measures.

The ongoing research developments are now focused on the validation of the methodology by testing it by predicting emissions in selected ports of Adriatic-Ionian area, according to the DEMASTER project's targets.

NOTE
This paper was presented at the scientific conference *Transport & Logistics 2026*, organized by the University of Applied Sciences of Rijeka and the Croatian Scientific Society for Transport, held in Opatija, Croatia, on 16–17 April 2026.

REFERENCES

Albo López, A. B., Carrillo, C. and Díaz Dorado, E. (2023) 'An approach for shipping emissions estimation in ports: The case of Ro-Ro vessels in Port of Vigo', *Journal of Marine Science and Engineering*, 11, p. 884. doi:10.3390/jmse11040884.

Barbagallo, A., Torrisi, V., Ricci, S., Twrdy, E. and Ignaccolo, M. (2026) 'Assessing ship emissions: An estimation approach applied to the Port of Catania (Italy)', in *ICCSA 2025 Workshops*. LNCS 15897. Cham: Springer, pp. 117–130. doi:10.1007/978-3-031-97660-5_9.

Canepa, M., Ballini, F., Dalaklis, D., Frugone, G. and Sciutto, D. (2023) 'Cold ironing: Socio-economic analysis in the Port of Genoa', *Logistics*, 7, p. 28. doi:10.3390/logistics7020028.

Das Chagas, V., Lopez Lambas, M. E., Marinacci, C., Ricci, S. and Rizzetto, L. (2021) 'Dimensioning of container terminals: Validation and application fields for a stochastic process', in *ICCSA 2021*. LNCS 12958. Cham: Springer, pp. 188–197. doi:10.1007/978-3-030-87016-4_14.

Defra (2010) *UK Ship Emissions Inventory*. Final report, November 2010. Doc Reg 21897-01. ENTEC UK Ltd.

Díaz Vázquez, A. M., Fuentes García, G. and Sosa Echeverría, R. (2024) 'Temporal variability of atmospheric carbon dioxide emissions in the Port of Veracruz, Mexico', *Marine Systems & Ocean Technology*, 20(1). doi:10.1007/s40868-024-00147-8.

European Environment Agency (2023) *EMEP/EEA air pollutant emission inventory guidebook 2023: Technical guidance to prepare national emission inventories. Part B: Sectoral guidance chapters 1.A.3.d*. doi:10.2800/795737.

Gharehgozli, A., Zaerpour, N. and De Koster, R. (2019) 'Container terminal layout design: Transition and future', *Maritime Economics & Logistics*, 22, pp. 610–639. doi:10.1057/s41278-019-00131-9.

Grigoriadis, A., Mamarikas, S., Ioannidis, I., Majamaki, E., Jalkanen, J. P. and Ntziachristos, L. (2021) 'Development of exhaust emission factors for vessels: A review and meta-analysis of available data', Tallinn University of Technology Estonian Maritime Academy. doi:10.1016/j.aeaoa.2021.100142.

Knežević, V., Radonja, R. and Dundović, Č. (2018) 'Emission inventory of marine traffic for the Port of Zadar', *Pomorstvo*, 32(2), pp. 239–244. doi:10.31217/p.32.2.9.

Knežević, V., Pavlin, Z. and Čulin, J. (2021) 'Estimating shipping emissions: A case study for Cargo Port of Zadar, Croatia', *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*. doi:10.12716/1001.15.03.16.

Marinacci, C., Ricci, S. and Rizzetto, L. (2022) 'Effects of ships' dimension on emissions of container and cruise fleets', *Ingegneria Ferroviaria*, 77(1), pp. 5–21. ISSN 0020-0956.

Pastorčić, D., Radonja, R., Knežević, V. and Pelić, V. (2020) 'Emission inventory of marine traffic for the Port of Šibenik', *Pomorstvo*, 34(1), pp. 86–92. doi:10.31217/p.34.1.10.

Peddi, K. P., Ricci, S. and Rizzetto, L. (2024) 'Reduction potential of gaseous emissions in European ports using cold ironing', *Applied Sciences*, 14, p. 6837. doi:10.3390/app14156837.

Radonja, R., Ivće, R., Zekić, A. and Catela, L. (2020) 'Emission inventory of marine traffic for the Port of Rijeka', *Pomorstvo*, 34(2), pp. 387–395. doi:10.31217/p.34.2.19.

Ricci, S. and Marinacci, C. (2009) 'Modelling support for maritime terminals planning and operation', *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*. ISSN 2083-6473.

Stazic, L., Radonja, R., Pelić, V. and Lalić, B. (2020) 'The Port of Split international marine traffic emissions inventory', *Pomorstvo*, 34(1), pp. 32–39. doi:10.31217/p.34.1.4.

Twrdy, E., Zanne, M., Stojaković, M., Cocuzza, E., Ignaccolo, M., and Ricci, S. (2025) 'Greening the gateways: Sustainable development of Adriatic and Ionian ports', *Transportation Research Procedia*, 91, pp. 505–512. doi:10.1016/j.trpro.2025.10.065.

Tzannatos, E. (2010) 'Ship emissions and their externalities for the Port of Piraeus', *Atmospheric Environment*, 44, pp. 400–407. doi:10.1016/j.atmosenv.2009.10.024.

Zekić, A., Ivće, R. and Radonja, R. (2022) 'Emission inventory of ships calling at the Port of Dubrovnik', *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*. doi:10.12716/1001.16.02.03.

Izvorni znanstveni rad
https://doi.org/10.31784/zvr.14.1.32
Datum primitka rada: 14. 2. 2026.
Datum prihvaćanja rada: 8. 5. 2026.

ELEKTRIFIKACIJA OBALA I PROJEKTIRANJE ZELENIH LUKA: METODE I NEIZVJESNOSTI U PROCJENI EMISIJA

Cristiano Marinacci
Dr. sc., istraživač, Sveučilište Sapienza u Rimu, Via Eudossiana 18, 00184 Rim, Italija;
e-mail: cristiano.marinacci@uniroma1.it

Stefano Ricci
Dr. sc., redoviti profesor, Sveučilište Sapienza u Rimu, Via Eudossiana 18, 00184 Rim, Italija;
e-mail: stefano.ricci@uniroma1.it

SAŽETAK

Progresivna dekarbonizacija projektiranja i rada pomorskih terminala obuhvaća niz strateških odluka koje uključuju angažiranje relevantnih resursa. Istraživanja u ovom području usmjerena su na pružanje potpore tim ključnim odlukama te na odabir najprikladnijih parametara za opisivanje okolišne učinkovitosti terminala. Polazeći od opsežnog prikupljanja podataka, istraživanje prikazano u ovom radu obuhvaća: I) odabir okolišnih parametara dostupnih iz javnih i pouzdanih izvora; II) analizu konzistentnosti i pouzdanosti podataka koji se odnose na te parametre; III) istraživanje korelacije između tih čimbenika i parametara povezanih s dimenzijama lučkih terminala, opremom i prometom; IV) odabir utvrđenih pouzdanih korelacija; V) primjenu korelacija za određivanje prioriteta pri provedbi elektrifikacije obala i drugih kriterija za projektiranje zelenih luka (npr. dimenzije i oprema kompatibilni s određenom razinom emisija) ili operativnih performansi (npr. promet kojim se može upravljati uz razinu podnošljivih emisija). Poseban naglasak stavljen je na neizvjesnosti utvrđene u procjeni globalnih i lokalnih plinovitih emisija, s osvrtom na kontejnerske, kruzerske i Ro-Ro terminale, kao i na utvrđivanje mogućih učinaka tih neizvjesnosti u sljedećim metodološkim koracima radi odgovarajućeg modeliranja mehanizama nastanka emisija te njihova predviđanja ovisno o sastavu flota koje uplovljavaju u luke. U ovom radu navedene neizvjesnosti emisijskih čimbenika prikazane su, interpretirane i povezane s različitim parametrima s ciljem njihove sustavne primjene u definiranju zelenog projektiranja luka, počevši od određivanja prioriteta obala koje je potrebno elektrificirati.

Ključne riječi: *luka, projektiranje, emisije, elektrifikacija, neizvjesnosti*